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Mapping Technological Paths with Patents: A Study on Hydrogen Generation via Electrolysis for Transport Applications

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Abstract

With the global emergency triggered by the oil crisis and the climate conferences initiated in the 1970s, many countries around the world found themselves compelled to seek alternatives to oil. This led, particularly in the transport sector—one of the largest consumers of oil and emitters of pollutants—to developments aimed at enabling plant-based biofuels, fleet electrification, and the use of alternative fuels, such as hydrogen. Hydrogen, which can be produced through various methods, from oil transformation to molecular water splitting, emerges as a key prospect for achieving the full decarbonization of the global economy. However, the challenges of making it widespread encounter barriers that remain difficult to overcome. Using the methodology of social network analysis, this study aims to map the main trajectory of patents involved in consolidating the processes for hydrogen production through electrolysis, specifically for applications in the transport sector—a sustainable method with potential for widespread adoption due to its high energy efficiency. The results reveal the prevalence of patents that combine electrolytic transformation with internal combustion systems reliant on fossil fuels, an outcome unexpected from a sustainability standpoint. These findings underscore the need to identify a secondary trajectory with clearer advancements toward sustainability. This research aligns with Sustainable Development Goals (SDGs) 7, 13, and 11.

Keywords: Hydrogen; Electrolysis; Hydrogen Economy; Sustainability.

JEL Classification: O25; O14; Q58

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Resumen

Con la emergencia global planteada por los shocks del petróleo y las conferencias climáticas iniciadas en la década de 1970, diversos países del mundo se vieron impulsados a buscar alternativas al petróleo. Como resultado, en el sector de transporte —uno de los mayores consumidores de petróleo y emisores de gases contaminantes— se observaron desarrollos orientados a viabilizar la producción de biocombustibles de origen vegetal, la electrificación de flotas y el uso de combustibles alternativos, como es el caso del hidrógeno. Este último puede obtenerse de diversas formas, desde la transformación del petróleo hasta la separación molecular del agua, y se presenta como una apuesta clave hacia la descarbonización total de la economía global. Sin embargo, los desafíos para popularizar su uso enfrentan barreras que todavía resultan difíciles de superar. Mediante la metodología de análisis de redes sociales, este estudio tiene como objetivo trazar la trayectoria principal de las patentes relacionadas con la consolidación de los procesos de obtención de hidrógeno a través de la electrólisis con aplicaciones en el sector de transporte, un método sustentable y con potencial de popularización debido a la elevada eficiencia energética lograda. Los resultados muestran la prevalencia de patentes que combinan la transformación electrolítica con sistemas de combustión interna de combustibles fósiles, algo inesperado desde la perspectiva de la sostenibilidad. Estos hallazgos indican la necesidad de identificar una trayectoria secundaria con desarrollos más claros hacia la sostenibilidad. Esta investigación se alinea con los Objetivos de Desarrollo Sostenible (ODS) 7, 13 y 11.

Palabras clave: Hidrógeno; Electrólisis; Economía del Hidrógeno; Sostenibilidad.

Código JEL: O25; O14; Q58.

1. Introduction

The historical episode known as the oil crisis of 1973 put the world on high alert. The major global economies, which relied heavily on fossil fuels for energy in their economic activities, were left powerless when the group of countries monopolizing oil production—and consequently its pricing—tripled the cost overnight. Alongside this unexpected situation came the first formal discussions on how carbon dioxide emissions could impact life on Earth. Consequently, governments of the world's leading nations at the time took measures to reduce oil consumption (Baran; Legey, 2011).

In the transport sector, a significant contributor to both environmental pollution and oil consumption, governments around the world sought alternatives to reduce reliance on fossil fuels. Solutions included developing biofuels from various sources (corn, soybeans, castor beans, sugarcane, and others), exploring electricity as a viable fuel, and researching new types of fuel, most notably hydrogen (Cordeiro; Losekann, 2018).

From 2003 onward, as noted by Kovac, Paranos, and Marcius (2021), the development of increasingly efficient and cleaner processes to produce hydrogen gained momentum. At that time, the technology had reached specific milestones that made the scaling of economically viable processes possible technologies first explored before the oil crisis.

Since then, various countries, led by the United States, Japan, and, more recently, China, have made consistent efforts in the form of patents for products and processes aimed at the safer and more efficient production of hydrogen. However, the use of hydrogen remains nontrivial due to several factors, primarily its high cost compared to other fuels and the dominance of fossil fuel transformation as the main method of hydrogen production. Environmentally appropriate processes, which convert water or bioproducts into hydrogen, remain more expensive than those derived from fossil fuels. Nonetheless, advancements in this direction have become increasingly evident since 2003 (Aldieri; Vinci, 2016).

This study focuses on sustainable developments in hydrogen fuel production. Numerous processes can produce this fuel. Therefore, after detailing these production processes, this research analyses electrolysis using the rigorous methodology of patent network analysis. Electrolysis is considered the most promising technological route to sustainably produce hydrogen due to its high energy efficiency, significant production volumes compared to other renewable sources, and straightforward application in the transport sector (Castro et al., 2023).

Using the detailed classification system of the Cooperative Patent Classification (CPC), this study filtered data from the Australian patent database Lens.org using code F02b2043/006. This code, under the broad category F (mechanical engineering, lighting, heating, weapons, blasting) and subclass F02 (combustion engines; hot-gas or combustion-product engine plants), specifically describes the generation of hydrogen through electrolysis with direct applications in the transport sector. Data were processed using the methodology developed by Hummon and Doreian (1989), Batagelj (2003), Verspagen (2007), and Fontana et al. (2009) to map the detailed main trajectory of knowledge within this complex network.

The goal is to identify the main trajectory within this patent network and pinpoint the key patents, actors, and countries leading technological development in this field. Patent filings provide more than registration numbers and citations, they also reveal details such as inventors, technology owners, jurisdictions, and other. This allows identification of the patents and actors occupying central positions and forming critical nodes within the network.

If the results indicate a predominant trajectory that is not environmentally sustainable, a second stage of investigation will explore secondary paths to analyse those that are more aligned with sustainability and a "clean" technological future.

Beyond this introduction, the document is divided into six sections. The first presents the theoretical framework underpinning the study. The second describes the technology under analysis and its main characteristics. The third details the methodology used. The fourth highlights the primary findings. The fifth focuses on the most significant sustainable trajectory, and the sixth offers conclusions based on the results. Additionally, the document includes an attachment detailing all patents within the main trajectory.

2. Paradigms and Technological Trajectories: The Theoretical and Conceptual Discussion

Many innovations have drastically changed human history. Airplanes, automobiles, mobile phones, and the internet have transformed how humanity interacts with the world and with one another. However, the path to achieving these revolutionary products has not been straightforward.

Technical and technological progress influences and reshapes the economy, subsequently affecting economic growth. This is because innovation drives changes in firm strategies and the socioeconomic fabric of a nation or, in the era of globalization, the world.

During the 1960s and 1970s, discussions emerged about how technological changes occur. Some scholars argued that technology acts as an autonomous force, driving development and disrupting established trajectories. Others saw social relations, particularly within the realm of demand, and economic evolution as prerequisites for technological advancement. The key difference between these views lies in how market signals influence the direction of technical and technological activity (Sahal, 1981; Dosi, 1982; Coombs, 1988).

The "demand-pull" school of thought, which emphasizes the role of demand in driving technological progress, suggests that increases in demand and changes in relative prices signal the market to adopt specific paths. Innovations then emerge to fill gaps created by rising demand (Dosi, 1982).

This perspective treats science and technology much like a magician's hat—expected to produce answers as new demands arise. However, this assumption often does not align with reality. Here, technology is seen as responsive and capable of shifting directions with ease. In this view, the market functions as an efficient and rational allocator, drawing freely available technological resources in response to needs (Dosi; Orsenigo, 1988).

Demand-pull theories fail to account for the radical uncertainty involved in the innovation process. They overlook that choosing a specific technological trajectory depends on previously built knowledge, which is not always available. Moreover, when such knowledge exists, it depends on past actions that might not have been developed due to alternative choices (Nelson; Winter, 1977; Dosi, 1982; Dosi; Orsenigo, 1988).

Conversely, "technology-push" theories, which view technological progress as driven by advancements within technology itself, have their own limitations. These theories often disregard how market demands can guide technological development. By treating technological advancement as exogenous to the market, they create an idealized view of development, ignoring the significant costs and uncertainties inherent in the process. As a result, they undermine the role of economic and social factors in directing and intensifying technical progress (Coombs, 1988).

Sahal (1985) argues that both perspectives fail because they overlook the feedback loop between the real economy and technological progress. These elements shape and influence each other continuously.

By the late 1970s, there was a shift in understanding the relationship between technological progress and its determinants. Innovations were no longer seen as isolated occurrences. Instead, the evolutionary progression of technology was viewed more broadly (Coombs, 1988).

Following Schumpeterian logic, where technological innovation drives economic and market creation and transformation, technological progress began to be seen as a problem-solving mechanism. However, this process also brings with it costs and uncertainties, as creating something new inherently involves risks.

Problems and their potential solutions require the involvement of numerous agents. Formal knowledge, specialized tools, and novel codifications must come together to build the foundation of knowledge. These foundations eventually enable innovation activities to yield results, addressing the challenges at hand (Dosi, 1982; Nelson; Winter, 1977; Winter, 1984).

Innovation activities, as described by Dosi (1988), involve processes of searching, discovering, experimenting, developing, and imitating. Each stage is fraught with uncertainty, extending beyond the inherent risks of research and development to include the acquired experience and the socioeconomic perception of whether the activity, product, or process will succeed as a technological trajectory.

Technology is thus understood as a collection of processes, activities, searches, uncertainties, know-how, and other elements that result in usable knowledge, whether practical or theoretical. This knowledge is not externally available to those who do not actively pursue it (Dosi, 1982).

Furthermore, the relationships between different agents lead to unequal developments of a given technology. Knowledge bases may progress at different points, be protected in varying ways within the private sector, and develop unevenly depending on the characteristics and interests of individual agents. Consequently, progress becomes selective, cumulative, and specific, depending on the internal capacities and "technological history" of firms or agents (Nelson; Winter, 1977; Sahal, 1985).

This dynamic results in internal technological paths that, when generalized to a broader economy, form distinct technological trajectories. These trajectories are essentially a limited set of problems that can be resolved or adjusted to a changing economic context, given the available knowledge at a specific point in time (Nelson; Winter, 1977; Utterback; Suarez, 1993). The boundaries within which these technological trajectories operate are what Dosi (1988) termed "technological paradigms."

The inherent logic of a paradigm involves viewing reality through a specific lens, identifying relevant problems that require solutions, and creating models and standards to address these problems. All of this occurs within a shared base of knowledge, scientific principles, technical materials, and technologies (Freeman, 1984; Dosi, 1988).

> *"A technological paradigm can be defined as a model for solving selected techno-economic problems, based on highly selective principles derived from natural sciences, along with specific rules aimed at acquiring new knowledge and ensuring its rapid diffusion among competitors whenever possible" (Dosi, 1988, p.127).*

According to Dosi (1988), within a paradigm, multiple technological trajectories—or paths of technical evolution—can exist.

> *"A technological trajectory, that is, a problem-solving activity defined by a paradigm, can be represented by the multidimensional trade-offs between the technological variables that the paradigm identifies as relevant. Progress can be defined as the improvement of these trade-offs" (Dosi, 1982, p.154).*

Additionally, technological trajectories dominating the social fabric until confronted and replaced by other trajectories involving new technological paradigms carry what Freeman (1984) termed "incremental innovations." These are significant improvements in products or processes within the existing paradigm.

Like these avenues and technological paths, Nelson and Winter (1977) described what they called the "natural trajectory of innovations". This idea adds that there is an inevitable trade-off in choosing one innovative path over another. It is within this trade-off that the uncertainty of the innovation process is concentrated, as technical alternatives and consumer preferences are not precisely known. However, as the paradigm evolves over time, an internal logic of incremental innovations tends to prevail.

The internal logic that standardizes the direction of innovation within a paradigm, almost creating a uniform trajectory, is referred to by Utterback and Suarez (1993) as a "dominant design." Typically established by leading firms, these designs reduce the inherent uncertainty of the innovation process until the possibilities for trajectory evolution are exhausted, or the firms' essential competencies and dominance are altered.

Depending on the nature of the paradigm and its innovative scope—or the possible innovative trajectories—different innovation rates can be observed, which in turn influence the maturity speed of the sector. Thus, the degree of cumulative innovation within a technological trajectory depends on the volume of possible innovations within that trajectory. A firm's ability to innovate or imitate is directly linked to its knowledge base and technological level, which varies among firms and determines their capacity to take advantage of certain technological advances (Dosi, 1981;1988).

Even when firms have high capacities for cumulative innovation, the lack of incentives for promoting innovation can hinder technical progress. Without the prospect of economic gains, firms are unlikely to pursue technological advancements. Caetano (1998) argues that the greater the private appropriation of the results of technical progress, the higher the firm's commitment to pursuing technological advancement. This is because the economic imbalance resulting from this differentiation can significantly alter the economic trajectories of the adopting firms.

This imbalance varies depending on the characteristics of the innovation. Nelson and Winter (1977) distinguished between "radical innovations," which can open new technological routes within an existing paradigm, and "incremental innovations," which focus on improving existing processes or products.

The ability of firms to absorb such innovations can create barriers to entry in the sector, leading to market concentration around the pioneering company. Alternatively, depending on the nature of the innovation and its creator, it can disrupt and destroy the essential competencies that previously secured market power for firms in the sector (Abernathy; Clark, 1985; Tuschman; Anderson, 1986).

Thus, the choice between taking the risks of innovation to reap the rewards as a "pioneer" or avoiding risks altogether—potentially betting on an obsolete paradigm in a competitive market—leads to unpredictable outcomes due to the high uncertainty involved (Achilladellis et al., 1990).

Additionally, Nelson and Winter (1977) highlighted the role of institutions and socioeconomic relations in selecting whether to adopt a given paradigm among the various possibilities initially opened by science.

From a firm's perspective, this selection would weigh costs, economies of scale and scope, and potential differential profits—both those provided by patent filings and the opening of new markets. On a broader scale, institutions could ensure markets through public procurement, financing, exemptions, regulatory changes, and other industrial policy strategies (Dosi, 1982).

In summary, prices and demand help dictate the rates of technical progress and the potential trajectories of advancement within a paradigm. They also serve, when comparing paradigms, as one of the possible selection criteria. However, these mechanisms require complementary factors to solidify technological paths, such as institutional interests, public agency or government incentives, entrepreneurial willingness, sufficient capital stock to handle the transition, and user capacity to adapt to changes (Dosi; Labini, 2007).

In recent years, environmentally sustainable innovations, which emerged after the oil crisis and the conclusions of the Stockholm Conference, gained momentum after 2015, following the implementation of the Sustainable Development Goals (SDGs). These innovations face even greater uncertainties compared to periods described earlier. This is because large global conglomerates, significantly expanded post-globalization (Santos, 2001), are immersed in environmentally unsustainable paradigms. Advancing towards a new way of production is not a trivial step, as it can lead, beyond monetary losses, to a redistribution of market shares currently controlled by some firms, considering that new paradigms present new windows of opportunity. (Andreoni, Chang, 2019; Mathews, 2020).

Given the need to create technological paradigms or improve trajectories to make them more environmentally friendly, we inevitably see greater actions from institutions to promote and encourage these pathways. These actions vary by sector and country, but a common thread is the promotion of clear legislation that delineates what is desired from what is not (Cohen; Lobel; Perakis, 2016).

Beyond legislation, the environmentally sustainable innovation process has gained clear global dimensions through industrial protection to incentivize emerging technologies in this sector. Currently, there are specific classifications for the registration of patents that encompass environmentally sustainable innovations (INPI, 2022).

Since the inauguration of the cooperative patent classification in 2013, a significant re-categorization effort has been underway. Patents that previously lacked such distinction are now classified as environmentally sustainable if they meet the criteria, regardless of the year they were filed. This opens possibilities to examine whether technological development followed a trajectory towards sustainability or could always have been classified as such if the classifications existed at the time. This study will explore this line of investigation.

Therefore, it is essential to proceed with a classification, detailing, and explanation of the environmentally sustainable study object here intended, the electrolysis process for hydrogen generation.

3. Green Hydrogen: Brief Context, History, and Production Routes

In this study, we apply social network analysis to examine the evolution of the knowledge trajectory involved in green hydrogen production via electrolysis. Therefore, it is necessary to conceptualize hydrogen fuel in its historical context and, given the numerous possibilities for producing this fuel, highlight the one that is the focus of this research. In this section, we will provide relevant information about the advancements of the chosen technology, placing it in a more general context that encompasses all forms of hydrogen production.

Hydrogen is a high-energy-density fuel, making it more efficient compared to other established fuels. It can be produced from various sources, ranging from petroleum to water, demonstrating its versatility as an input. When analysed from a sustainability perspective, its production primarily involves processes utilizing water, other biofuels, or biomass (Chantre et al., 2023).

Globally, Zhou et al. (2024) identify three crucial phases for the development of technologies involved in hydrogen fuel production. The first phase begins in the 1970s as a result of the oil shock, but it did not see significant advancements due to the high volatility of hydrogen, which prevented its commercial use, although it laid the theoretical foundations for later developments. The second phase spans from 2003 to 2013 and is considered the densest in terms of basic research on hydrogen production and its applications as a fuel. The third phase starts in 2014 and continues to the present, marked by what the authors call "nodes and connected lines," indicating a period of greater technological transfer and increased commercial use of this technology.

Institutionally, countries such as the United States, China, South Korea, the United Kingdom, Germany, and Japan lead in patent filings related to this technology. However, patents specifically addressing environmentally sustainable production have historically been concentrated in the United States, with recent contributions from China and South Korea, particularly after the COVID-19 pandemic.

3.1 The Evolution of Hydrogen and Its Applications

Chemically, hydrogen is the most abundant element in the Earth's atmosphere and one of the simplest, being composed of one electron and one proton. However, as a gas, it is odorless, colorless, and highly flammable. Although it has gained attention since the 2000s, the discovery of hydrogen's energy and economic potentials has been observed for at least 150 years (Daewoo et al., 2020).

First observed by Paracelsus as a result of combining sulfuric acid with iron, hydrogen received its first formal notation in the 16th century. Years later, in the 17th century, also in Switzerland, where Paracelsus resided, Myelin discovered that hydrogen gas was highly flammable (Sasaki et al., 2016).

The first formal experiment aimed at transforming other components to produce hydrogen—then unnamed—was conducted in 1761. Similar to Paracelsus's earlier experimental work, this involved combining iron with various acids. The name "hydrogen" was assigned 15 years later when Henry Cavendish published an article in the Royal Society of London (Rivkin; Buttner, 2015).

In 1800, Nicholson and Carlisle successfully produced hydrogen fuel through water electrolysis. However, the process only became practical, allowing hydrogen to be stored and used as fuel, nearly 90 years later when James Dewar managed to liquefy the gas (Boudellal, 2018).

From this point onward, the history of hydrogen fuel and fuel cells became intertwined. In the transport sector, the most practical solution for utilizing hydrogen involves incorporating it into a fuel cell system. Here, the combustion of hydrogen rotates a motor, transforming this motion into energy to power batteries and, subsequently, an electric motor that propels the vehicle (Riveira; Hernandez, 2007).

In 1832, Michael Faraday formally described the two main laws involved in the process of electrolysis. The first law states that the mass of a substance produced at an electrode during electrolysis is proportional to the amount of electricity transferred at that electrode. The second law states that the number of Faradays of electric charge needed to discharge one mole of a substance at an electrode is equal to the number of excess elementary charges on that ion (Princeton, 2007).

It took six years after Faraday's formalization for the first fuel cell capable of transforming hydrogen fuel into motion to be developed. In 1838, William Grove combined platinum electrodes with sulfuric acid, sealing the product of this reaction in a container filled with hydrogen and oxygen. He called it a gas battery, marking the invention of the first fuel cell (Rivkin; Buttner, 2015).

Attempts to improve Grove's concept continued until the early 20th century. Contributions by Ludwig Mond and Wilhelm Ostwald helped formalize chemical and mathematical knowledge on tension, materials, and other factors that could enhance the efficiency of the process, including the reaction of iron and acids into hydrogen, its condensation, and storage (Riveira; Hernandez, 2007).

The 20th century, particularly the post-oil crisis years, saw numerous incremental advancements in hydrogen production, use, and storage as a fuel. The first large-scale applications of hydrogen fuel for transport were in airships, popular during the 1920s and 1930s. However, this usage did not persist due to the safety risks associated with hydrogen, culminating in the Hindenburg disaster.

Asa Chemical in the United States published the first patent describing a gasoline-hydrogen engine with an internal electrolyser in 1941. This patent laid the foundation for developments in the sector, marking the beginning of publications focused on making hydrogen production via electrolysis economically viable (Lens, 2024).

In 1958, when NASA was established, hydrogen regained prominence for its potential to propel space launches. By 1961, NASA had become the world's largest purchaser of hydrogen fuel (Sasaki, 2015).

in the Soviet Union in 1988, advances in space technology led Tupolev, the country's main aircraft manufacturer, to develop the first hydrogen-powered airplane. The TU-155, which was launched into operation, conducted over 100 commercial flights before being retired following the dissolution of the Soviet Union years later (Sasaki, 2015; Daewoo et al., 2020).

The 21st century, particularly the period from 2003 to 2013, saw a significant volume of patent filings and scientific publications on the topic. Many significant advancements have been achieved, and today various firms use hydrogen as a primary energy source.

However, most of this hydrogen is still derived from fossil fuel transformation. In the transport sector, the most notable advancements are observed in Japan, where Toyota and Honda have been mass-producing hydrogen-powered models since 2007. Despite this, the most prominent patents in the sector continue to originate from U.S. firms and inventors (Akpan; Olanewaju, 2023; Zhou et al., 2024).

Numerous challenges still affect hydrogen's production, distribution, and storage. Perhaps the most significant issue is the unsustainable nature of most hydrogen currently available worldwide. Additionally, the volatility of hydrogen poses storage risks that must be addressed.

In summary, the trajectory of hydrogen can be synthesized as shown in Table 1.

Table 1: Time frame in the history of hydrogen fuel.

Date	Country	Inventor	Description
Century XVI	Switzerland	Paracelsus	Iron + sulfuric acid
Century XVII	Switzerland	Myelin	Hydrogen is highly flammable
1761	Ireland	Robert Boyle	iron filings+dilute acids
1776	England	Henry Cavendish	named hydrogen
1800	England	William Nichols and Anthony Carlisle	Describe the electrolysis of water
1832	England	Michael Faraday	Two laws of electrolisys
1838	England	Robert Grove	Create the first Fuel Cell
1889	Germany	Ludwig Mond	Experiments whit fuel cells
1893	Germany	Wilhelm Ostwald	Improve theories on how fuel cells work
1920-1940	USA	_	Hydrogen fuel used in airships
1941	USA	Asa Chemical	Patent first oil/hydrogen electrolysis motor
1958-1961	USA	NASA	Use of hydrogen in space studies
1962	USA	Pratt & Whitney	Fuel Cell to powered Apollo Apace Aircraft
1988	Soviet Union	Tupolev	The world's first experimental aircraft operating on hydrogen
1990	USA	University of California	Methanol Fuel cell for Nasa aircraft jet propulsion
2007-2025	Japan	Honda	Mass produce FCX fuel cell model
2008	USA	Toyota	Control system for hydrogen addition internal combustion engine
2015-2025	Japan	Toyota	Mass produce Mirai fuel cell model
2023-2025	China	Dongfeng	Mass produce Venucia V hydrogen-powered model
2025	Korea	Hyundai	Mass produce Nexo fuel cell model

Source: Riveira-Hernandez, 2007; Daewood et al, 2020.

The production of hydrogen through electrolysis, initially conducted in Paracelsius' experiment in the 16th century and its subsequent developments, including the patent by Asa Chemical, leading to mass production of vehicles and airplanes using the fuel, is the central focus of this research. This trajectory is highlighted as one of the most promising for commercially viable and sustainable hydrogen production due to the use of clean energy sources (water or ethanol) and the high efficiency in converting one product to another. These factors will be analyzed in detail in subitem 3.2.

3.2 Hydrogen fuel productive routes

Currently, there are three main environmentally sustainable methods for producing hydrogen as a fuel: electrolytic, thermal, and photolytic processes. These technological pathways enable various processes to yield hydrogen suitable for use as a fuel. Specifically, the electrolytic process employs water electrolysis; thermal processes obtain hydrogen from the transformation of biomass, bio-derivatives, natural gas, and the thermal decomposition of water; and photolytic processes produce hydrogen through photodecomposition, both biological and electrochemical (Nikolaidis & Poullikkas, 2017; Wanniarachchi et al., 2022).

The thermal technological pathway, capable of transforming hydrocarbons, ethanol, and biogases into hydrogen, is currently the most efficient and economically viable set of processes for producing the fuel. It includes three possible processes: steam reforming, partial oxidation, and autothermal reforming (IEA, 2021).

Steam reforming is the most widely used mechanism globally, accounting for over 96% of hydrogen production worldwide. Its conversion efficiency, transforming the base fuel into hydrogen, is among the highest, achieving nearly 85%. However, the primary concern with this process lies in its reliance on petroleum derivatives, rendering it unsustainable in the context of "greening" economies (Dawood, Anda & Shafiullah, 2020; Chang & Rajuli, 2024).

Partial oxidation, on the other hand, was designed for fuel cells in vehicles or small-scale applications. This process involves transforming methane or biogas at high temperatures and pressures. However, it remains costly and less efficient compared to steam reforming (Nikolaidis & Poullikkas, 2017).

Autothermal reforming, which involves injecting steam to enable partial catalytic reduction, combines aspects of steam reforming and partial oxidation. This method is considered promising among technological pathways for hydrogen production, as it generates fewer byproducts, offers high efficiency, and provides operational flexibility compared to its counterparts (Ogo & Sekine, 2020).

Thermal transformation, as the name suggests, has the drawback of producing undesirable toxic gases, including greenhouse gases (GHGs). To address this issue, gas capture strategies are often adopted, though these can increase production costs by up to 30%. However, in the case of ethanol, this environmental impact is offset by the sugarcane cultivation process, which serves as the raw material for the fuel (Ogo & Sekine, 2020; IEA, 2021).

According to Holloday et al. (2009), gasification is one of the oldest processes for hydrogen transformation, aiming to heat biomass or coal to temperatures above 700°C and then use a second reactor to catalyze the by-products of this controlled heating, resulting in H2 used as fuel.

One of the fuel sources for the gasification process is biomass, which can lead to the environmentally sustainable production of hydrogen. However, the barrier to overcome is the high cost of the reactors necessary for the process and the large amount of biomass needed for large-scale production. Additionally, biomass carries significant moisture, making the process much less efficient than when using coal.

Thermal decomposition of water is a theoretically simple process but encounters significant practical challenges, primarily economic feasibility. While the chemical process of separating hydrogen molecules from oxygen is well understood, it requires temperatures above 2,500°C, necessitating advanced technological machinery and, consequently, high costs for scalable production (Kalamaras & Efstathiou, 2013).

Although not yet economically viable, thermal decomposition is considered one of the most promising future methods for sustainable production, as its inputs are simple and its output is environmentally clean (Serra et al., 2023).

Photolytic transformation uses semiconductor electrodes energized by sunlight to split water molecules, chemically resembling the thermal water decomposition process. Using solar energy and water is one of this technological pathway's key advantages. However, this is still a nascent and inefficient method. Nevertheless, due to its simplicity in terms of raw materials, it offers the potential for large-scale and low-cost production if improved in the coming years (Tee et al., 2017; Serra et al., 2023).

Electrolytic reforms are a distinct field of study with over 200 years of advancements in production techniques involving various types of gases. In hydrogen production, three processes stand out: alkaline transformation (low temperature, high pressure, and high energy consumption), proton exchange membrane (exclusive use of water, low temperature, high-pressure, high-energy consumption, and commercial use), and high-temperature electrolysis using ceramic membranes (use of water vapor, high temperature, low pressure, and still restricted and non-commercial use). Technical details regarding the operation and functionality of these processes are well described in the works of Garlyyev et al., 2020; Chi and Wu, 2018; Ursua et al., 2011; and Zoulias et al., 2004.

The electrolytic reform process, besides studies dating back to the 18th century, features a high volume of patents, indicating significant technological development and wide applicability. (Tenhumberg & Büker, 2020).

> *"Hydrogen production from water electrolysis associated with renewable energy sources is undoubtedly a promising pathway for future energy sustainability. However, high electricity consumption and energy costs still inhibit the expansion of this technological route" (Serra et al., 2023, p. 34).*

The radiation in the hydrogen peroxide compound to produce hydrogen fuel is one of the most recent technological pathways used to achieve the product. This places the process at the center of numerous research and hypotheses, as, although data on the efficiency of the process are not yet defined, large-scale generation in adapted reactors could be of great value for clean, industrial-scale production of this input within a few years. (Souza, 2021).

Among the technologies mentioned, those involving electrolysis, photolysis, photodecomposition, chemical decomposition, and radiation are considered environmentally sustainable for hydrogen fuel production, from source to use. While sustainable production currently accounts for only 4% of global hydrogen production, economic and social pressures toward sustainability are likely to drive the valuation and acceleration of these developments (Nikolaidis & Poullikkas, 2017; Serra et al., 2023).

In summary, the technological pathways for hydrogen production, their methods, and input materials are outlined in Table 2. It should be noted that any type of energy that uses non-fossil raw materials and/or results in neutral or zero greenhouse gas emissions is considered green. The technological pathway to be analyzed by this research is considered green as it meets both of the criteria mentioned above.

Table 2: Hydrogen fuel production processes.

Technological path	Fuel	Raw material	Range efficiency	Green energy?
Electrolisys	Eletricity	Water	62-90%	Yes
Electrophotolisys	Eletricity/photonic	Water	0,5-12%	Yes
Photolisys	Photonic	Water/Algae	1,6-5%	Yes /No
Biophotolisys	Photonic Bioenergy	Algae/Bacteria/Residues/ Biomass		No
Bioelectrolisys/biothermolisys	Electric Bioenergy *(+ fermentation)*	Biomass	70-80%	No
Biolysis	Bioenergy + *(fermentation + CO*)	Algae/Bacteria/Residues/ Biomass	35-85%	No
Biothermolisys	Thermal bioenergy	Biomass/Acids/Microwave	35-45%	No
Thermolisys/Thermoelectrolisys	Thermal	Water/Coal/Oil/Methane/ other fossil fuel	20-75%	Yes /No
Chemical (gasification)	Chemical reaction(oxireduction)	Water/Hydrate/Hydroxide /Metal	3-5%	Yes
Radiolisys	Radiation	Peroxide of hydrogen/water	Not reported	Yes

Source: DAWOOD; ANDA; SHAFIULLAH, 2020. Note: The variation in the range of energy efficiency arises from the raw materials used and the machinery used, it is a characteristically unstable process that can produce different yields in its production. Processes that use raw materials considered clean and not considered green energy normally generate toxic gases in fermentation sub-processes.

It is possible to identify several technological pathways for the environmentally sustainable production of hydrogen. Among these, this research will focus particularly on production via electrolysis.

This focus is due to four key reasons:

1. The high energy efficiency of this process, which stems from using a basic input such as water or, as suggested by Ni et al. (2007), ethanol.
2. The maturity of this process, which provides a substantial set of data sufficient to deliver satisfactory insights for this study (Tenhumberg & Büker, 2020).
3. The fact that 96% of hydrogen production comes from non-sustainable sources, and among the 4% produced through sustainable methods, electrolysis is the most significant pathway. (Castro et al., 2023; Chang & Rajuli, 2024).
4. The facilitated applicability of electrolysis in the transportation sector, as hydrogen can be generated within the engine system itself (Chang & Rajuli, 2024; Ursua et al., 2011).

The above-mentioned knowledge network can be studied and evaluated through different approaches. Perhaps the most common methods involve examining outcomes in the form of patents or scientific articles. Bibliometric and statistical tools can be employed to identify central points within trajectories, highlight key inventions, and conduct additional analyses. These approaches allow for effective investigative work on the publication trajectory of articles and patents. However, the level of disaggregation and detail required for the in-depth analysis of a knowledge network, combined with this study's objective of mapping the main knowledge trajectory within the extensive dataset of a paradigm, leads us to employ social network analysis tools. This method is frequently used across various economic and social sectors (Mina et al., 2007; Ramlogan et al., 2007; Verspagen, 2007; Fontana et al., 2009; Jang et al., 2012; Keskitalo et al., 2014; Sun et al., 2018; Tatsch et al., 2023).

4. Social network analysis and identification of a main trajectory

This research focuses on analysing patents, characterized as detailed documents containing features, specifications, drawings, and other information about the invention, as well as the names of the creators, references to prior patents, and patent citations. These elements fulfil legal requirements and situate the invention within a network of knowledge that often involves multiple actors and other inventions (Verspagen, 2007).

> *"Broadening this legal interpretation, it has been argued that a reference to a previous patent indicates that the knowledge in the latter patent was in some way useful for developing the new knowledge described in the citing patent. This is exactly the type of interpretation that allows us to use patent citations as a tool for mapping technological trajectories" (Verspagen, 2007, p.7).*

In this sense, capturing technological routes in a globalized world, where various countries aim to dominate different technological areas, is not a trivial task. Social network analysis can contribute to identifying interactions that enable knowledge evolution and analysing the contributions of different actors, institutions, and countries.

The application of social network studies to understand main trajectories began with the work of Garfield et al. (1964), who observed a strong correlation between the history of events driving the advancement of a specific knowledge field and the academic publications accompanying this progress. Garner (1965) significantly advanced this methodology by applying graph theory to this analysis.

In their pioneering study, Hummon and Doreian (1989) analysed the main path of ideas leading to the discovery of DNA. They introduced three indices capable of balancing social networks, highlighting the most critical parts and offering an easier understanding of the nodes and edges forming the most important communities in such networks.

Methodologically, this study adopts a similar approach to those of Hummon and Doreian (1989), Verspagen (2007), and Fontana et al. (2009). Using the Lens.org patent database, it aims to map the main knowledge trajectory underpinning inventions related to sustainable hydrogen production via electrolysis (Cooperative Patent Classification = F02b2043/106).

Hummon and Doreian (1990) originally described the social network of patent analysis as a set of vertices representing patents and edges representing connections between two or more patents through citations. What distinguishes patent network analysis from other bibliometric analyses is the ability to direct edges from one point to another—from a cited patent to the citing one—thus forming a knowledge path. Depending on its weight, this path can become a significant piece of the network (Batagelj, 2003).

The citation network is represented by a matrix C, where an element $c(i,j)$ equals 1 if patent j cites patent i, and 0 otherwise. A symmetric matrix C^* is defined by taking the maximum value of the elements below and above the diagonal in C. A (weak) component in the network C is a subset of patents where a path exists between any two patents i and j in C^* Citation networks are acyclic; if there is a path from i to j, there is no path from j to i due to the nature of citations (Hummon & Doreian, 1989, 1990).

Fontana et al. (2009) classified the vertices of the matrix C network as sources (not citing but cited), sinks (citing but not cited), and intermediaries (both citing and cited). Isolated vertices are patents that neither cite nor are cited. While sources are often treated as starting points of a trajectory, intermediaries and sinks may be part of the main network components. Isolated points, often excluded from main trajectory analyses, fundamentally do not contribute to network construction (Sun et al., 2018; Tatsch, 2021; Mazlumi & Kermani, 2022).

The main contribution of Hummon and Doreian's (1989) analysis lies in assessing the importance of different nodes and edges within a network. One of the simplest balancing methods they proposed is the Search Path Link Count (SPLC), which calculates the possible paths within a network based on matrix C, even if not all points are interconnected (Hummon & Doreian, 1989).

Conversely, a more precise method for identifying the main trajectories in a network was achieved by the authors through the Search Path Node Pair (SPNP) measure. Although the authors did not sufficiently advance a precise mathematical formulation for SPNP, they defined it as merely counting the connected nodes along the observed trajectory in the network (Batagelj, 2003).

In this context, it is essential to highlight the work of mathematician Batagelj (2003), who advanced the discussions proposed by Hummon and Doreian (1989, 1990). Batagelj formulated a computational algorithm capable of identifying the main technological routes within a large network, assigning weights to the routes based on their importance in the network. This facilitates the identification of technological paths that form significant components of knowledge.

Batagelj (2003) proposed a computational formulation for SPNP using the Search Path Count (SPC) method. In this approach, node weights increase if their trajectory includes a growing number of paths or edges. For the method to work effectively, the matrix $N(u, v)$ requires auxiliary components that denote the number of different paths $s - v\ with\ N^{-}(s - v)$ e $N^{+}(v - t)$ which indicate the same information for $v - t$. As a result, every trajectory $s - t$ contains the edges $(u - v)$.

After this transformation, the algorithm enables efficient balancing of both SPNP and the third balancing method proposed by Hummon and Doreian (1989), called Node Pair Projection Count (NPPC). This method identifies the most important pairs in constructing the main trajectories within the network. By automating the network's topological ordering, the algorithm automatically assigns weights to the most significant nodes in the network (Batagelj, 2003; Newman, 2006).

Simplifying, Verspagen (2007) showed that SPNP's balancing algorithm functions as a combination of patent pairs converging on a main node. The resulting weight of the trajectory, or its importance, is calculated by multiplying the number of edges connected successively to nodes within a given trajectory.

The methodology thus demonstrates that each link between edges and nodes represents a relationship between actors at a specific point. The greater the number of connections and the set of actors involved, the higher the likelihood that the trajectory forms a significant piece of knowledge. Graphically, this trajectory can be illustrated in Figure 1.

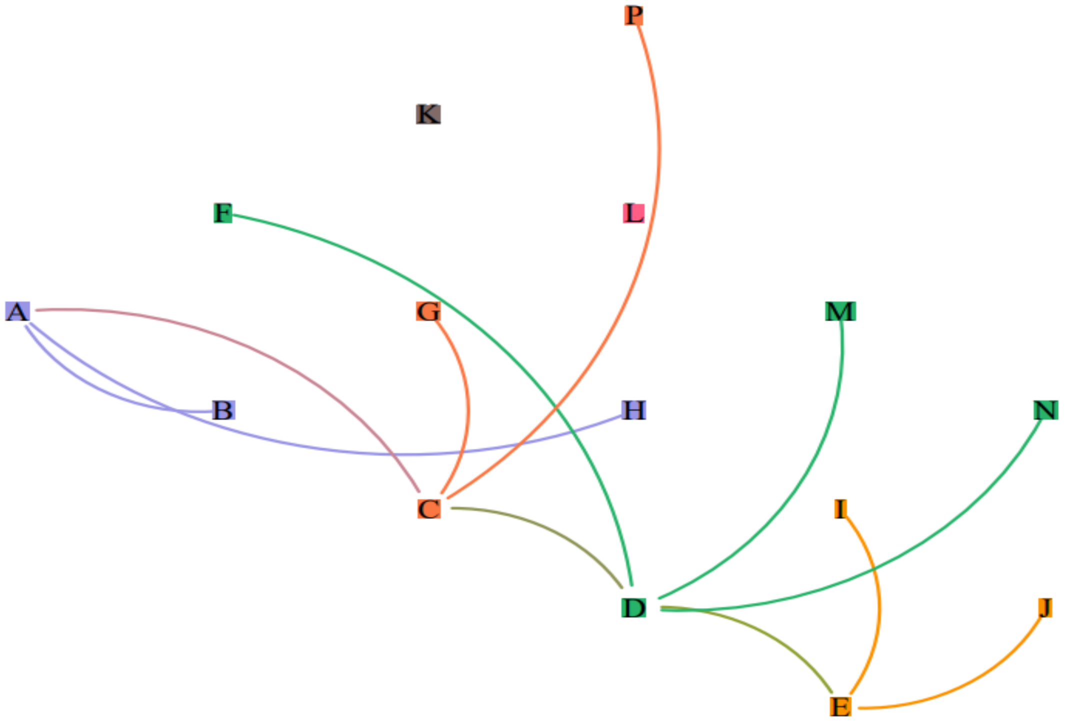
In this hypothetical figure, the edges represent citations between patents, while the nodes represent the meeting point of these citations at the same patent. The more citations a patent has, the greater the significance of its node within the trajectory. Moreover, if one patent is connected to another that is itself highly connected, the trajectory gains more weight as a main trajectory.

The main trajectory is represented by the points A-C-D-E, indicating the path of actors with the highest number of connections while passing through intermediate connections. This trajectory, when considering only the main nodes of the primary trajectory, characterizes the simpler model described by Hummon and Doreian (1989) as SPLC.

In contrast, the SPNP model considers all edges that constitute the main set, as these are ultimately responsible for creating a trajectory fundamental to the network's structure. In Figure 1, when we consider nodes A-C, we observe that they are formed by the configuration of two previous vertices, H-B-A. At the same time, these initial vertices support the connection to the trajectory's endpoint at E through other connections (C-D). Thus, the SPNP value equals the multiplication of the combination of vertices by the number of primary nodes created. In this case, *(4×9=36)*, resulting in 36 possible combinations of connected vertices within this trajectory. This combination of edges is referred to as the "weights of the nodes" (Fontana et al., 2009).

The concept of assigning weights to these connections within a network aims to ensure that the most robust knowledge trajectories are identified. This is referred to by Fontana et al. (2009) as "pieces of knowledge," which, if removed, can dismantle the network either entirely or significantly.

Figure 1: Representation of a SPNP and its main trajectory.



Source: Own elaboration in Gephi

The network analysed in this research focuses on investigating advancements in one of the various methods for obtaining hydrogen fuel in an environmentally sustainable manner. The production of biofuel via electrolysis, examined through patent records classified under the Cooperative Patent Classification (CPC) as "Engines or plants characterized by use of other specific gases – Hydrogen obtained by electrolysis"

(F02b2043/106), yields 1,377 patents. These include 409 simple application families and 676 patents citing other patents.

The data source is the Australian aggregator Lens.org, which not only consolidates patents from numerous global repositories but also includes scientific articles. This makes Lens.org's dataset broader than those of the United States Patent and Trademark Office (USPTO), the World Intellectual Property Organization (WIPO), and others, as it also incorporates national patent agencies from countries such as Brazil, Mexico, South Korea, Taiwan, Argentina, and many others.

It is noteworthy that USPTO, WIPO, and the European Patent Office are official collaborators of this aggregator, ensuring data accuracy and synchronization with these agencies. Additionally, Lens.org's reliability stems from the institutions that support it, including the Queensland University of Technology, the Bill and Melinda Gates Foundation, the Rockefeller Foundation, Syngenta, Qualcomm, Amazon AWS, and others. Universities such as Cambridge, South Dakota, Guelph, MIT, Colima, Bond, and Syracuse, among others, subscribe to the aggregator (LENS, 2024). Prominent works, evaluated for their citations and publication venues, also use the aggregator as a data source (Castello-Cogolos et al., 2018; Outili & Maniai, 2023; Ishar et al., 2024; Ochoa et al., 2024; Afia et al., 2024).

The Cooperative Patent Classification (CPC), a collaborative effort between the USPTO and the European Patent Office, was created in 2013 and is now adopted by 45 patent offices worldwide. It reclassifies patents dating back to the 19th century, with over 53 million classified documents (CPC, 2024).

The choice of a specific subclassification, such as CPC F02b2043/106, enables a detailed examination of the fundamental characteristics of deposited patents (Yu et al., 2024; Bekamiri et al., 2024). Furthermore, in 2014, a Y category was introduced, designed to classify emerging technologies and those spanning multiple sectors. Specifically, subclassification Y02 encompasses patent deposits aimed at mitigating climate change effects, covering innovations from construction to waste treatment (INPI, 2022).

Since hydrogen generated via electrolysis is a relatively old technology compared to other eco-innovations, the focus goes beyond identifying and exploring the main trajectory. Special attention is given to environmentally sustainable innovations, capturing patents prioritized under CPC F02b2043/106 that also include Y02 in their priority lists.

Analysis of the patents reveals that filings related to hydrogen electrolysis began well before the historical oil shock, starting in 1941 with patent US 2365330 A, titled "Apparatus for electrolytically producing oxygen and hydrogen." Continuous records exist up to the present day.

Before proceeding with network analysis based on the methods proposed by Hummon and Doreian (1989), it is beneficial to process the social network data graphically and statistically. This helps enhance the intended analysis. Processing modularity and applying degree-weighted filters are essential. Additionally, applying the Force Atlas 2 gravity-based distribution filtered by Lin's logarithm is another graphical strategy used in this research.

In social network analysis, identifying the fundamental and central actors is crucial. Over time, various measures of weight and centrality have been developed, most based on the "closest partner" concept, measuring the average distance or shortest paths to similar nodes (Bavelas, 1948; Sabidussi, 1966; Freeman, 1979).

The advancement of computing in the early 1990s and the growing volume of network data rendered previous algorithms impractical for handling such networks. This led to a temporary retreat in social network analysis, simplifying weight and centrality metrics to work with large datasets. This was achieved by Everett et al. (1999), who proposed a simplified algorithm connecting neighbours to key actors.

To address the limitations imposed by such analytical simplifications, Brandes (2001) developed the betweenness centrality algorithm, enabling centrality conditions to be met efficiently regardless of network size. This innovation aligned with the computational capacity of processors at the time. The author integrated previous methods that utilized average distances or shortest paths, accumulating them across various network points to create a unified trajectory for achieving a robust network centrality metric.

Brandes' (2001) algorithm is mathematically developed around eight theorems testing centrality and shortest paths n times for all possible network trajectories. The algorithm's efficiency is theoretically unlimited, depending on the computer's processing power.

In addition to Brandes' centrality metric, Hwang et al. (2006) emphasize that point centrality is vital for network analysis. However, nodes serving as knowledge bridges—connecting densely connected regions—should also be valued for understanding knowledge trajectories. The authors assert:

> *"We also claim that these bridging nodes, which bridge densely connected regions, should be attractive and important essential components in a network. We introduce a novel centrality metric, bridging centrality, that successfully identifies the bridging nodes located between densely connected regions, i.e., modules, using high modularity or high clustering property, which is one of the most important properties of scale-free networks. Experiments on several real-world network systems are performed to demonstrate the effectiveness of our metric" (Hwang et al., 2006, p.2).*

The analysis gains central importance by identifying bridges, enabling the detection of trajectory shifts, new knowledge flows, and critical components of what Verspagen (2007) called "pieces of knowledge."

Graphically, clustering coefficients are calculated for each node, representing the number of connections it has. Higher connectivity indicates greater clustering. On average, the clustering coefficients of nodes in a graph determine the clustering coefficient for that graph. Nodes identified as bridges create interconnections across the entire graph and are highlighted based on their high bridging centrality relative to other nodes (Hwang et al., 2006, p.3).

Graphical data analysis requires didactic approaches for clarity and ease of understanding, and social network analysis is no exception. Modularity provides clear graphical visualization, supported by relevant mathematical foundations for network studies. The modularity algorithm proposed by Newman (2006) and refined by Blondel et al. (2008) and Noack (2009) identifies distinct data groups by assigning unique colours to each group with shared characteristics. The algorithm operates in two iterative phases: first, assigning each node to its community, then recalculating modularity gains through reassignment until no further gains are possible. The second phase assigns weights to communities and repeats the process until a plateau is reached, ensuring stability.

This modularity approach provides not only a visually distinct representation of similar communities but also a powerful data-balancing algorithm, assigning weights based on importance within the network. The visual representation of the principal communities is enhanced through degree-weighted averaging, assigning greater size to nodes with higher averages.

After identifying the social network surrounding CPC F02b2043/106 and analysing relevant data to identify the main trajectory, the graphical style will shift. Based on tabulated data in Gephi, the research will return to the database, selecting patents from the main trajectory to add detailed individual patent information.

This process identifies whether patents are classified under CPC Y02 for environmental sustainability, tracks their origin by country, and determines if they are attributed to companies, universities, or individual inventors. Further emphasis is placed on patents filed in the U.S. but originating from other regions, examining whether the U.S. genuinely leads technological development in the sector or merely benefits from its robust patent protection system.

To integrate all information into a unified graphical dataset, manual adjustments within the graphical application are required. This ensures proper emphasis on each patent's unique characteristics.

The visualization employs Gephi's Force Atlas 2 distribution, described as follows:

> *"ForceAtlas2 is a force-directed layout: it simulates a physical system to spatialize a network. Nodes repel each other like charged particles, while edges attract their nodes like springs. These forces create a movement that converges to a balanced state. This final configuration is expected to help the interpretation of the data" (Jacomy et al., 2014, p.2).*

The algorithm ensures that nodes with greater weight or centrality are proportionately spaced, balancing attraction (for connected nodes) and repulsion (for all nodes). It is especially suited for networks with over a thousand nodes. For smaller datasets, its predecessor algorithm may be more appropriate as it adjusts gravity more effectively for fewer observations. Notably, the spatial arrangement is not tied to Cartesian plane coordinates, and thus the data's distribution in the graphical output cannot be interpreted geographically or spatially in traditional terms.

After the Force Atlas 2 distribution, any "leaf nodes"—nodes connected to only one other node—are identified and excluded. These nodes can clutter the visualization, as they have minimal impact on network structure. The Force Atlas 2 algorithm automatically pushes such leaf nodes to the outer edges of the graph, separating them from the main network.

Following this, a second filter, Noack's Lin Log mode, is applied. This logarithmic distribution increases the attraction forces among the network's main nodes, pulling communities closer and reinforcing the visualization of knowledge clusters or "pieces of knowledge," as proposed by Verspagen (2007). The Lin Log mode modifies the network's overall shape, emphasizing the interrelationships between key nodes and communities.

Once the social network related to CPC F02b2043/106 is structured and the data analysis is complete, the graphical layout transitions to focus specifically on patents within the primary trajectory. This step involves revisiting the database to analyse and highlight patents along the trajectory that meet additional criteria, such as prioritization under the CPC Y02 classification. This classification indicates technologies addressing environmental sustainability, helping identify transitions from non-sustainable to sustainable technologies.

Furthermore, the analysis highlights whether the patents originate from companies, universities, or independent inventors and determines their geographical source. Particular attention is paid to patents deposited in the U.S. that originate elsewhere. This aims to assess whether the U.S. is genuinely a global leader in the sector's technological development or benefits from a historically robust patent system that attracts deposits from other regions.

To ensure clarity and effectiveness, the final graphical representation is refined within the software manually. Individual adjustments are made to emphasize key patents, their origins, classifications, and associations within the broader network. This detailed graphical treatment allows a comprehensive and accessible interpretation of the data, supporting the study's conclusions about the evolution of hydrogen electrolysis technologies and their transition toward environmental sustainability.

5. Descriptive analysis and results

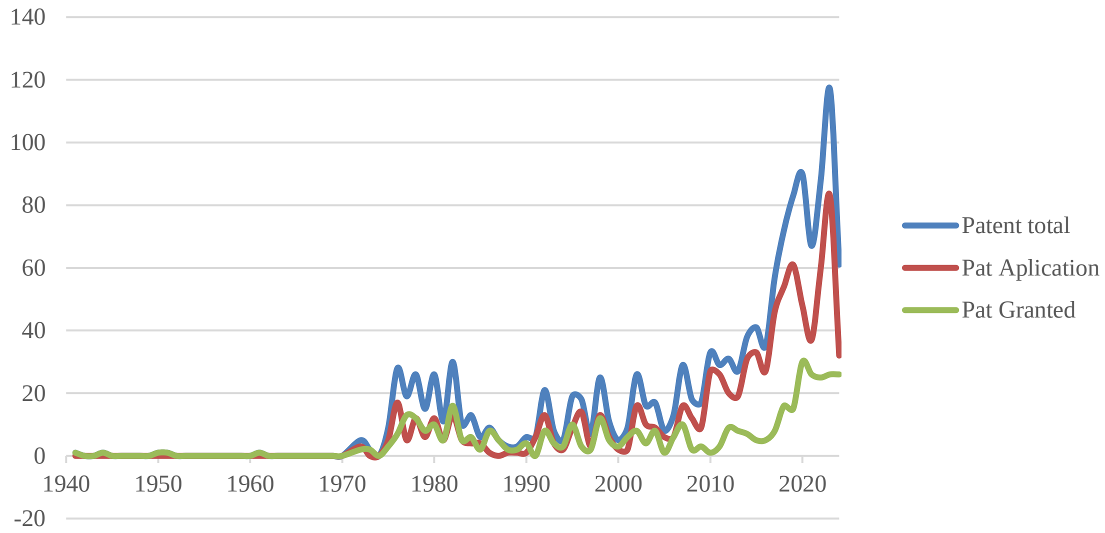
After defining the theoretical and methodological framework, operationalizing it in specialized software, and processing the data, it remains to examine the details of how the 1,377 patents, including 676 patents with data citing other patents, relate over time in terms of the agents responsible for their filing, the jurisdictions of origin, and the connections they establish with other depositors or stakeholders in the sector.

Descriptive data regarding the volume of publications and their characteristics, combined with a descriptive table of the main depositors and the jurisdictions from which these filings originate, will be presented to provide an appropriate understanding of how this sector, as delineated by the chosen CPC classification, is structured. Once these data are organized, it is believed that it will be possible to advance toward understanding the relationships among patents, specifically the dynamics of citation and being cited, thereby forming the social network of this sector. Following this, the next step addresses the central objective of this research: to identify and explain the main trajectory constructed within this technological paradigm.

Thus, Graph 1 allows for an evolutionary summary of the patent filings analysed in this study (Patent total), highlighting, beyond the total number of filings, those that were ultimately granted patents (Patent granted) and those that remained at the application stage (Patent application). In total, the number of patents (Patent total) also includes a minor distribution of amended and limited patents. Among these data, apart from the overall growth observed since 2017, a noteworthy feature is the increasing gap between the number of patent applications and those that were granted, which may occur for numerous reasons, each of which could warrant a separate article (Guellec; Potterie, 2000).

In general, the distribution of patents by year of publication and details regarding their filing, as related to hydrogen production through electrolysis in transport sector, can be observed in Graph 1. It is worth noting that, among all the patents listed, those classified with CPC priorities related to greenhouse gas mitigation total 1,284 entries, with a predominance of the Y02T10/30 subclassification (Road transport of goods or passengers uses alternative fuels, e.g., biofuels) and Y02E10 (Energy generation through renewable energy sources).

Graph 1: Deposit of patents in CPC F02b2043/106 (01/1941-09/2024)



Source: Lens.org

The filing of patents, particularly in sectors linked to the sustainable economy, exhibits a high degree of specificity and, to some extent, novelty. As a result, the actors involved in these filings and, consequently, the products derived from them, are highly diverse. It becomes necessary to establish a taxonomy of the main actors involved in patent filings and, most importantly, identify the countries they originate from. Since the end of the Cold War, there has not been such an intense competition for the dominance of technological pathways as is now observed between the United States and China.

Accordingly, the data regarding the applicants of patents within the analysed network, the number of applications per actor, and whether these are independent companies/inventors or universities, are presented in Table 1. It is worth noting that other entities also filed patents but were excluded from the table for reasons of space. However, those that filed fewer than eight patents during the analysed period were still considered in the broader analysis. The remaining data highlight the predominance of firms and independent inventors. Other public entities represented include the North American Space Agency, Princeton University, Tianjin University, Polytechnic University of Bucharest, the University of Texas, the Chinese Government's Department of Engineering, and Shanghai Electric Company.

The distinction between independent companies/inventors and universities is significant because, in developing fields of knowledge, it is natural to observe a substantial contribution from universities. Over time, as the sector matures, universities typically cede ground to incremental innovations that add value to commercialized products, which are predominantly patented by firms (Huang et al., 2020). Furthermore, the inclusion of the "jurisdiction" column indicates the origin of these entities, which may not necessarily align with the jurisdiction where the patents were filed, as the data reveal a strong predominance of filings in the United States (Dachs; Pyka, 2009).

At this point, it is indicative that the green hydrogen production sector, via electrolysis, has moved beyond the basic research phase, which specialized literature identifies as occurring between 1970 and 2013 (Zhou et al., 2024; Castro et al., 2023; Ogo; Sekine, 2020). The sector is now in a stage focused on commercial gains, which explains the predominance of data related to firms rather than universities.

Table 3: Patent applicants and the distinction between universities and companies (1941-2024)

Aplicant	Patent Count	Type	Jurisdiction
Fuelsave GMBH	62	Enterprise	Germany
Beaston Co	61	Enterprise	United Kingdom
Hytech power LCC	48	Enterprise	United States
JCB res	27	Enterprise	United Kingdom
Hydrogen tech LTD	24	Enterprise	United Kingdom
Dynacert INC	23	Enterprise	Canada
MIT	15	University	United States
DEEC INC	14	Enterprise	United States
Lynntech INC	13	Enterprise	United States
Saudi Aramco	13	Enterprise	Saudi Arabia
Mcneil PPC	12	Enterprise	United States
Meyer Stanley	12	Individual	United States
Asa Energy	11	Enterprise	United States
Canadian hydrogen Energy	11	Enterprise	Canada
Martinrea INC	11	Enterprise	Canada
Sas Thom THO INC	11	Enterprise	France
GTE productions INC	10	Enterprise	United Kingdom
Innnovative Hydrogen Soluctions INC	10	Enterprise	Canada
Phos Global INC	10	Enterprise	United States
Gaj Jabionsky	9	Individual	United States
Haring Christopher	9	Individual	United States
NRG logistics	9	Enterprise	México
Sangermano Luca	9	Individual	United States
Sangermano Paolo	9	Individual	United States
Siemens Ag	9	Enterprise	Germany
Smorra Ferdinando	9	Enterprise	United States

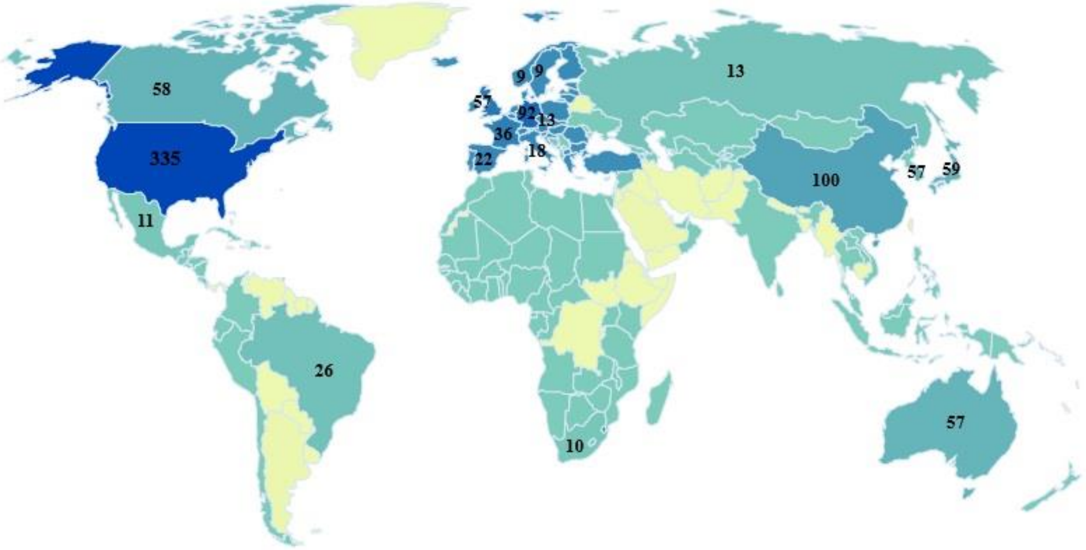
Source: Lens.org

The geographical distribution of patent filings complements the information about the main filing agents and confirms the prominence of nodes with a high weighted average degree in U.S. patents. Historically, the United States has been the largest repository of patents within the analysed technological trajectory, and the knowledge network detailed in Figure 2 highlights the dominant role of U.S. bridging nodes as fundamental to knowledge construction up to the present day.

Japanese patents are noteworthy throughout the technological trajectory but do not occupy central roles in knowledge construction comparable to those of U.S. patents. Countries such as China, South Korea, Canada, Great Britain, and Australia, despite having a few notable patents in the years prior to 2000, achieve significant numbers and important patents in more recent years. However, these achievements do not allow them to occupy central positions in the network as American patents do.

In detail, all countries with more than eight patent filings are represented in Figure 2, along with the number of filings corresponding to their territories. Visually, the map's colour scheme aids in identifying the largest filers, as it is constructed on a scale of relevance using shades of blue.

Figure 2: World Map of the largest patent applicants in CPC F02b2043/106 (1941-2024)



Source: Lens.org. Modified

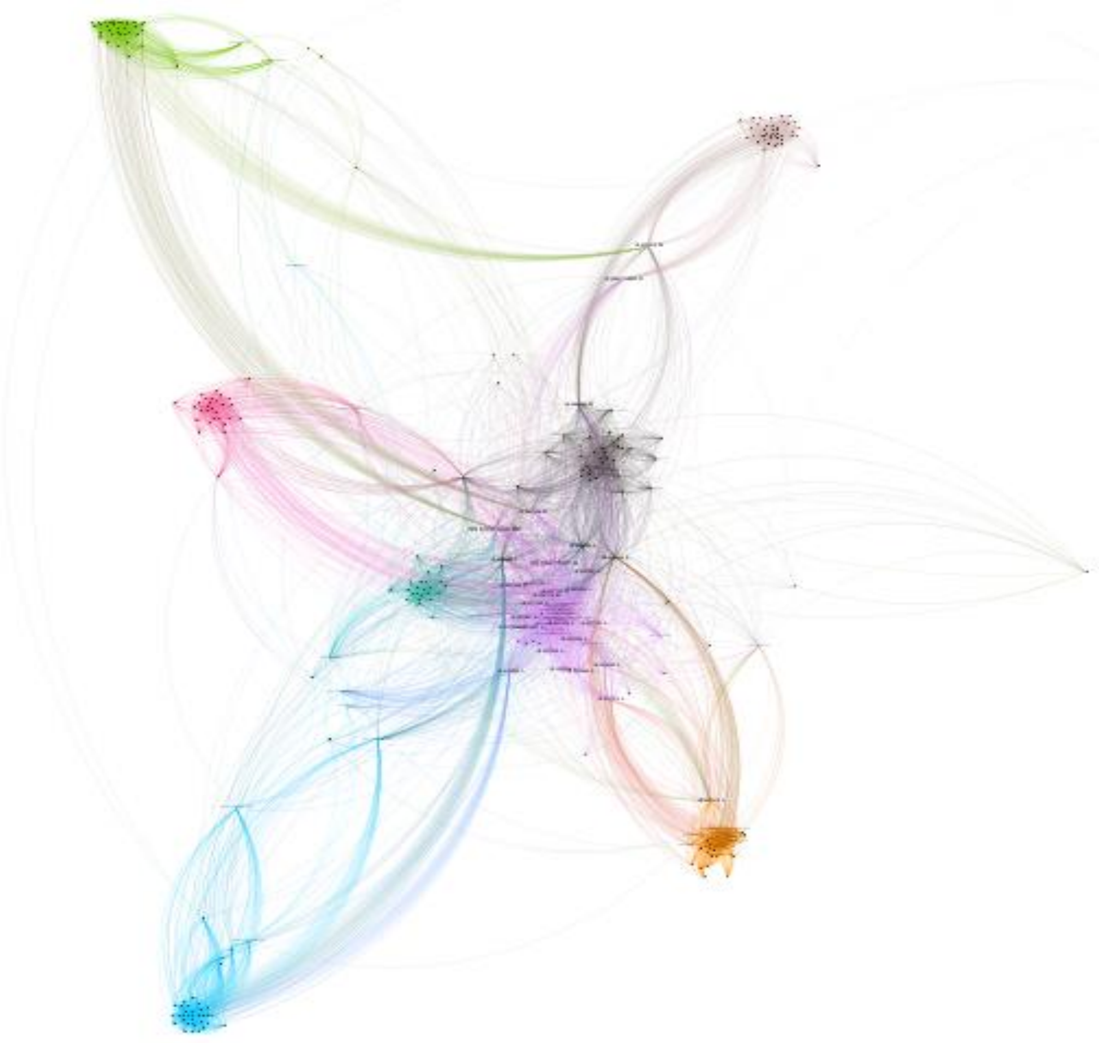
The data concerning patents that cite other patents are crucial for analysing the connections among different patents, thereby creating citation networks that, as analysed by Hummon and Doreian (1990), form knowledge networks.

Examining 676 patents that cite other patents and analysing each in detail revealed that many cited only once and were also cited only once. These patents were excluded from the scope of the citation network analysis because their inclusion would concentrate them on the network's periphery, affecting centrality metrics, median points, and distances. Following this adjustment, the analysis focused on a network comprising 211 patents, resulting in 1,495 nodes and 21,466 edges.

Using the methodological framework described in the previous section, spatial distribution was applied through a community detection algorithm (Noack, 2009; Jacomy et al., 2014), alongside statistical tools to capture modularity and identify communities with higher interrelations (Newman, 2006; Blondel et al., 2009; Noack, 2009). Additionally, weighted average degree distributions and centrality measures (Brandes, 2001; Betalgej, 2003; Hwang et al., 2006) were applied, leading to the spatial distribution encompassing the previously identified 211 patents.

As a result, the social network constructed from the use and analysis of patents citing patents within the CPC F02B2043/106 classification exhibits the following spatial distribution.

Figure 3: Spatial distribution of the patent network that cites patents in F02b2043/106.



Source: Lens.org; Graph by Gephi

This network is characterized by having at its core several nodes with similar weights that form the basis of the knowledge developed in this area. There are various components at the margins of the network's centre that still cite patents linked to the central nodes. The main component of this network, shown in Figure 4, includes 62 patents out of a total of 211 that cite other patents.

Although the patents at the centre of the network connect to various points in the analysed network, the fact that the main component connects less than one-third of the network indicates that many unrelated technologies emerge from the same knowledge base.

Following the logic proposed by Hummon and Doreian (1989) and developed by Betalgelj (2003), we built the main path network as explained in the methodology section. It is worth noting that due to the size of the data analysed, the graphical representation, although following the same logic, does not have as uniform a format as the exemplary network shown in Figure 1.

Figure 4 shows the largest component of the main path of the analysed network. This network is characterized by a set of large nodes concentrated along its main vertical line. The sequence of patents marked by the largest node, number 5231954 (electrolysis system safety through vacuum line), connects fourteen other patents, with the path ending with patent 0220039 (adds hydrogen directly to the combustion chamber). This path, called the "top path" by Fontana et al. (2009), yields the highest SPNP and weight for the main path.

The second most prominent path also connects fourteen patents, but its cumulative SPNP is not as high as the "top path," hence it is not the leading path in this model. It starts with patent 3939806 (System for improving electrolysis reactions in gasoline/hydrogen engines) and extends to patent number 4003384 (pressurized duct for hydrogen transport). Patents with more than ten internal citations, which consequently characterize what Verspagen (2007) called "pieces of knowledge," are highlighted in Figure 4 with colors leaning towards yellow. This is because, in addition to being "green," they have gained prominence as main patents.

The variation in colours results from the level of detail possible given the manual construction of the patent network forming the main path.

In detail, the manual construction of the main path aimed to highlight, beyond the main path, the patents that form knowledge pieces within this main path, highlighting these patents with a yellow square. Conventional patents are brown when not classified by CPC Y02 and green if they have this classification. The green or brown border on patents highlighted in yellow indicates whether they are classified under Y02. Additionally, due to the small volume of patents in the network that are not U.S. deposits, the highlight is given by the initial nomenclature, present in only two cases compared to the main path (CA or WO).

Beyond the circles delimiting the patent numbers, differentiations were also made to capture whether they are from companies, independent inventors, or universities, so the code number is red for companies, blue for universities, and black for independent inventors.

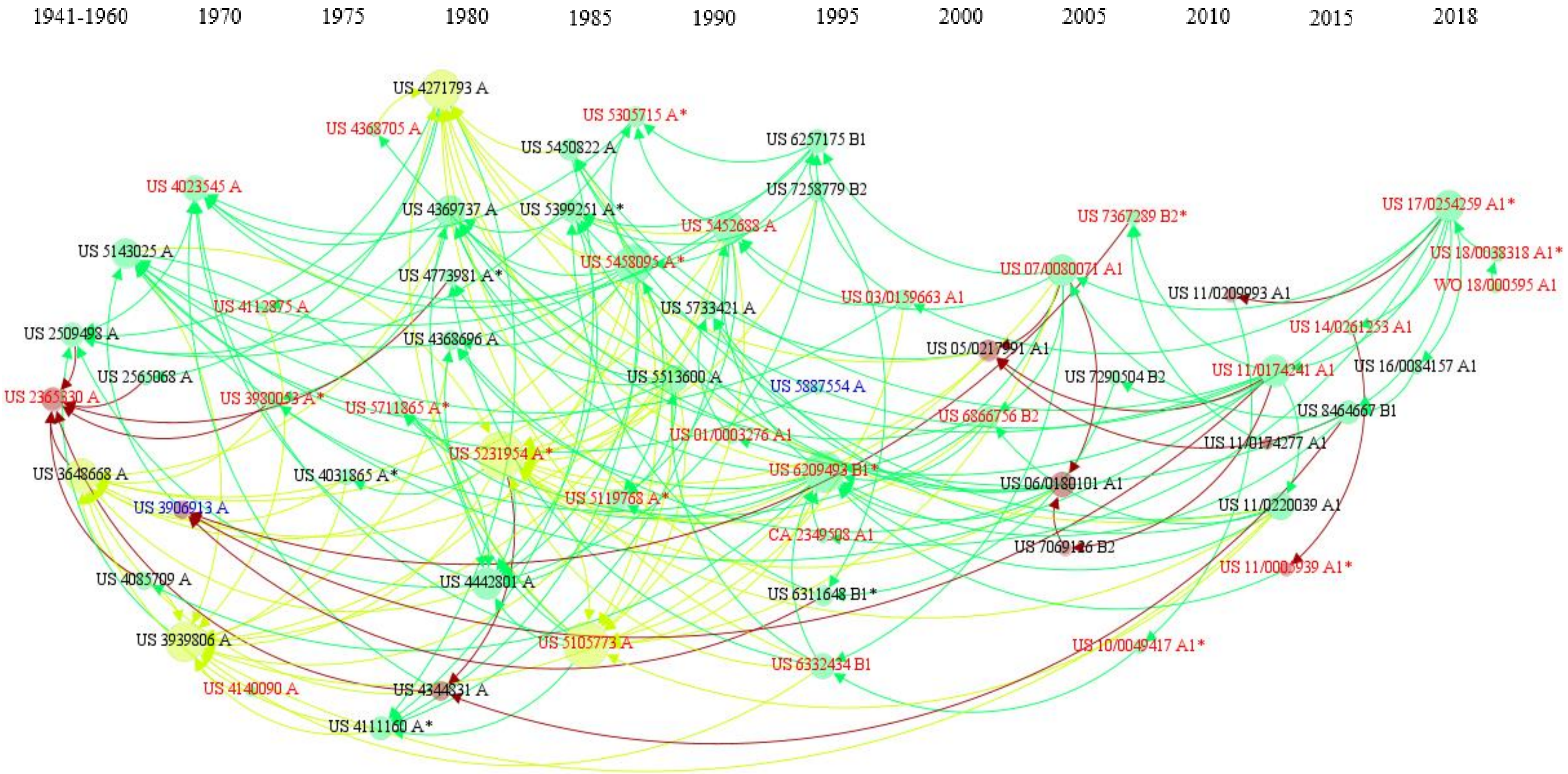
Finally, the last classification refers to patents deposited in the United States by agents, firms, or universities that are not U.S.-based.

Historically, this happened on a large scale because depositing at the U.S. patent office provided the highest protection possible for the created document. This is because, for many years, as a hegemonic power, the country built modern mechanisms for document protection, and its global reach ensured that inventions from outside had the same protective status as local deposits. Thus, the U.S. patent agency attracted the interest of inventors worldwide by effectively protecting their inventions and putting them in front of the main global producers and consumers (Criscuolo, Narula, & Verspagen, 2005; Dachs & Pyka, 2009; Danguy, 2017).

To achieve this graphically, the patent number will have an asterisk (*) at the end if it is a U.S. application from firms, independent inventors, or universities that are not based in the U.S. As stated, there are patents from other places that make up the main path and were deposited in other countries, and these already have their differentiations in the code in Figure 4. The question is to identify this other peculiarity to verify if such a practice has changed over the years or is still common, even with all the advancement and interconnection of global patent databases.

Figure 4 shows a snapshot of the main path of the CPC F02b2043/106 patent network. The green circles represent patents considered environmentally sustainable by the CPC Y02 classification, and the brown circles represent those that do not have this classification. Circles leaning towards yellow are central patents in the main path, and this trend occurs because yellow blends with green, as all five highlights are patents considered environmentally sustainable. Patent numbers with asterisks at the end indicate that the patent was deposited in the U.S. by a non-U.S. agent. The patent number in red indicates it was deposited by a company, black by an independent inventor, and blue by a university. This way, all desired classifications are easily visible and decipherable within the presented main path.

Figure 4: Main trajectory connecting 62 patents from CPC F02b2043/106



Source: Lens.org.

In addition to the graphical representation, the 62 patents are numbered, titled, named by their applicants, and dated in Table 3 attached to this document. Furthermore, they are described one by one in detailed continuous text that encompasses the incremental innovations and advancements achieved, covering all the patents in the main path. The order presented follows the earliest submission that connects to all the others up to the sixty-second patent, over a period extending from 1941 to 2018.

There is a noticeable correlation between the patents present in the main path and the volume of citations they receive in the overall CPC network. Table 2 reports the number of internal citations a patent received within the main path of hydrogen fuel obtained through the electrolysis process, compared to the total citations received within the entire network of patents obtained through CPC F02b2043/106. For this analysis effort, we selected the top twenty patents in the main path in terms of the volume of internal citations they received within the main path. Additionally, the total citations refer to the total number of citations regardless of the CPC delineated here, showing that some patents hold importance in other areas not circumscribed by the analysed CPC.

Moreover, the weight of these patents within the constructed network, characterized by the volume of citations they receive—i.e., the edges arriving from different nodes and connecting to the node identified by the described patent—is listed in the table as weight in network. To adequately represent the importance of each patent to the main path, the weight within the main path is described as weight in main path.

Table 4: Top 20 F02b2043/106 patents by internal citations

Patent number	Internal Citation	Weight in main path	Citation in network	Weight in network	Total Citations
US 5231954 A	14	197.0	27	380.0	118
US 3939806 A	14	155.0	20	227.0	74
US 3648668 A	12	132.0	23	262.0	83
US 4271793 A	12	118.0	35	342.0	102
US 5105773 A	10	164.0	23	372.0	79
US 4442801 A	8	96.0	36	434.0	128
US 4023545 A	8	88.0	25	279.0	62
US 2017/0254259 A1	8	94.0	16	188.0	105
US 6209493 B1	7	111.0	18	279.0	70
US 4369737 A	7	82.0	25	292.0	63
US 5399251 A	6	73.0	23	277.0	58
US 4368696 A	6	68.0	14	164.0	96
US 4111160 A	6	64.0	26	280.0	82
US 2011/0174241 A1	6	74.0	6	74.0	76
US 5119768 A	5	69.0	16	224.0	54
US 6332434 B1	4	103.0	13	338.0	112
US 5452688 A	4	85.0	15	316.0	35
US 6257175 B1	4	69.0	12	213.0	124
US 5450822 A	4	67.0	12	197.0	102
US 5458095 A	3	61.0	8	163.0	76

Source: Lens.org and Gephi app.

Patents like the Canadian 2349508 (compressor kit for fuel/hydrogen engines) and others do not appear directly in the field of most citations in this main network. In this case, the analysis method by Hummon and Doreian (1989) identified as central a patent that is not central in terms of the number of direct citations but serves as an important "bridge node" throughout the technological development, linking paths that relate engine operation to energy generation through the electrolysis process (Fontana et al., 2009).

As mentioned, other patents fall into this situation, and if we consider the method by Hummon and Doreian and the works of other authors who use the methodology, such as Mina et al. (2007), Verspagen (2007), and Fontana et al. (2009), we can consider it capable of identifying the most significant knowledge flows, designating these patents as secondary in terms of the volume and extent of knowledge flows passing through patent 5231954 (PVC vacuum lines to accommodate system temperature variations).

The search path node pair - SPNP can be calculated for the entire analysed period and presented, as previously done, as a large network of information. However, given the volume of information in the overall graph, interpretation can be difficult or confusing. Therefore, to facilitate the visualization of all the information, it is possible to conduct an individualized analysis of each piece of information contained therein in different graphical representations, as developed in Figure 5. Furthermore, it is also possible to create temporal slices that help us to count and visualize the evolution of this path over periods more easily. For this purpose, the work by Zhou et al. (2024) offers a good perspective on the ideal time frame to capture the most important paths involving hydrogen studies. This exercise provides a valid perspective for analysing major technological paths, and in this case, four periods are expected to exist.

In our case, we observed that the foundational development of technology and the first viable projects for both electrolytic components and engines that accept hydrogen gas were achieved from 1941 to 1979. The main inventions of these periods are embodied in patents 3939806 (System for improving electrolysis reactions in gasoline/hydrogen engines) and 3648668 (internal combustion engine operated by gases), which describe a complete viable prototype of a hydrogen engine, encompassing both the part responsible for generating fuel through internal electrolysis and sending it for combustion along with gasoline in the pistons via direct injection.

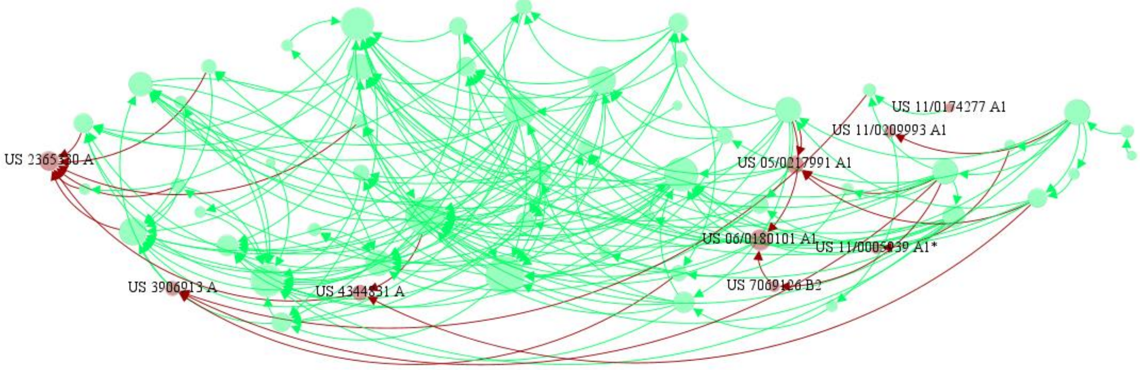
The following period, from 1980 to 2002, is characterized by Zhou et al. (2024) as a slower development period for hydrogen fuel and fuel cells. It is observed that for the electrolysis process to generate fuel, reality is not as close, as here, the highest volume of patents was deposited in the main path. Of course, the relevance and quality of the patents in the main process can be questioned but given the volume of direct citations described in Table 4, patents 4271793 (prototype of gas/gasoline internal combustion engine), 5105773 (Canister model to optimize electrolysis), 4442801 (gas supplementation to improve system efficiency), and 6209493 (electrolysis kit for combustion engines) are among the top 10 in the sample, proving that developments in this sector continued to advance. Another point to consider is the still preliminary nature of the inventions, with few being presented by companies, leading us to believe that they are not economically viable processes, except for the software and hardware deposits applied by Caterpillar Inc for monitoring and control, which indeed entered the assembly lines during this period.

Another period highlighted by the author as fundamental to basic research developments involving hydrogen and fuel cells begins in 2003 and ends in 2013. The electrolysis process for hydrogen generation does not exhibit a similar characteristic, as the developments seen in the main path refer much more to incremental improvements than to fundamental and central developments, which in this study are observed with greater rigor in the patents deposited between 1941 and 2002. This observation comes from the most relevant and impactful deposits for the path, with patents 6209493 (new system combining electrolysis and fossil combustion) and 6332434 (improvement in components aimed at hydrogen/gasoline systems) being company deposits that improve the necessary apparatus for better efficiency of the electrolysis process within an engine's system.

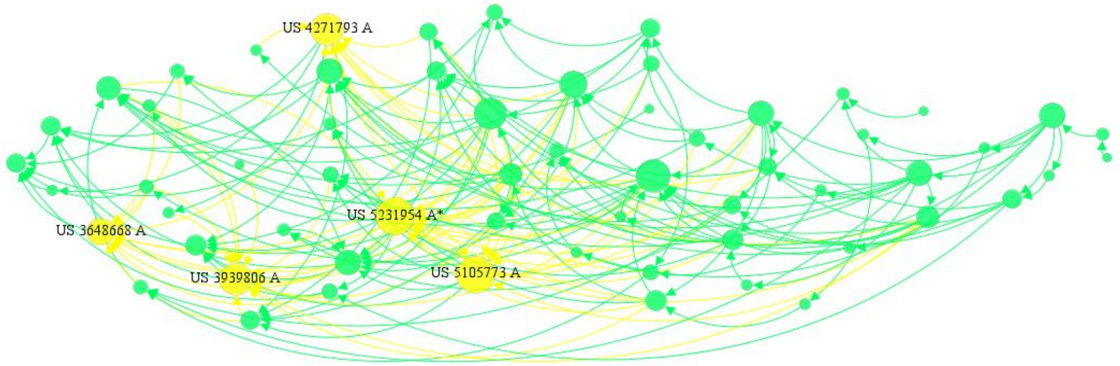
The patent data from the main path corroborate this conclusion since the profile of depositor inventors compared to depositor firms changes by the end of the 20th century. While until 1999, out of the 36 patents present in the main path, 22 were from independent inventors, two from universities, and one from a non-profit state enterprise, totalling 30% of companies as patent depositors in the area; from the 2000s onwards, this number rises to 60% of deposits in the main path. This indicates that after the period of basic research and patents with little commercial value but technically viable, firms gradually enter when they foresee economically viable applications for these inventions, usually improving them incrementally to expand the viable range of these applications from a commercial perspective (Pavitt, 1991; Krieger et al., 2021; Wen et al., 2023).

The period starting in 2004, described by Zhou et al. (2024) as the period of greatest technological transfer and connections, finds its parallel in the main path of this analysis, as the last patent in the main path is Chinese, and in the overall network of CPC F02b2043/106, nearby it, there are several patents from countries like Germany, Brazil, Canada, South Korea, Great Britain, Mexico, Taiwan, and others. It is worth noting that most of them come from companies rather than universities.

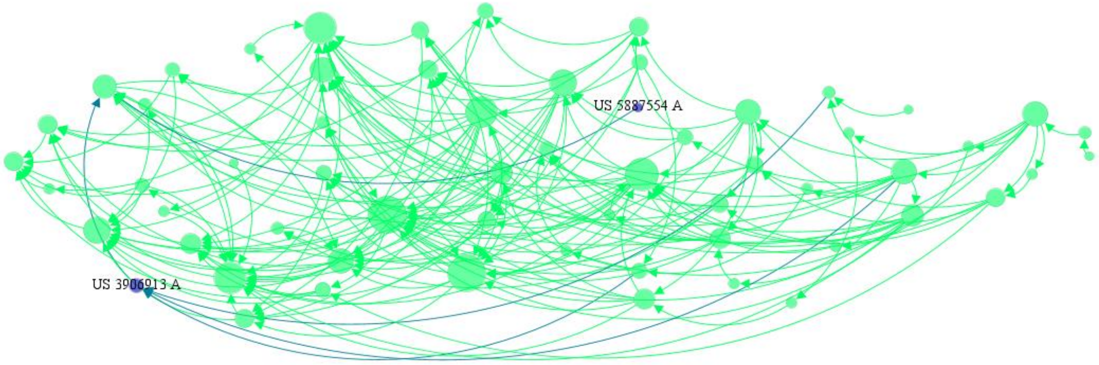
Figure 5: Separate main path information



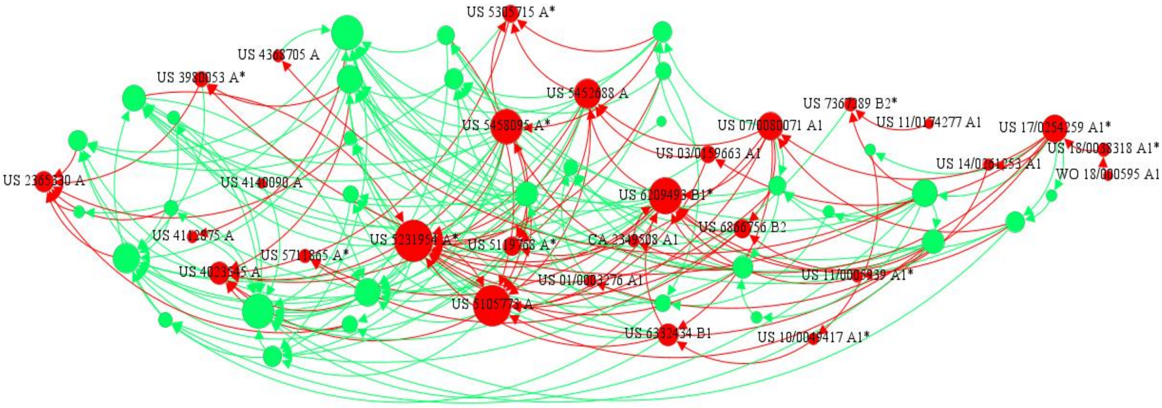
Patents considered not environment sustainable (without CPC Y02 classification)



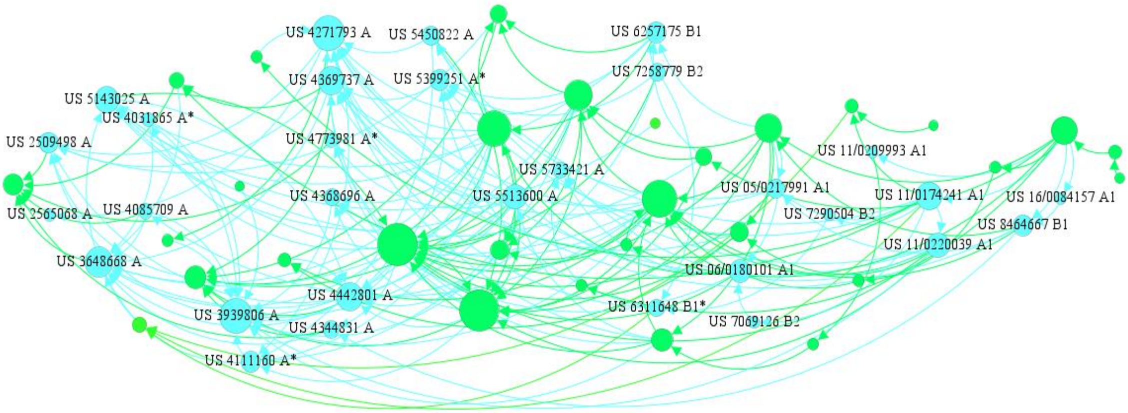
5 main network patents (weight in main path)



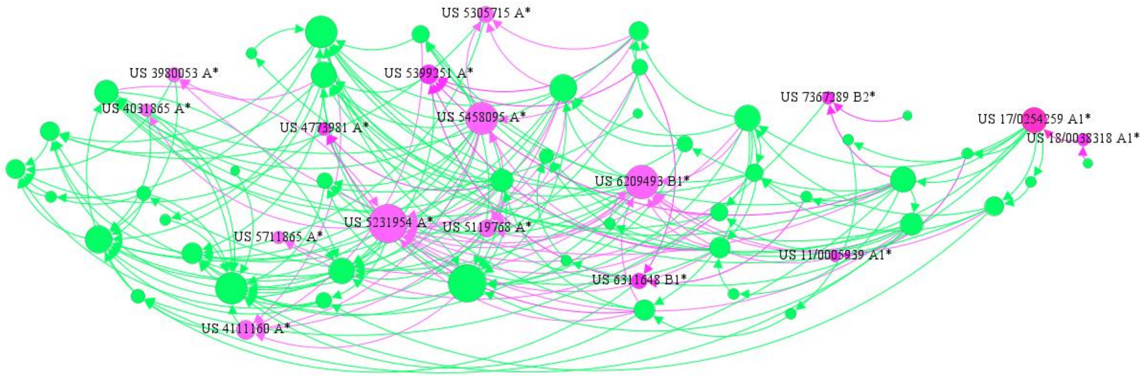
Patents that are filed by universities in the main trajectory



Patents that are filed by companies in the main trajectory



Patents that are filed by independent inventors in the main trajectory



Patents filed in the United States that do not belong to firms or inventors in that country
Source: Lens.org. Graph by Gephi.

In summary, the analysed main path demonstrates various points of divergence from the main node that open paths beyond the analysed CPC towards other technological trajectories. Examples include the patent filed by Caterpillar in 1983 developing software and hardware for system information monitoring (No. 4368705), the developments by Russell International in 1992 for engines that combine diesel and hydrogen (No. 5119768), and the record of rotary engines that, while driving electrolysis, convert energy into movement for other components, which certainly accelerated industrial applications for hydrogen generated through electrolysis (No. 2018/003818).

Furthermore, the long main path constructed here allows for detailed reflection and visualization of the development process of electrolysis for generating hydrogen confined to motor systems and shows the predominance of this process being carried out within systems that combine use with fossil fuels. The logic initiated in 1941 with patent number 2365330 (apparatus for producing hydrogen and oxygen) involves creating the necessary apparatus to safely conduct the electrolysis process and store both the produced oxygen and hydrogen. In 1951, patent 2565068 (hydrogen/gasoline internal combustion engine) presented the first invention that combined the advances achieved in 1941 with the emission of these gases together with the fuel to increase engine efficiency. Various incremental improvements and new ways of performing this process were systematically patented, with five of them being among the main patents in the main path, given the efficiency gains achieved since the first invention in 1951.

The central point of the main path, patent 5231954 filed by Water Fuel International in 1993, adds to the complex hydrogen engine system a safety system that, while reusing gases from the transformation and combustion of hydrogen with fossil fuel, reduces the system's explosion risk to nearly zero. This was quickly incorporated into almost all subsequent developments that involved creating a mechanism combining electrolysis and gas utilization in an internal combustion engine.

From this point onwards, what is observed are constant reformulations and improvements in components for both electrolysis and hydrogen storage and dispersion for engine operation. Various patents in the main path from firms or inventors seem to seek improvements to a system that is ready and functional. The central issue becomes efficiency gains and materials that perform the same functions but are simpler, as corroborated by patent number 7367289 filed by Toyota in 2008 (hydrogen/gasoline injection control system), which years later launched its first mass-produced model with an engine operating under similar principles.

It is noted that between theory and practice, the use of electrolysis has little to do with the environmentally sustainable and emission-free production that theory advocates in Chapter 2. The generation of hydrogen and oxygen indeed uses only water and produces fuel in this reaction within a system. However, the patent record and the analysed main path clearly demonstrate that the predominant use should occur in conjunction with an internal combustion engine that theoretically accommodates gasoline or diesel.

Other fuels like ethanol could improve this scenario from a sustainability standpoint, or perhaps electrolysis and hydrogen generation should provide energy to charge an electric motor as described by fuel cells. This might be why recent literature focuses so much on fuel cells rather than the electrolytic process for hydrogen production (Ogo; Sekine, 2020; Aminudin et al., 2023; Helder et al., 2024; Zhou et al., 2024).

Thus, the discrepancy between theoretical construction and business practice through patent filings becomes evident, which, although they improve energy efficiency and reduce greenhouse gas emissions, still favour the use of fossil sources, undermining the sustainable idea of achieving fuel through water with zero carbon emissions.

Despite the almost widespread application of the CPC Y02 patent classification in the main path patents, which practically validates environmentally responsible inventions, the conclusion remains unchanged. This is because CPC Y02 literally addresses applications for mitigation or adaptation to climate change, something that indeed occurs in all "green" applications in the main path. The point is that the patent classification ends up favouring and placing under the same environmentally sustainable scope, patents with different applications and technological uses that often involve the use of dirty energy, if they fulfil the objective of mitigating the carbon footprint.

Therefore, it is justified to move towards a second analysis, involving the same database and the same theoretical and methodological basis, but this time seeking to find the most significant path, and consequently the most important one for the network, that does not mix in its technological development scope the operation together with fossil fuels or polluting generation sources.

6. Secondary trajectory and carbon-free hydrogen

Since this set of patents falls under category F, it is expected to find patents that directly or indirectly cite engines, as that is what the category (Engines or Pumps) is about. In this context and given that the subcategory F02b2043/106 includes the subclassification: engines characterised by operating on gaseous fuels; plants including such engines: hydrogen obtained by electrolysis, it is unlikely to find, in any of the paths within this network, patents that are not directly linked to engines and internal combustion. The issue for the study of a secondary trajectory analysis is to find one that does not combine fossil fuel with the use of hydrogen obtained through electrolysis.

Even this goal proved difficult within a relatively narrow universe of patents, as is the case. In paths that initially seemed promising, patents quickly emerged combining different ways to integrate fossil fuel with the electrolysis process.

Thus, the path identified to explore inventions that do not unite fossil fuels with the electrolytic process was found outside the main communities of the analysed network, in a set of edges branching off from an area close to the main path, specifically from patent

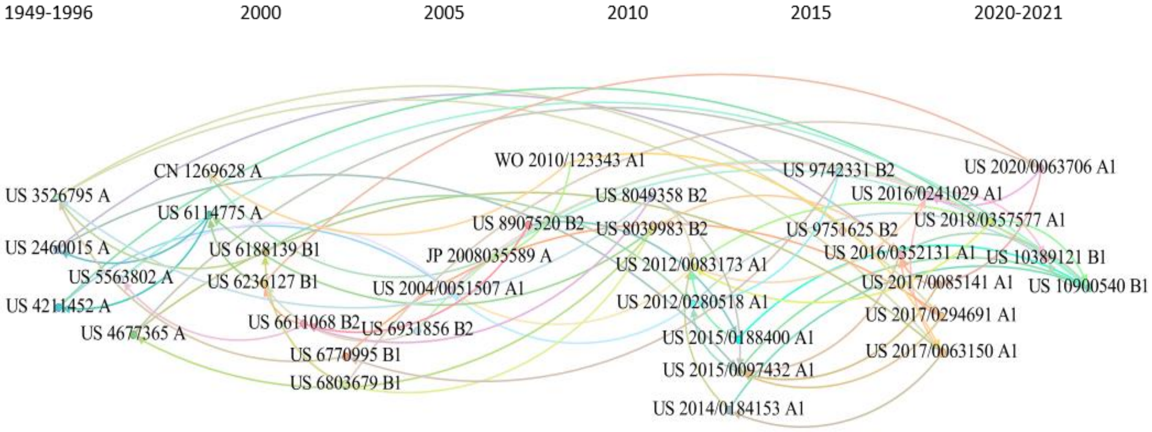
US 4442801 (describes an apparatus to supplement the electrolytic process in an internal combustion engine).

As mentioned, the path, although it branches from a part of the main path, cannot be considered a "second best" secondary path in terms of node weights. The aim here is to seek a path that carries developments that do not rely on fossil fuels and still contribute to technological advancement.

Another point to consider is that the developments in this path are closer to the current period and, therefore, may not have experienced the degree of maturation to allow them to rank among the most cited, as this factor requires time and the advancement of the technological path opened by such an invention.

Thus, the secondary path with the largest number of inventions not linked to the use of fossil fuel is presented in Figure 6.

Figure 6: Secondary trajectory unrelated to fossil combustion (1949-2021)



Source: Lens.org. Graph by Gephi

Within this group of patents, the relative weights of the edges are low, as this network represents 2.91% of the total patents in the general network, which explains the lack of details and distinctions among the presented nodes, since they all have very similar weights and a potential increase in scale would only clutter the graphical presentation visually.

In this set of patents, what can be observed is an evolution in devices and applications related to the use of potential energy and the storage of energy generated by the electrolytic process and other means capable of charging batteries. Additionally, there are patents that relate different electrolytic mechanisms and applications resulting in movement, whether naval or terrestrial.

Furthermore, the search for a path free from applications linked to fossil fuels led us to a set of patents that have far more relations and sets of citations outside the analysed CPC network than within it. For this reason, some patents may seem out of place in the network, such as (US 2020/0063706 A1) which deals with a hydroelectric application but demonstrates, in parts related to the storage of generated energy, factors that could lead to applications involving gaseous energy sources, including hydrogen.

Among the 36 patents in this path, 21 are inventions related to energy generation and storage, none of which have primary applications in the electrolytic process, but all have possible uses indicated. These patents present the CPC code in its various degrees of patent priority, not necessarily as the first, like what was observed in the analysis of CPCs with the environmentally sustainable code Y02.

To maintain an analytical standard, all the patents in this path are considered, from the perspective of CPC patent classification, environmentally sustainable.

A distinguishing point from what is observed in the main path is the volume of deposits from other countries, which in this case, reaches one-third of the sample, or 12 patents, with depositors from: Germany, Japan, Taiwan, France, South Korea, China, and Malaysia.

Additionally, there is a higher concentration of patents from companies, some from individual inventors, and no presence of universities. The tendency to prioritize deposits in the American market by foreign companies remains, as of the 12 non-American depositors in this path, 9 are deposits made in the American market, even in more recent patents covering the period from 2015 onwards.

Thus, the patents in this path stem from a common base initiated with the invention by Jones Naven (US 2460015 A) which developed a motion transmission mechanism, something refined and currently understood as a flywheel or clutch box. This invention transforms and gains complexity until it results, in the 2000s, in a mechanism for energy generation and conversion with the German patent (US 6236127 B1). From this point onwards, various patents showcasing energy generators have leveraged this clutch mechanism to enhance the necessary movements for rotors and coils that convert motion into energy, accelerating the number of movements for the same amount of impulse.

Concurrently in this path's evolution, load conversion mechanisms to store different voltage levels from various energy sources in the same battery were presented, with notable mention to the German patent by ABB (US 9742331 B2), which deals with a system for distributing and generating energy from multiple sources converging to a single storage point.

Although the difference is minimal, the most significant patent in this path is the American patent (US 10900540 B1), which deals with a combination of flywheel for generating electrical energy that can be powered by an electrolyser and with distinct combinations to battery storage systems. It is interesting to note that this patent, among its various CPC classifications, includes codes common to fuel cell applications, something generally observed in all inventions in this path due to their involvement in charge storage, something crucial for electric vehicles using fuel cells. Additionally, it is worth noting that this patent combines two of the main trends developed by the technological path, possible due to its filing year of 2021, a period when both technologies were maturing (Markard, 2020).

In detail, the patent codes, their titles, filing year, companies, inventors, and jurisdictions are provided along with a detailed explanation of each patent in this path in Attachment II of this work.

Thus, having highlighted the main patents in the path and their main achievements, it is possible to verify that it is feasible to find within the developments of the CPC network constructed through code F02b2043/106 developments that are not tied to the use of fossil fuels. The critical point is that 97.01% of the network had to be excluded from the analytical scope to allow the visualization of this path. Nevertheless, it is worth noting that this path includes many recent developments, indicating the possibility of significant advancements in clean fuel generation within this patent network in the coming years.

Concluding Remarks

This work, utilizing a well-established methodology for analysing social networks with patents, aimed to identify and characterize the patents that compose the main path of the social network delineated by the Cooperative Patent Classification number F02b2043/106, which specifically deals with hydrogen obtained through the electrolysis process in engine systems or apparatuses.

This code encompasses a network of 1377 patents, of which 676 cite patents, 552 are cited by patents, and among those that cite and are cited at least once, there are 211 patents, resulting in 1495 nodes and 21466 edges. All of this was achieved through searches in a specific classification within the aggregating application Lens.org.

The methodology used to identify the main knowledge trajectory of this social network comes from the work of Hommon and Doreian (1989) and its subsequent applications in the works of Verpagen (2007) and Fontana et al. (2009), which helped consolidate and detail the methodology with greater rigor. Among the possible options, the research focused on an analysis of the main trajectory that takes into account the nodes and their main connections. In this way, the Search Path Node Pair analysis can be performed, and the main trajectory with 62 agents is duly presented both graphically and in a table with relevant details.

Applying treatments of modularity, betweenness centrality, weighted average degree, communities, and spatial distribution with Noach's logarithm approximation, the social network can be graphically constructed. Its communities, as well as main nodes and principal trajectory, can be easily visualized using the Gephi application.

After identifying the main trajectory using the Gephi application, and considering the need for a detailed analysis of the entire main trajectory, with an interest in verifying key agents, dates, jurisdictions, environmental sustainability, and whether there are filings in the United States from non-U.S. firms, the Gephi graphical application cannot be used in its automated form for the main trajectory analysis due to software limitations regarding the numerous filters required for such a detailed graphical observation. Given this scenario, a graphical representation was entirely constructed manually, taking into account all the mentioned particularities.

With the data and graphical and tabulated representations of the main paths at hand, detailed patent-by-patent analyses of this path were carried out, presenting five main nodes with a high volume of citations and significant weight within the main path and the network.

This allowed us to verify, first, that there is a predominance of companies in the periods following the foundational developments. The prevalence of company activities is in components and processes that improve parts or the efficiency of the existing system.

There is low participation of universities in patent deposits in this sector, even in periods considered foundational for knowledge consolidation. Additionally, there is an almost unanimous concentration of U.S. patents as the most important in the main path and the network. However, when analysing the origin of firms or inventors of patents opting for deposit in the United States, the reality changes, considering that 30%, or 19 patents, in the main path are from firms or inventors based in other countries opting for the U.S. protection system.

Except for isolated cases in Canada, Germany, Japan, the Soviet Union, and Great Britain, patents deposited in the United States predominate until the 2000s. This period saw a diversification in the volume of deposits in other global protection agencies with increasing participation from China and South Korea.

The years with the most characteristic developments of the knowledge base (basic science) in the sector end in the late 1990s, and after this period, there is a greater volume of patents in the main path, but they lose relevance from the perspective of citations and are much more concentrated in companies, fundamentally dealing with incremental improvements to an already established system of operation. This is corroborated by the persistence of post-2000 patents still citing the 1976 patent that created a mechanism for generating, transmitting, and burning hydrogen as fuel in an internal combustion engine (No. 3939806).

Moreover, the main path shows a linear evolution from the perspective of knowledge advancement. Although some patents revisit the creation of engines with different configurations, altered functions, and different materials, it is noticeable that the generation of hydrogen through electrolysis shows increasing improvements and continuous modernizations, culminating in the 2018 Chinese patent that brings to the electrolysis mechanism a diminutive size with energy efficiency like its previously developed counterparts.

The path does not prioritize industrial applications, an opportunity that, given the energy efficiency of the process, indicates a certain delay in being perceived by firms as potential opportunities. According to the cited text by Wen et al. (2023) and Krieger et al. (2021), there is a gap between what is produced in universities and industrial-scale applications by companies, and this specific point presents a potential opportunity to continue this study, bringing to the analysis the main path of scientific publications, given the disruptive potential that hydrogen and the so-called hydrogen economy can offer to sustainable development of humanity (Chantre, et al., 2023).

Finally, a concerning discrepancy is observed between the theory involving the transformation of water into hydrogen and oxygen through electrolysis and its product as fuel that, after combustion, results in oxygen and water, and the use that independent inventors, universities, and firms gave to it, always merging it into an internal combustion engine system that uses fossil fuels alongside hydrogen. This persists even in current patents because maintaining this path, following the logic put forth by CPC Y02 classification, will guarantee a sustainable patent, as the mixture of fossil fuel with hydrogen ultimately improves the energy efficiency of the process and reduces carbon emissions.

Beyond the study of articles, the insufficiency of adequate responses to accommodate the sustainable production and use of hydrogen through the electrolytic process raises possibilities for a more generalist analysis that captures all CPCs dealing with hydrogen generation through electrolysis, not just those with clearer directions towards the transport sector.

The discrepancy, in this research's view, lies in the theoretically sustainable electrolysis process and its practical construction, in this CPC, not being so, which explains why many current studies and a greater volume of patents in the transport sector focus on the development and improvement of fuel cells rather than efforts to improve the electrolytic process, as the process involving fuel cells indeed breaks the link with petroleum. Similar processes involving other technologies that are supposed to be environmentally sustainable occur in (Barros et al., 2021; Chernev & Blair, 2021; Joloaso et al., 2024; Neves et al., 2024).

That said, it is worth highlighting that the electrolysis process, even with combustion engines, can be a key to decarbonizing global economies if combustion is combined with biofuels, such as ethanol or biodiesel, or if it evolves sufficiently in electrolytic generation efficiency to the point where the system operates solely by burning hydrogen.

Additionally, the search for a secondary path that does not involve any patents mixing fossil fuels in their developments was achieved in a branch departing from the main path, specifically from patent US 4442801 A (describing an apparatus to supplement the electrolytic process in an internal combustion engine), showing a relatively long path but not showing relevance compared to the analysed network, as removing this path would leave 97.01% of the network unchanged. This shows that developments in the sector are linked to fossil products, which can be considered positive from a classification perspective but insufficient from an environmental standpoint (Salvi & Subramanian, 2015; Kwilinski et al., 2023).

Thus, it is possible to verify that the intended objective was achieved, and indeed the main path and its detailed characteristics could be thoroughly examined in this work. The results are positive and consistent with specialized literature, and the methodology used proved to be of great value for conducting this type of social network analysis. Indications for future work emerged considering divergences and apparent shortcomings that this technological route presents, and it is essential to advance towards a combined analysis of articles and other sets of patents to fill gaps in this work.

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Appendix I

Here, we develop in detail the analysis of the main path, succinctly describing how the patents connect in the main path, accompanied by a descriptive table with the patent holders, titles, numbers, and dates of all the patents in the main path. To facilitate the reader's understanding, it is recommended to read it together, consulting both the table and the text.

The main path of the network, in its entirety consisting of 62 patents, begins in 1941 with patent 2665330, the first from a company registering a commercial mechanism for electrolysis of water to produce hydrogen. This patent is directly cited within the scope of the analysed CPC by patent number 2509498 from 1944, which seeks loading mechanisms to improve the performance of electrolysers generating hydrogen and oxygen. In 1951, patent 2565068 develops the first viable internal combustion engine compatible with hydrogen combustion, which due to its higher energy efficiency, produces stronger combustion on pistons and other engine components.

New patents will connect to patent 2565068 from 1951 only in the 1970s. Patent 3648668 from 1972, leveraging developments achieved in the internal combustion engine capable of handling hydrogen, registers a new product capable of dealing with hydrogen in its gaseous form to generate kinetic energy for the gas-adapted engine.

Similar to what was done in 1941, John Munday registered in 1972 a new mechanism for electrolysis of water within the engine system, separating into two compartments what is hydrogen and what is oxygen, to calibrate the optimal air-fuel mixture for the engine's operation. In 1973, the California Institute of Technology presented a concept with characteristics close to those described by Walter Drabold in the 1951 patent, presenting a combustion engine that mixes quantities of gasoline and hydrogen and calibrates oxygen flow aiming to reduce greenhouse gas emissions and improve the efficiency of both fuels.

Directly citing John Munday's creation, patent 4023545 from 1975 presents a system connecting the fuel tank and the engine, but this time using hydrogen in its pressurized and liquid form to fuel the combustion engine. In the same year, patent 4085709 makes a similar effort, but this time using a gas balloon that exits to an electrolyser within the vehicle system, directing the obtained hydrogen to the engine system.

In 1976, Bradley Curtis presents the innovative patent 3939806, which brings a closed and complex system for the operation of a hydrogen engine. From the start of operation, the heat from the engine cooling system and/or exhaust heats a working fluid in a closed system. This heat turns the fluid into gas, which is sent to a turbine that drives a generator. The generator supplies direct current to an electrolysis cell, where water is decomposed into hydrogen, which, upon combustion, converts potential energy into motion. Something similar is described by the North American Space Agency's patent number 4112875, with the difference that in this case, even the combustion product is reused as a new energy source, as hydrogen combustion generates, in this case, oxygen and water that re-enter the electrolytic and combustion systems.

Patent 3980053 filed by Beeston and Co. brings significant incremental improvements to vehicles conducting the process of converting water into hydrogen and oxygen within the system. The patent addresses new electrolysis methods with new cathode membrane models and better control of the electric current needed to electrolyze water.

Patent 4031865 is the first to refer to the internal system that converts hydrogen into energy as a fuel cell. The author proposes an internal water hydrolysis system based on sodium hydroxide and potassium carbonate, energized by an internal battery. When the gas is generated, it is directed to a mixer that ensures the correct quantities needed for proper combustion and engine operation.

The work by Talenti Pier in patent 4111160 presents consistent differences in the process to be carried out in the mixed system of hydrogen generation and mixing it with fossil fuels to reduce emissions and increase efficiency. The idea is very close to that seen in Walter Drabold's patent, but the construction engineering is different.

In 1979, Feuerman Arnold publishes patent number 4133847, presenting an inventive model that mixes water and gasoline in an electrolysis process, generating gases to be burned in a motor prepared for this combustion. Patent 4140090 uses pre-combustion to generate energy for oxidants, which will, within a water tank, conduct the electrolysis process and generate hydrogen.

The first non-American patent in this study was filed in the United Kingdom in 1980 under number 2073317, addressing a mixed process where hydrogen is used alongside other fuels. Instead of improving efficiency and reducing emissions in the same air-fuel mixture, it enters individually in some operational phases of the engine, also to increase efficiency as its accelerated combustion generates higher starting power, but sustainability is not mentioned.

Reinhardt Weldon's work with patent 4368696 significantly advances what Pier and Drabold were doing. His internal hydrogen generation system is activated by the operation of the internal combustion engine, excluding the battery. The generated gas goes to a separate carburettor that sends commands to the engine's electronic control unit to gradually reduce the air-fuel mixture, maintaining normal engine operation with more dynamism, using larger or smaller amounts of gasoline depending on the quantity obtained from water electrolysis.

Publication 4344831 improves the energy efficiency of the electrolysis conversion by keeping the system's temperature always below 150 degrees Celsius, reducing unnecessary aqueous formations and thus relevant process losses and consequent conversion efficiency.

Valdespino Joseph, with patent 4271793, improves on the work of Pier, Drabold, and Weldon, giving special emphasis to the electrolyser and the combination of cathodes and anodes used to ensure this essential part of a mixed system functions adequately without excessive breakdown risks. This is one of the main nodes in the main network due to the significant improvement in the engineering involved for safe and durable construction of this process. In 1984, patent 4442801 changes positions in the system to seek greater stability for the electrolyser, aiming for higher efficiency and eliminating losses related to the natural movement of the system in which it is inserted. An incremental improvement is observed in patent 4773981 from 1988, where the same functioning mechanism finds new materials, lower costs, and significant improvements in system efficiency.

Citing patent 4442801, Cunningham John, under patent 5450822, improves the efficiency of the Canister where the conductive plates of anodes and cathodes are housed, achieving more efficient results in the transformation of water into hydrogen. Another incremental improvement, this time to improve the pathway of hydrogen and oxygen to the combustion parts, is achieved by patent 5458095 and patent 6508210, which promote improvements in the gas passage chamber, creating a more stable flow.

Shelton Gleen, when publishing patent 4573435, describes a mechanism like the patents by Pier, Weldon, Drabold, and Joseph, but instead of a gasoline engine, adapts the model to a diesel engine for large vehicles, aiming to improve the energy and environmental efficiency of these engines. Gleen's publication is significantly improved in 1992 when Russell International Inc presents a potentially commercially viable prototype of a diesel/hydrogen engine under deposit 5119768. Patent 0220039, in this context, proposes gas and liquid injection into the same duct that distributes fuel to the combustion system.

Caterpillar INC., under patent number 4368705, presents a hardware and software system that improves the control of electronic fuel injection, the opening of the oxygen collector, among other mechanisms aimed at improving the overall energy efficiency of engines. Another patent that uses programming to improve the electronic control unit of vehicles, this time adapted to hydrogen vehicles, is achieved by patent 0003276, which creates specific mechanisms to control the use and injection of hydrogen into the system. Similarly, patent 6332434 uses the same justifications but controls various other components, marking a significant advance in the capabilities and possibilities of the electronic control unit of engines that utilize hydrogen.

In 2008, a significant advance was achieved regarding the software used to monitor system operation. The registration by Advanced Comb Technologies, number 0049417, creates an electronic control unit that not only controls but also designs and executes different consumption models depending on the user's needs.

Patent 4369737 presents a new electrolysis apparatus, new materials for tanks, electrodes, and an aqueous solution that shows a higher degree of efficiency. A similar achievement is made by Ryddings Pty Ltd in 1985 with patent 5711865, describing new methods and materials to achieve a more efficient and commercially viable electrolysis process. Something similar, but this time focused on the electrolytic tank and variable combinations of electrodes immersed in a new solution, is presented by patent 5105773. In 2011, patent 0174241 conditions the electrolysis apparatus and its entire storage and distribution system into cylinder formats, aiming to optimize space.

To contain oxidation and reduce explosion risks, patent 5733421 from 1996 moves towards a sealing process for the electrolysis mechanism, preventing corrosion and consequently leaks and explosions. Patent 7258779 brings another mechanism for water electrolysis, altering electrodes, electric current, partial immersion, and a pulsed application. Code 0159663 from 2003 adds a condenser to the system to remove water impurities and improve the efficiency of converting the oxygen and hydrogen from the reaction. Patent 0217991 bets on the purity of electrode materials to enhance the reaction efficiency. Application 0180101 creates a mechanism to send additional energy to the fuel cell if more hydrogen is demanded by the system.

Code 0005939 foresees a dual hydrolysis process aimed at creating high-octane hydrogen using acetic acid, suitable for high-performance engines. This patent is also one of the main patents in the main path due to its innovative construction of the electrolysis system, utilizing all normal engine operations as a heat source to conduct the process, which is further improved by the materials involved in electrode preparation. The energy efficiency of this process and its innovative construction is why it is cited so often. Another important incremental innovation in this sector is characterized by patent 5305715, which uses stainless steel anodes and cathodes and "glacial acetic" electrolyte, creating significantly fewer unwanted sediments in the process tanks. Other materials producing similar results but commercially more competitive were explored by patent 5452668 from Arizona Hydrogen Manufacturing Inc and patent 5399251 by Nakamats Yoshiro.

Enhancing the safety of hydrogen use in an internal combustion system, Water Fuel International Inc, with registration 5231954, created for its fuel cells a vacuum line between the electrolytic tank and the injection into pistons and cut-off mechanisms for generation in case of accidents. The cut-off mechanism feeds the system with gases other than hydrogen, which, during engine operation, improves energy efficiency and, in anomalous operation cases, reduces explosion risks involving exclusive hydrogen use. The efficient and safe operation of such a system places this patent among the most cited in the main path of this network. Patent 0174277 introduces an additional safety component, a carburettor prepared to handle abrupt temperature rises resulting from hydrogen combustion in engines switching between gasoline or diesel and hydrogen.

Incrementally, patent 6209493 presents a kit of level and temperature sensors to constantly monitor the system. Additionally, it activates a compensation mechanism to protect the system and generate or cut off incoming hydrogen amounts in the internal combustion system. The Canadian registration 2349508 inserts a compressor into the system for effective control of the air-fuel mixture connected to the system's air intake. Additionally, patent 0209993 proposes the active pumping of gases from the electrolytic cell to prevent gas bubbles that create discontinuities in fuel supply.

Patent 6257175 creates reservoir mechanisms for hydrogen and oxygen generated during system operation, preventing the process from starting from zero at each system start, thus increasing system efficiency. Regarding efficiency, patent 7290504 foresees the capture of hydrogen and its application in otherwise lost points, such as when directly lost in admission or as an unused combustion product, and projects precise control in injectors depending on system demand. This patent is like Toyota Motor Co.'s patent filed a year later under number 7367289.

In 1996, Teves Antônio publishes under number 5513600 a completely different construction of a gasoline/hydrogen engine. His idea involves a simplified construction requiring less energy for the electrolysis process. His concept, through hardware and software controls, is for the engine to reduce gasoline usage or control hydrogen production as it reaches equilibrium points, seeking better energy efficiency throughout the system, from generation to exhaust. A similar construction is made by patent 6311648 in 2001, aiming to test a new arrangement of operating mechanisms for efficiency gains. Patents 0261253, 8464667, 0254259, 0038318 deal with improving hydrogen engine operation through new materials and ways of organizing the electrolysis process, deposition, and distribution.

The creation by the Massachusetts Institute of Technology, patent number 58811896, greatly differs from everything previously done in this technological path and represents the opening of a new and important technological route in 1999. The project aims to achieve a "hydrogen-rich gas" derived from the direct transformation of gasoline in an electrolytic tank that would generate, in addition to hydrogen, various other gases resulting in high energy efficiency, rotating a generator, and powering an electric motor or a combustion engine prepared to handle the gas. This invention opens the door for subsequent studies investigating the transformation of ethanol into hydrogen (Maia et al., 2007).

In 2006, Bernard Lee published patent 7069126, which may be considered the first to focus on greenhouse gas emissions and their quantification in engines for various applications. His invention displays the volume of emissions instantaneously on a screen, also useful for monitoring the reduction when hydrogen and gasoline/diesel applications are combined.

A patent that characterizes another knowledge path derived from the main route begins with Hudson Charles' application in 2014. Deposit number 0084157 presents a completely different method of achieving the electrolysis process and transforming this energy into motion. The patent describes an internal combustion engine with a water rotor self-powered by electrolysis and the combustion of hydrogen and oxygen. The engine has several wheels connected to an electric generator, which produces electricity. This electricity is used for water electrolysis, generating hydrogen and oxygen for combustion.

The last patent in the main path dates from 2018 and is the first Chinese patent analysed here. The highly detailed patent in each of its micro components constructs a compartment for water electrolysis of diminutive size compared to conventional inventions with similar productive efficiency. The size, which guarantees higher allocative efficiency, especially in automotive compartments, is made in forms and materials very different from those previously seen, a strong indication that by 2018 China was already at the forefront of hydrogen developments. As of 2023, China is already marketing hydrogen versions of vehicles from domestic brands in its internal market (King, 2023).

Table 5: Patents and relevant information on the main trajectory

Patent number	Title	Apliccant	Data
US 2365330 A	Apparatus for electrolytically producing oxygen and hydrogen	Carmichael Asa B	11/10/1941
US 2509498 A	Electrolytic charge forming device	Edward Heyl George	28/11/1944
US 2565068 A	Internal-combustion engine	Walter Drabold	21/08/1951
US 3648668 A	Gas-Operated Internal Combustion Engine	Ebert Michael , Eugene J Kalil , Francisco Pacheco	14/03/1972
US 5143025 A	Hydrogen and oxygen system for producing fuel for engines	Munday John F	01/09/1972
US 3906913 A	System for minimizing internal combustion engine pollution emission	California Inst of Techn	10/08/1973
US 4023545 A	Energy means for internal combustion engines	Mosher Edward G , Webster John T	24/01/1975
US 4085709 A	Hydrogen fuel system for a vehicle	Tangri Kuldip Chand	04/12/1975
US 3939806 A	Fuel regenerated non-polluting internal combustion engine	Bradley Curtis E	24/02/1976
US 4112875 A	Hydrogen-Fueled Engine	Nasa	27/08/1976
US 3980053 A	Fuel supply apparatus for internal combustion engines	Beeston Co Ltd	14/09/1976
US 4003345 A	Fuel regenerated non-polluting internal combustion engine	Bradley Curtis E	18/01/1977
US 4031865 A	Hydrogen-oxygen fuel cell for use with internal combustion engines	Dufour Patrick	28/06/1977
US 4111160 A	Method and Apparatus for Operating Combustion Engines	Talenti Pier F	05/09/1978
US 4133847 A	Vaporized fuel for internal combustion engine and method and apparatus for producing same	Feuerman Arnold I	09/01/1979
US 4140090 A	Precombustion chamber, stratified charge internal combustion engine system using a highly combustible gas in the precombustion chamber	Owen Wickersham & Erickson	20/02/1979
GB 2073317 A	Hydrogen-oxygen thermochemical combustion initiation	Escher Foster Tech Inc	21/03/1980
US 4368696 A	Electrolytic supplemental fuel generation for motor vehicles	Reinhardt Weldon E	29/07/1980
US 4344831 A	Apparatus for the generation of gaseous fuel	Weber Charles T	12/09/1980
US 4271793 A	Internal combustion engine	Valdespino Joseph M	09/06/1981
US 4368705 A	Engine control system	Caterpillar Inc	18/01/1983
US 4369737 A	Hydrogen-oxygen generator	Sanders Cledith A , Sanders Margaret M , Sanders Ii Cledith A	25/01/1983
US 4442801 A	Electrolysis fuel supplementation apparatus for combustion engines	Glynn John D , Glynn Daniel R , Andrews Arthur R	17/04/1984
US 5711865 A	Electrolytic gas producer method and apparatus	Ryddings Pty Ltd , Renjean Pty Ltd	10/10/1985
US 4573435 A	Apparatus and method for generating hydrogen gas for use as a fuel additive in diesel engines	Shelton Glenn F	04/03/1986
US 4773981 A	Apparatus for improving internal combustion engine efficiency	Masiuk Stephen	27/09/1988
US 5119768 A	Petroleum and hydrogen driven engine	Russell International Inc	09/01/1992
US 5105773 A	Method and apparatus for enhancing combustion in an internal combustion engine through electrolysis	Alternate Fuels Inc. a Ny Corporation	21/04/1992
US 5231954 A	Hydrogen/oxygen fuel cell	Water Fuel International Inc	03/08/1993
US 5305715 A	Supplement fuel generator for vehicle engines	Hytec Fuel Systems Inc	17/08/1993
US 5452688 A	Method and apparatus for enhancing combustion in internal combustion engines	Arizona Hydrogen Manufacturing Inc	27/12/1994
US 5399251 A	System for generating hydrogen and oxygen	Nakamats Yoshiro	21/03/1995
US 5450822 A	Apparatus and method for electrolysis to enhance combustion in an internal combustion engine	Cunningham John E	19/09/1995
US 5458095 A	Air pump-assisted hydrogen/oxygen fuel cell for use with internal combustion engine	Energy Reduction Systems Inc	17/10/1995

US 5513600 A	Water fuel converter for automotive and other engines	Teves Antonio Y	07/05/1996
US 5733421 A	Hydrogen-oxygen fuel cell	Pettigrew J W , Monette Gregory R , Hirsch David H	19/09/1996
US 2001/0003276 A1	Hydrogen Generating Apparatus	Environmental Applications Research Technologies for Hydrogen Inc	29/06/1998
US 5887554 A	Rapid response plasma fuel converter systems	Massachusetts Institute of Technology	30/03/1999
US 6155212 A	Method and apparatus for operation of combustion engines	Mcalister Technologies Llc , Advanced Green Innovations Llc	05/12/2000
US 6209493 B1	Internal combustion engine kit with electrolysis cell	Global Tech Environmental Products Inc , Canadian Hydrogen Energy Company Limited	03/04/2001
CA 2349508 A1	Electrolysis Cell and Internal Combustion Engine Kit Comprising the Same	Global Tech Environmental Products Inc	04/06/2001
US 6257175 B1	Oxygen and hydrogen generator apparatus for internal combustion engines	Mosher Edward G , Webster John T	10/07/2001
US 6311648 B1	Hydrogen-oxygen/hydrocarbon fuel system for internal combustion engine	Larocque Jean-Louis	06/11/2001
US 7258779 B2	Method and means for hydrogen and oxygen generation	Casey Alan Patrick , Smith Stewart	13/11/2001
US 6332434 B1	Hydrogen generating apparatus and components therefor	Environmental Applications Research Technologies for Hydrogen Inc	25/12/2001
US 6508210 B2	Fuel supply system for a vehicle including a vaporization device for converting fuel and water into hydrogen	Tyma Inc	21/01/2003
US 2003/0159663 A1	Hydrogen generation apparatus for internal combustion engines and method thereof	Proton Energy Systems	09/12/2003
US 2005/0217991 A1	Fuel system for internal combustion engine	Dahlquist David F Jr	07/02/2005
US 6866756 B2	Hydrogen generator for uses in a vehicle fuel system	Hydrogen Technology Applications Inc	15/03/2005
US 2006/0180101 A1	Hydrogen-oxygen production device	Monette Gregory R	15/02/2006
US 7069126 B2	Emission monitoring display device	Bernard Lee	27/06/2006
US 2007/0080071 A1	Internal combustion apparatus and method utilizing electrolysis cell	All My Relations Inc , Go Green Fuel n.a. l.p	06/10/2006
US 7290504 B2	System and method for operating an internal combustion engine with hydrogen blended with conventional fossil fuels	O'reilly Hugh	06/11/2007
US 7367289 B2	Control system for hydrogen addition internal combustion engine	Toyota Motor Co Ltd	06/05/2008
US 2010/0049417 A1	Dual ECU for aftermarket conversions of vehicles and boats to oxy-hydrogen or hybrid fuels	Advanced Comb Tecnology	28/08/2008
US 2011/0209993 A1	Dual Cylinder Hydrogen Generator System	Barmichael Joseph	24/10/2008
US 2011/0174277 A1	Universal Hydrogen Plasma Carburetor	Socolove Bert	20/01/2010
US 2011/0220039 A1	Hydrolysis System to Produce Hydrogen-Oxygen Gas as a Fuel Additive for Internal Combustion Engines	Nowicki Richard , Herzstock James J , Spurgin Blake , Dragan Joseph	09/03/2010
US 2011/0174241 A1	Cylindrical Hydrogen Fuel Generator Having Passive Tubular Cells	Go Go Green World Inc , Macgregor John , Christensen Conchita , Hydrogen Injection Technology Inc	09/04/2010
US 2011/0005939 A1	Generation of High Octane Hydrogen Gas From Acetic Acid	Haylin Hydrogen Systems Llc	09/07/2010

US 2014/0261253 A1	Power Generation System	Clean Power Providers Llc	15/03/2013
US 8464667 B1	Hydrogen system for internal combustion engine	Stama Giulio	18/06/2013
US 2016/0084157 A1	Water-Rotor-Internal-Combustion Engine (Wrice)	Hudson Charles	19/09/2014
US 2017/0254259 A1	Method of Generating and Distributing a Second Fuel for an Internal Combustion Engine	Htp Inc , Hytech Power Llc	07/03/2016
US 2018/0038318 A1	Water Capture System, Electrolysis Cell and Internal Combustion Engine Kit	Emission Technologies Limited	05/08/2016
WO 2018/000595 A1	Oxyhydrogen Gas Generator Used for Vehicle	Dongguan City Lvnengbao Automotive Supplies Tech Co Ltd	04/01/2018

Source: Lens.org Note: Patent numbers marked with *** are those that do not have a CPC linked to category Y. This does not mean that they are "brown" technologies, that is, not linked to sustainability. Except for the first patent in the table, all the others are related to products and processes linked to engineering, chemistry, and physics of materials, not necessarily to unsustainable activities, so it does not mean that they are environmentally harmful, just that they do not carry environmentally friendly classifications.

Appendix II

The patents listed in this secondary path do not entirely prioritize CPC F02b2043/106 in their list of possible application areas for their inventions. As a result, it is common to find patents in this path that sometimes seem to diverge from the scope involving engines, apparatuses, electrolysis, and hydrogen. Unlike the main path that needs to capture such aspects, a secondary path that does not even refer to fossil fuels and is on the periphery of the primary developments of the CPC would not share such affiliation regarding products and objectives.

Nevertheless, even if in the background, the generation of hydrogen through the electrolysis process can be seen in the patent developments observed here. It is worth noting that the connection to the main path centres on patent US 10900540 B1 (sustainable energy production through a mechanical clutch assembly), which coincidentally is the last patent in the analysed path. This also explains the differentiation observed in the patent filings of this path, as the route tends to bear greater similarity to the main path patent, here represented by the patent linked to the main path.

The observed path begins in 1949 with the publication of patent 2460015, which creates a motion transmission mechanism that transforms a single impulse into a larger volume of movements through gears of various sizes, thus allowing for energy savings to perform the same movement. Years later, the mechanism was capable of generating energy (US 4211452 A – Flywheel for energy potential generation; US 5563802 A – generator and apparatus for energy generation using flywheels; CN 1269628 A – new type of apparatus for energy generation; US 6236127 B1 – energy accumulator built through gears transforming movements; 2004/0051507 A1 – vacuum system for mechanical energy generation via gears; 2012/0280518 A1 – energy generator system with improved gear method; US 9742331 B2 – dual method for energy generation and storage emphasizing mechanical generation; 2017/0085141 A1 – mechanical energy generation with hydraulic apparatus).

Over time, various developments were linked to this invention, and this idea of pulleys or gears enhancing movements began to be used as a basic principle applied to energy generation, something well described by patent 6770995, which uses a system of bearings, magnets, and metals to achieve magnetic bearing, later used to generate and store energy from the movement of various vehicles.

Movements of gears, pulleys, and bearings, and the subsequent energy generation found applications years later in electric vehicles, hybrids, ships, and airplanes, which required storing this energy in battery systems. The problem involved the voltage difference, which proved problematic for this storage, something addressed and improved by patents from various sectors, from naval to aerospace (US 6114775 A – auxiliary energy control system in hybrid vehicles; US 6188139 B1 – energy system integration in maritime navigation systems; US 8039983 B2 – methods for powering motors with alternating current in airplanes).

The application in engine systems that require batteries to generate motion is another development spread in this path, with the main patent being US 10900540 B1 (sustainable energy production through a mechanical clutch assembly), which not only produces electrical potential but also stores it in batteries that accommodate different entries regarding voltage and amperage and have various protections against discharges and other defects resulting from their use. Additionally, patents that contributed to this patent's development in terms of battery storage and charging include deposits 2017/0063150 A1 – uninterrupted power supply to battery systems; 2018/0357577 A1 – system for optimizing the charging and use of stored energies; US 2014/0184153 A1 – method for charging battery pairs with different voltages and currents.

Thus, having highlighted the main patents in the path and their principal achievements, it is possible to verify that indeed it is feasible to find within the developments of the CPC network constructed through code F02b2043/106, developments that are not linked to the use of fossil fuels. The latent issue is that to do so, 97.01% of the network had to be excluded from the analytical scope to allow the visualization of this path, showing that the process of hydrogen fuel production through electrolysis aimed at the transport sector will hardly have developments free from fossil fuel use.

Table 6: Secondary Path Patents (No Fossil Fuels)

Patent nº	Title	Date	Institution	Name	Country
US 2460015 A	Motion transmitting mechanism	25/01/1949	Individual	Jones Neven	USA
US 3526795 A	Torque Reaction Attitude Control Device	01/09/1970	Individual	William Pecs	USA
US 4211452 A	Inertia wheel	08/07/1980	Enterprise	Aerospatiale	France
US 4677365 A	Automotive charging system having generator with multiple windings and regulators	30/06/1987	Individual	Yang Tai Her	USA
US 5563802 A	Generator power system and method	08/10/1996	Enterprise	Onan Corp	USA
US 6114775 A	Control system of auxiliary power system for a hybrid electric vehicle	05/09/2000	Enterprise	Mando Machine Co.	Korea
CN 1269628 A	New-type power generator set	11/10/2000	Individual	Xing Shunxin	China
US 6188139 B1	Integrated marine power distribution arrangement	13/02/2001	Enterprise	Electric Boat Corp	USA
US 6236127 B1	Flywheel energy accummulator	22/05/2001	Enterprise	Karlsruhe Forschzent	Germany
US 6611068 B2	Power system	26/08/2003	Enterprise	Sure Power Corp	USA

US 6770995 B1	Passive radial magnetic bearing	03/08/2004	Individual	Foshage Gerald K	USA
US 6803679 B1	Parallel redundant power system and method for control of the power system	12/10/2004	Enterprise	Phoenixtec Power Co Ltd	Taiwan
US 6931856 B2	Multi-spool turbogenerator system and control method	23/08/2005	Enterprise	Mes Int Inc	USA
US 2004/0051507 A1	Long-life vacuum system for energy storage flywheels	30/05/2006	Individual	Gabrys Christopher	USA
JP 2008035589 A	Power Feeding Method and Device	14/02/2008	Individual	Tagami Minoru	Japan
US 8907520 /B2	Parallel redundant power distribution	09/12/2009	Enterprise	Zonit Structured Solutions Llc	USA
WO 2010/123343 A1	Power Generator	28/10/2010	Enterprise	Green Tech Holdings Sdn Bhd	Malaysia
US 8039983 B2	Systems and methods for providing AC power from multiple turbine engine spools	18/10/2011	Enterprise	Boeing Co	USA
US 8049358 B2	Marine power distribution and propulsion systems	01/11/2011	Enterprise	Converteam Technology Ltd	USA
US 2012/0083173 A1	Marine Propulsion Devices, Systems and Methods	05/04/2012	Individual	Mcmillan Scott	USA
US 2012/0280518 A1	Power Generation Systems	08/11/2012	Enterprise	Powersys LLC	USA
US 2015/0097432 A1	Hybrid Power Generation with Variable Voltage Flux	09/04/2015	Individual	Gurin Michael H	USA
US 2015/0188400 A1	Magnetic Flywheel Induction Engine-Motor-Generator	02/07/2015	Individual	Kemp Robert Louis	USA
US 2014/0184153 A1	Method for Recharging a Pair of Vehicle Batteries of Different Nominal Voltages, and Associated System	09/05/2017	Enterprise	Renault S.A	France
US 9742331 B2	Doubly-fed, variable-speed, dual-voltage AC generation and distribution systems	22/08/2017	Enterprise	ABB tecnology Ag.	Germany
US 9751625 B2	Micro hybrid generator system drone	05/09/2017	Enterprise	Top Flight Tech Inc	USA
US 2017/0294691 A1	Power Storage System and Power Storage Method	12/10/2017	Enterprise	Fujikura LTD	Japan
US 2016/0241029 A1	Modular direct current power distribution network, and a method for its use	21/11/2017	Enterprise	Liteideas LLC	USA
US 2017/0085141 A1	Mechanical Energy-to-Electricity Transformer Using Kinetic Energy of a Hydraulic Machine	03/05/2018	Individual	Wang Yao Lin	Taiwan
US 2016/0352131 A1	Apparatus and Method for Charging and Discharging a Multiple Battery System	13/11/2018	Individual	Nelson Larry	USA
US 2018/0357577 A1	Building Energy Optimization System With Economic Load Demand Response (Eldr) Optimization	13/12/2018	Enterprise	Johnson Controls Tech Co.	USA
US 10389121 B1	Efficient portable AC/DC power generator system	20/08/2019	Individual	Sherry Raimond	USA
US 2017/0063150 A1	Uninterruptible Power Supply Unit	03/09/2019	Enterprise	FDK corp	Japan
US 2020/0063706 A1	Hydroelectric Power Generation Device Using Multistage Cascade Structure	27/02/2020	Individual	Park Jungchi	USA
US 10900540 B1	Mechanical renewable green energy production	26/01/2021	Enterprise	3b Energy LLC; Phos Global	USA

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