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Impurity Mitigation Technologies in PEM Fuel Cells

A Patent Landscape Analysis

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Abstract

This thesis investigates impurity mitigation technologies in Proton Exchange Membrane Fuel Cell systems through a patent landscape analysis. PEM fuel cells have become one of the most advanced fuel cells that could be used to power electric vehicles and to produce stationary power due to their low operating temperature, rapid start-up, high power density and dynamic characteristics. Nevertheless, the large-scale usage of PEM fuel cells faces a number of technical obstacles associated with cost, durability, water and thermal management, use of platinum catalysts and impurities in the fuel. Presence of impurities in the hydrogen or air leads to negative effect on the PEMFC characteristics due to decrease in the efficiency of the catalysts, decrease in the conductivity of the membrane, transport losses and deterioration of the stack. In other words, the problem of impurities removal cannot be viewed as materials issue only. The objective of the thesis is to identify and analyse patented technological solutions addressing impurity-related problems in fuel cell systems. The patent search was conducted using Lens.org through an iterative query-building process. Initial keyword-based searches produced excessive noise due to the ambiguity of terms such as contamination, impurity, poisoning, sulfur, ammonia and purification. Similarly, the use of the IPC code H01M8/06 alone proved too broad. The final selected query combined H01M8/06 with impurity-related keywords searched in title and abstract fields, providing the best compromise between technological scope and semantic precision. The selected dataset includes 2,117 patent records, corresponding to 1,260 simple families and 1,209 extended families. The analysis examines the dataset through several dimensions: temporal evolution, legal status, geographical distribution, applicant structure and citation visibility. Results show that patenting activity was particularly concentrated between 2000 and 2010, with a peak in the mid-2000s, suggesting a phase of strong system-level innovation in fuel cell reactant treatment and protection strategies. The predominance of expired patents, together with the presence of pending and active documents, indicates that impurity mitigation is a mature but still active technological field. Geographically, patent protection is mainly concentrated in the United States, Japan, China and Europe, reflecting the strategic relevance of fuel cell technologies in major industrial regions. The applicant analysis highlights the role of automotive companies, electronics firms, energy-related actors and specialized fuel cell developers, confirming the cross-sectoral nature of impurity mitigation. Citation indicators further suggest that the selected patents have meaningful visibility within the patent system. Overall, the thesis shows that impurity mitigation is a key enabling area for PEMFC deployment. It connects the electrochemical sensitivity of the stack to the practical need for clean, controlled and reliable reactant streams, supporting the durability, reliability and commercialization of PEM fuel cell systems.

Table of Contents

List of Figures IV

1 Introduction to the Technology – Reference Context 1
- 1.1 Fuel Cell Technologies Overview . . . 2
- 1.2 Proton Exchange Membrane Fuel Cells: Operating Principles . . . 4
- 1.3 Applications of PEM Fuel Cells . . . 7
- 1.4 Market, Policy and Industrial Relevance . . . 11
- 1.5 Hydrogen Purity and Why Impurities Matter . . . 14

2 Method 19
- 2.1 Patents as a Data Source . . . 20
- 2.2 Building Search Queries . . . 24
  - 2.2.1 Query 1 . . . 24
  - 2.2.2 Query 2 . . . 26
  - 2.2.3 Query 3 . . . 27
  - 2.2.4 Query 4 . . . 28
  - 2.2.5 Query 5 . . . 29
- 2.3 Final Search Strategy and Dataset Selection . . . 31

3 Analysis and Results 32
- 3.1 Overview of the Selected Dataset . . . 33
- 3.2 Temporal Evolution of Patenting Activity . . . 35
- 3.3 Legal Status and Technological Maturity . . . 38
- 3.4 Geographical Distribution and Industrial Context . . . 40
- 3.5 Applicant Structure and Concentration . . . 44
- 3.6 Forward Citations and Portfolio Visibility . . . 47
- 3.7 Discussion of the Selected Patent Landscape . . . 49

4 Conclusion 52

References 56

List of Figures

1.1 Schematic representation of a fuel cell. 2
1.2 PEMFC representation 5
1.3 Schematic representation of a PEMFC stack 6
1.4 Schematic representation of a Generic fuel cell electric vehicle (FCEV) [5]. 8
1.5 Schematic diagram of the BoP of the PEM fuel cell stack [5] 9
1.6 Simplified model of the methanol reforming PEMFC system. [6] . . 11
1.7 Hydrogen as an energy carrier connecting energy production, infrastructure and multiple end-use sectors.[7] 12
1.8 Diagram of PEM fuel cell impurites. 18

2.1 Temporal evolution of patenting activity across the five query datasets 21

3.1 Priority-date distribution of the selected patent dataset based on Query 5 36
3.2 Legal status distribution of the selected patent dataset based on Query 5. 39
3.3 Jurisdiction distribution of the selected patent dataset based on Query 5. 42

Chapter 1

Introduction to the Technology – Reference Context

This chapter introduces the technology that will be needed to comprehend the significance of fuel cells within the hydrogen economy and, more precisely, PEMFCs. The fuel cell is an electrochemical device that produces electricity from the chemical energy of a fuel without any combustion process associated with heat engine technology. Fuel cells thus offer a direct method of converting chemical energy to electrical energy, which makes them quite interesting for producing electricity in a clean and efficient manner. Firstly, the chapter discusses some of the major types of fuel cells, describing and comparing their characteristics and limitations. Emphasis is laid on PEMFCs, one of the most promising fuel cells because of their relative low operation temperature, fast startup, small size and high power density [1]. All these advantages enable PEMFCs to be applied in a variety of fields, from transportation to portable systems and small stationary generators. Nonetheless, there exist several technical challenges that prevent the commercialization of PEMFCs, such as high costs, low durability, water and heat management problems, the use of platinum catalysts, and contamination of the fuel streams [2]. Against this backdrop, the purity of the hydrogen and air supplied to the cell becomes one of the key determinants of performance and reliability of such a system. The presence of even trace amounts of contaminants may influence the efficiency of the catalyst, membrane durability, and cell performance as a whole. Thus, the study of problems associated with impurities becomes a valuable technological approach to the analysis of existing innovative trends in PEMFC systems. This opening chapter provides the theoretical foundation for subsequent chapters of this thesis.

1.1 Fuel Cell Technologies Overview

Fuel cells can be described as electrochemical devices for converting chemical energy to electrical energy. In contrast to the conventional thermal engine, where the chemical energy contained in the fuel is first transformed into heat energy, then into mechanical energy, and lastly into electrical energy, fuel cells generate electricity by the process of electrochemical reactions [2]. This is among the many factors which make fuel cells considered clean and more efficient compared to the conventional thermal engines [2]. When hydrogen serves as the fuel, the major end products are electrical energy, heat energy, and water, making hydrogen fuel cells quite interesting in the overall low carbon energy production system [2, 1]. Technologically speaking, a typical fuel cell usually comprises three primary components that actively participate in its operation process: the anode, cathode, and electrolyte between them. Fuel enters into the anode side of a fuel cell, whereas oxygen from air goes into the cathode side of it. The electrolyte is used for the passage of certain ions between electrodes but does not allow any electrons to go across the cell. Hence, electrons have to be moved through an external circuit which creates electricity. The exact operating principle of a fuel cell greatly depends on the fuel cell design [2].

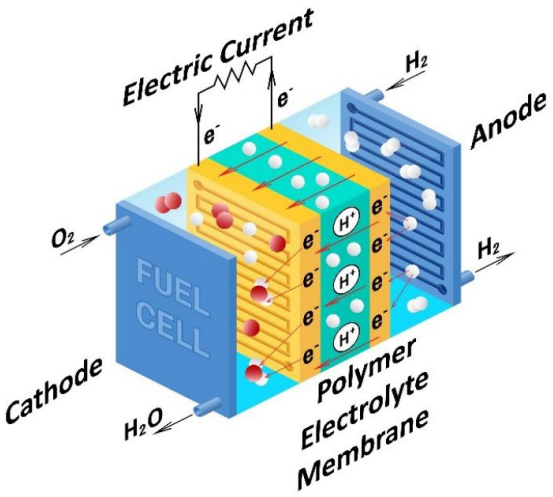


Figura 1.1: Schematic representation of a fuel cell.

The major difference between fuel cells and batteries relates to the use of the reactants. While batteries function as energy storage and energy conversion devices where the chemicals used as reactants are contained within the battery itself, and the battery ceases to produce any energy once these reactants run out, or once the electrodes wear out, fuel cells are essentially energy conversion

devices. This is because the reactants are provided from the outside, thus enabling a fuel cell to produce energy for as long as there are reactants available and products are removed from the system [2, 1]. Fuel cells are classified based on the nature of the electrolyte used. Some of the major classes of fuel cells are proton exchange membrane fuel cell (PEMFC), direct methanol fuel cell (DMFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC). There are a lot of variations between different fuel cells because of their operating temperatures, fuel flexibility, power generation capacity, efficiency, technological readiness level and application areas [2, 1]. Low-temperature fuel cells like PEMFCs and DMFCs are typically appropriate for applications that demand quick startup, compact designs and dynamic operation capability. On the other hand, high-temperature fuel cells like MCFCs and SOFCs are most suitable for stationary power production and combined heat and power applications. Among these technologies, the PEM fuel cell technology has gained much importance due to its lower operating temperature, higher power density, faster start-up ability, small size, and good dynamic response [2, 1]. The above-mentioned features make the PEM fuel cell a very good choice for transportation sector applications such as fuel cell electric vehicles, buses and many other mobile applications, as well as portable or small-scale distributed power generation applications. Moreover, PEMFC technology is usually looked upon favorably because they can operate at comparatively lower temperatures than other fuel cell types, hence having a shorter start-up time [2, 1]. However, PEMFC technology still faces several barriers to large-scale commercialization. The main challenges include high system cost, limited durability, dependence on platinum-based catalysts, complex water and thermal management, and sensitivity to contaminants in the reactant streams [2]. The cost issue is strongly linked to the use of expensive materials, especially platinum group metal catalysts, as well as to the balance-of-plant components required to operate the system. Durability is another critical issue, because PEMFC performance can degrade over time due to material degradation, fuel starvation, voltage reversal, membrane dehydration, flooding, catalyst degradation and contamination phenomena [2, 1]. Other fuel cell types present different advantages and limitations. SOFCs and MCFCs operate at high temperatures and can achieve high electrical efficiencies, especially in stationary and combined-cycle applications. Their high operating temperature also enables internal reforming and the use of different fuels, but it creates challenges related to material durability, thermal stress, slow start-up and sealing. PAFCs are relatively mature and have been used in stationary combined heat and power systems, although they generally have lower power density and require expensive auxiliary systems. AFCs can achieve high performance, but their sensitivity to carbon dioxide and other contaminants has limited their use mainly to specific applications where pure reactants are available [2]. DMFCs, on the other hand,

are attractive for portable applications because they use liquid methanol, which is easier to store and handle than compressed hydrogen, although they suffer from lower power density and efficiency compared with PEMFCs [2, 1]. The use of fuel cells has a wide variety of applications. In the portable category, fuel cells are applicable in the generation of power for battery chargers, military hardware, laptops, mobile phones and small power systems in general. Stationary applications include provision of backup power, power in remote areas, distributed generation and combined heat and power. Fuel cells are applied or studied for usage in cars, buses, trucks, forklifts, auxiliary power units, rail transport, boats and unmanned aerial vehicles [2]. The wide application opportunities of fuel cells are determined by their modular nature; the power output increases when several cells are stacked together to form larger stacks [2, 1]. Although there are many benefits of using fuel cells for generating electricity, however, the overall performance of a fuel cell system is dependent not only on the stack but also on the associated sub-systems. All the associated sub-systems of a fuel cell system include fuel, oxidant supply, thermal management, water management, power electronics, and control systems. In the case of PEMFC, the above-mentioned associated systems are extremely essential because the operation of a fuel cell stack requires very specific temperature, humidity, pressure, and reactants' flow conditions. The inadequate fuel or air supply could result in fuel-starvation, voltage loss and long-term degradation while inadequate water management will cause dehydration or flooding of the membrane [1]. Hence, PEMFC development does not only cover materials and electrochemistry but also systems integration. In the context of this thesis, this broad perspective on the field is crucial since it allows one to realize that fuel cell technology is more than the electrochemical stack, but an entire system needed to ensure its proper functioning. With regard to PEMFCs, the quality of fuel and oxidant streams plays an especially significant role due to their influence on the efficiency of catalysts and membranes. This means that the examination of impurity removal technologies in PEM fuel cells should be viewed within the broader context of fuel cell technologies.

1.2 Proton Exchange Membrane Fuel Cells: Operating Principles

"A proton exchange membrane fuel cell or PEM fuel cell turns the energy from hydrogen into electricity"[3]. This happens because of some reactions that occur inside the fuel cell. "The term PEM fuel cell alludes to a kind of membrane that helps make this occur"[3]. This membrane is similar to plastic that allows certain things pass through while keeping others out. A single PEM fuel cell is made up of a main parts: one side is called the anode the other side is called the cathode and in between them is the proton exchange membrane. The membrane touches two

layers that are really good at conducting electricity and these layers are usually made out of carbon. Where the membrane meets the electrodes there are helper layers that make the chemical reactions happen more easily. In PEM fuel cells these helper layers are made out of tiny pieces of platinum that are stuck to carbon as said by Barbir in his book, about PEM fuel cells. The basic operating principle is based on the separation of the ionic and electronic paths. Hydrogen is given to the anode part of the cell, while oxygen, in general from air, is supplied to the cathode side. "Consider the anode, hydrogen molecules are divide into protons and electrons"[3]. The hydrogen oxidation reaction is written as:

$$H_2 \rightarrow 2H^+ + 2e^- \tag{1.1}$$

The protons produced at the anode migrate through the proton exchange membrane approaching the cathode. The electrons, instead, cannot pass through the membrane. As a result, they are forced to travel through the external electrical circuit, where they generate useful electrical current before reaching the cathode side of the cell [4]. At the cathode, oxygen reacts with the protons that have crossed the membrane and with the electrons that have returned through the external circuit. The oxygen reduction reaction produces water according to the following reaction:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{1.2}$$

The overall electrochemical reaction of a PEM fuel cell is therefore:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{1.3}$$

The end effect of all the above processes occurring simultaneously is the generation of electricity, heat, and water. In the fuel cell, the hydrogen part acts as the negative electrode and is known as the anode, while the oxygen acts as the positive electrode and is known as the cathode [4].

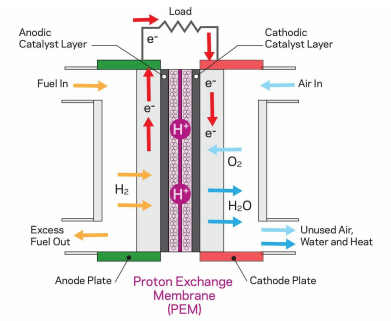


Figura 1.2: PEMFC representation

The membrane performs a very important function within the cell. It must facilitate proton transport from the anode to the cathode while, at the same time, preventing gas crossover and electronic short-circuiting. If the gases were allowed to come into contact directly, problems in electrochemical reaction and safety concerns would develop. For this reason, the membrane is not only an ionic conductor but also a physical separator between the fuel and oxidant streams [4]. The porous structure of the electrodes is also essential. Being both gases, it is necessary for hydrogen and oxygen to be able to access the catalytic sites where the electrochemical reaction takes place. On the other hand, the electrons produced at the anode and the ones used at the cathode need to be conducted via electrical conduction. The porous electrodes therefore support gas transport, electron porous electrodes therefore support gas transport, electron conduction and access to the catalyst layer. On the cathode side, they also contribute to the removal of the water produced by the reaction [4]. A single PEM fuel cell produces a relatively low voltage, approximately around one volt under ideal or near open-circuit conditions. In practical operation, however, the voltage decreases when current is drawn from the cell due to activation losses, ohmic losses and mass transport limitations. For this reason, practical PEMFC systems require several cells connected in series to form a stack. By stacking multiple cells, the total voltage can be increased to values suitable for real applications, such as vehicles, portable power units or stationary systems [4].

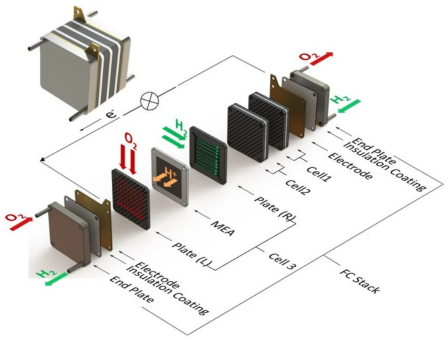


Figura 1.3: Schematic representation of a PEMFC stack

It is clear that operating conditions play an important role in determining the performance of a fuel cell. The PEMFC needs proper control of temperature, pressure, and rate of flow of reactants along with humidity. There should be enough moisture in the membrane to ensure good conductivity of protons; however, too much moisture can obstruct gas transport channels and decrease performance. Similarly, reactant flow rates must be controlled to ensure that enough hydrogen and oxygen reach the reaction sites, while avoiding unnecessary losses and excessive parasitic consumption from pumps, blowers or compressors [4]. From the perspective

of this work, the operating principles of PEMFCs are particularly important because they explain why the quality of the reactant streams has a direct impact on cell performance. Since hydrogen must reach the anode catalyst sites and oxygen must reach the cathode catalyst sites, any impurity present in the fuel or oxidant stream may interfere with the electrochemical reactions, reduce catalyst activity, alter membrane behavior or affect water and gas transport. Therefore, the study of impurity mitigation technologies in PEMFCs is closely connected to the fundamental operation of the cell itself.

1.3 Applications of PEM Fuel Cells

PEM fuel cells can be considered as some of the most applicable fuel cell systems in mobile applications due to such factors as relatively low operating temperatures, fast starting ability, power density, small size and good response characteristics. This makes PEM fuel cells very applicable where variable loads, space limitation, noise and local emissions become significant factors. For this reason, PEMFCs have attracted significant attention in road transport, marine systems and other mobility-related sectors where hydrogen can be used as an energy carrier for clean electrochemical power generation [5, 6]. One of the most advanced areas of PEM fuel cell applications is transportation by road. In this case, fuel cell electric vehicles (FCEVs) are viewed as a potential solution for minimizing the impact of transportation on the environment, particularly where direct battery electrification could be constrained by issues associated with the range, cargo weight, mass of the vehicle, or refuelling time. PEMFCs have become one of the best fuel cell technologies for light- and heavy-duty road transport applications, as proved by their use in vehicles from major car manufacturers like Toyota, Hyundai and Honda [5]. In passenger cars and light-duty vehicles, the PEM fuel cells are employed for onboard generation of electrical power using compressed hydrogen gas. In this regard, the electricity generated from the fuel cell stack drives the electric motor along with working together with the energy storage device such as batteries and supercapacitors in most vehicle designs. The use of such a combination of the fuel cell system with an energy storage system makes it possible to have the baseline power provided by the fuel cell, whereas transients are supported by the energy storage system [5]. Fuel cell vehicles can be classified into two main configurations. In all-fuel-cell vehicles, the traction power is entirely provided by the fuel cell system. However, this configuration is less common because fuel cells generally have a slower dynamic response and lower power density compared with batteries. In hybrid FCEVs, instead, the fuel cell is integrated with an onboard energy storage system. Hybridization is particularly relevant because road vehicles operate under highly dynamic driving cycles, where the requested power changes frequently.

The battery or supercapacitor can therefore compensate for rapid load variations, reducing stress on the fuel cell stack and potentially improving durability [5].

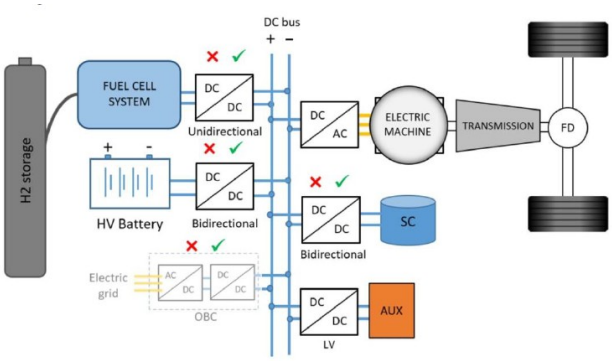


Figura 1.4: Schematic representation of a Generic fuel cell electric vehicle (FCEV) [5].

Compared with battery electric vehicles, FCEVs are not necessarily a competing solution in every segment. Rather, the two technologies can be considered complementary depending on the application. Battery electric vehicles generally show higher well-to-wheel efficiency and are often more suitable for small and medium passenger vehicles. On the other hand, hydrogen fuel cells could become more appealing in applications where long distance, large payloads, quick refuelling and continuous operation are needed. This is especially true for heavy duty transport where large batteries would lead to a reduction in payloads and increase in the vehicle mass [5]. Heavy duty vehicles are considered among the most interesting fields of using PEMFCs. Trucks, buses, material handling trucks and long-distance transport systems can be good candidates due to high energy density of hydrogen, predictable routes and convenient refuelling facilities. In these applications, the relatively short refuelling time of hydrogen systems represents an advantage over battery charging, especially where high vehicle availability is required. Moreover, for similar autonomy ranges, fuel cell heavy-duty vehicles can offer lower mass and more available payload space compared with battery-based alternatives [5]. Another instance of PEMFC application is fuel cell buses. In many cases, the transportation of public buses is carried out along predetermined routes, after which they return back to the depot, which makes it relatively easy to develop a hydrogen refuelling infrastructure. In such a case, the PEM fuel cells can help provide an environmentally friendly mode of urban transportation without sacrificing the operational capabilities of the bus. Also, forklifts and material handling trucks with fuel cells can prove useful for industrial applications. Despite these advantages, road transport applications still face important challenges. Fuel cell costs are still high due to the utilization of platinum based catalysts and expensive stacks and

Balance Of Plant (BOP) subsystems. There is also an issue with durability since the PEM fuel cells have to withstand many start-stop conditions, changes in load, moisture, and temperature [5]. In addition, the high cost of hydrogen production and the lack of refueling stations are also serious limitations to the widespread use of these systems. A complete PEMFC vehicle system is not limited to the stack. It also includes the balance of plant, which is composed of several auxiliary subsystems required to operate the fuel cell safely and efficiently. In road transport applications, the main subsystems include the air supply system, the hydrogen supply system and the thermal management system. The air supply system usually includes a compressor, humidifier and filter; the hydrogen supply system includes the tank, pressure regulation devices, recirculation devices and purge valves; and the thermal management system includes pumps, radiators, heaters and coolant circuits. These components are essential because stack performance depends strongly on air pressure, hydrogen supply, humidity, temperature and water management [5].

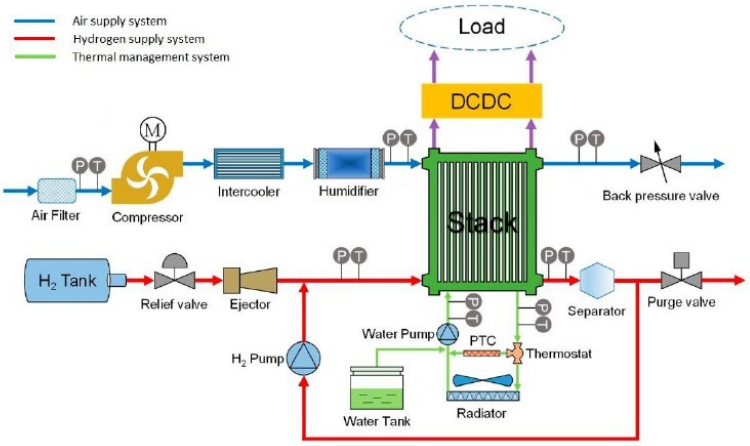


Figura 1.5: Schematic diagram of the BoP of the PEM fuel cell stack [5]

Air supply system has special relevance as PEMFCs operate under cathodic oxygen drawn from ambient air. The use of pressurized air is beneficial in that it improves the performance of the stack due to oxygen availability and reduced concentration loss; however, it requires increased power input for the operation of the compressor. In addition, water and thermal management is important as it is vital that the membrane remains hydrated for effective proton transfer, as well as avoiding any problems with flooding. Hydrogen starvation can severely damage the cell, while excessive hydrogen supply requires recirculation and purge strategies to avoid fuel losses and manage water and impurity accumulation [5]. Marine applications represent another important field for PEM fuel cells. Although the adoption of fuel cells in the marine sector is less developed than in road transport, their potential use is

increasing for both surface ships and submarines. In surface ships, fuel cells may be used as auxiliary power units and, in the future, may share propulsion tasks with conventional diesel engines. In submarines, fuel cells are especially attractive for air-independent propulsion systems because they can generate electricity without atmospheric oxygen and with a very low acoustic signature, due to the absence of major moving parts [6]. The marine environment imposes specific requirements on PEMFC systems. A power generation system installed on board a ship must satisfy strict constraints in terms of weight, volume and specific power. It must also operate reliably in a hostile environment characterized by dynamic loads, ship motion and corrosion. These conditions make the integration of fuel cell systems more complex than in many stationary applications. Furthermore, the lack of dedicated infrastructure and the relatively high cost of electricity generated by fuel cells have limited their diffusion in the civil marine sector. Nevertheless, fuel cells have already found significant interest in military applications, where cost is not always the main constraint and where silent operation is a strategic advantage [6]. In submarine applications, PEM fuel cells can be integrated into air-independent propulsion systems. These systems convert the energy stored in fuels and oxidants into mechanical or electrical energy independently from the atmosphere. The power required for submerged low-speed operation is relatively limited compared with surface propulsion, and fuel cells are suitable because they provide quiet and efficient electrochemical conversion. Hydrogen/oxygen PEM fuel cells have therefore been adopted or investigated for conventional submarines equipped with AIP systems [6]. A key issue in marine PEMFC applications is the storage and supply of reactants. Oxygen can be stored in liquid form, while hydrogen may be stored directly, for example in metal hydrides or carbon nanofibres, or generated on board from liquid fuels such as methanol or ethanol. The latter solution is attractive because liquid fuels are easier to store and handle than compressed hydrogen and may have a lower impact on ship design. However, onboard reforming introduces additional components and may generate carbon monoxide, which must be removed before the hydrogen-rich gas enters the PEM fuel cell, since CO poisons the catalyst and reduces cell performance [6]. The study [6] compares two possible configurations for marine power production using liquid methanol: a hydrogen/oxygen PEMFC system fed with hydrogen generated by methanol reforming and a direct methanol fuel cell system directly fed with liquid methanol. In the methanol reforming PEMFC configuration, methanol and water are vaporized and sent to a steam reformer to produce hydrogen; because carbon monoxide is generated during the process, a CO shift converter and a CO remover are included before the PEMFC stack. This configuration is particularly relevant for this thesis because it shows that fuel processing and contaminant removal are essential elements in real PEMFC applications where hydrogen is not supplied as a pure compressed gas [6].

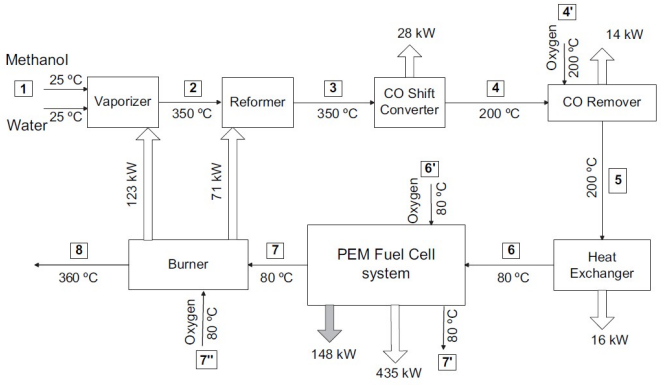


Figura 1.6: Simplified model of the methanol reforming PEMFC system. [6]

The comparison between road and marine applications highlights the versatility of PEM fuel cell technology, but also shows that each application imposes different design priorities. Road transport emphasizes dynamic response, compactness, durability, hydrogen storage, refuelling time and cost reduction. Heavy-duty vehicles require long range, high power and minimal payload penalty. Marine systems, especially submarines, prioritize quiet operation, reliability, integration constraints, reactant storage and operation in harsh environments. In all cases, PEMFC performance depends not only on the electrochemical stack, but also on the surrounding subsystems that supply, condition and manage the reactants. For the purpose of this thesis, the application perspective is important because it clarifies why impurity mitigation is a technologically relevant issue. Hydrogen or air contaminants in road transportation may lead to quicker catalyst deterioration and reduced stack lifetime, which is one of the major obstacles for commercialization anyway. In case of marine power systems that involve hydrogen production on board, the issue becomes even more serious due to possible presence of carbon monoxide in the hydrogen flow. Therefore, the development of purification systems, contaminant-tolerant materials, control strategies and recovery methods can be seen as a cross-cutting innovation area supporting the broader deployment of PEM fuel cells in real applications.

1.4 Market, Policy and Industrial Relevance

Hydrogen technologies and fuel cells have increasingly become linked to larger energy, industry and climate policies. Hydrogen is referred to as a strategic energy vector due to the fact that it has the ability to aid in the process of decarbonizing sectors where direct electrification proves to be too difficult, uneconomical or impractical. Such sectors include energy intensive industries, heavy duty transportation, marine

purposes, power generation and energy storage. In this context, proton exchange membrane (PEM) fuel cells have become one of the most important technologies for electricity production from hydrogen. From a European viewpoint, hydrogen has turned into one of the main elements of the energy transition plan. The European Commission regards renewable hydrogen as a tool for helping the decarbonization of the European energy system, especially in the industry and transport sectors. In 2022, hydrogen contributed only 2 percent of Europe's energy consumption, and around 96 percent of the consumed hydrogen was produced through natural gas, emitting a lot of carbon dioxide during the process. It can be concluded that today the hydrogen industry is highly dependent on fossil-fuel production methods, whereas in the future it will depend on more sustainable approaches. A policy framework for the promotion of renewable and low-carbon hydrogen has thus been put forth by the European Union. As stated by the REPowerEU strategy, the goal has been set to produce 10 million tons and import 10 million tons of renewable hydrogen by 2030. In the long run, the European Commission believes that the share of renewable hydrogen should make up about 10 percent of the EU energy demand by 2050. This is to be done by the decarbonization of energy-intensive industries and transport sectors [7]. The EU policy framework also includes regulatory instruments designed to create investment certainty and stimulate demand. The European hydrogen policy framework was first proposed as part of the "Fit for 55" package and includes binding targets for renewable hydrogen uptake in industry and transport by 2030. In addition, the Hydrogen and Decarbonised Gas Market Package supports the development of dedicated hydrogen infrastructure and an efficient hydrogen market.

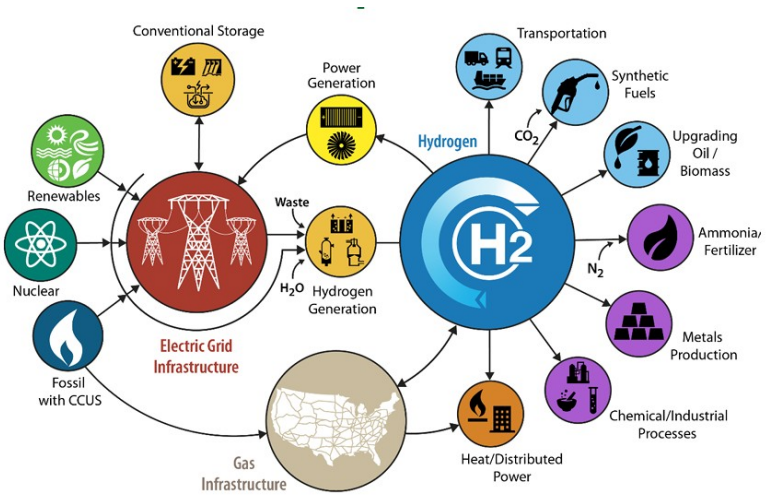


Figura 1.7: Hydrogen as an energy carrier connecting energy production, infrastructure and multiple end-use sectors.[7]

These measures are particularly relevant for fuel cell technologies because their deployment depends not only on stack performance, but also on the availability of hydrogen production, distribution, refuelling and storage infrastructure [7]. Hydrogen is equally important in the U.S., where it has an important role to play in the country's energy policy. U.S. National Clean Hydrogen Strategy and Roadmap outlines how large-scale hydrogen production and utilization will be achieved and explores different scenarios from 2030, through 2040 until 2050. The roadmap focuses on the production, transportation, storage and utilization of hydrogen and notes the importance of coordinated efforts of many different parties such as federal government agencies, industries, academia, national laboratories and others. It means that hydrogen technologies are not only technological developments, but part of a larger ecosystem [3]. The U.S. Department of Energy Hydrogen Program further illustrates the industrial relevance of hydrogen and fuel cells. The program conducts research and development activities in hydrogen production, delivery, infrastructure, storage, fuel cells and multiple end uses across transportation, industrial and stationary power applications. The program will also encompass activities linked to technology validation, manufacturing, integration, safety, codes and standards, and workforce training [8]. Such broad focus is necessary since it emphasizes the fact that the process of commercializing hydrogen energy technologies entails simultaneous advancements in various areas. Fuel cells occupy a specific position within this broader policy and industrial context. As per US Department of Energy, fuel cell technology can be used as an alternative to the internal combustion engine in vehicles as well as a source of energy for stationary and portable applications because fuel cells are efficient, environment-friendly, and flexible with regard to the choice of fuel. In transportation sector, there are mostly fuel cells based on hydrogen as a fuel. For stationary applications, fuel cells may be used for distributed generation, backup power and auxiliary power systems [9]. PEM fuel cells are particularly relevant within this landscape because they are suitable for transportation and compact power applications. However, their industrial deployment is still affected by technical and economic barriers. The U.S. Department of Energy identifies cost reduction and durability improvement as key areas of research and development for PEM fuel cells. Current activities focus on improving electrocatalysts, membranes for both ambient and high-temperature applications, and bipolar plate materials [9]. These research areas are directly connected to the long-term competitiveness of PEMFC systems, since catalysts, membranes and bipolar plates strongly influence stack cost, performance and durability. The market relevance of PEM fuel cells therefore depends on both external and internal factors. The factors that affect deployment of PEMFCs externally include hydrogen availability, price of fuel, infrastructural development, policies and demands. The internal factors influencing the competitiveness of PEMFC include efficiency, lifetime, cost of the system and balance-of-plant performance. This dual dependence explains why PEMFC

innovation is not limited to the electrochemical cell itself, but extends to auxiliary systems, fuel processing, air management, thermal management, diagnostics and control strategies. For this work, the policy and market context is particularly important because it explains why impurity mitigation is a relevant technological field. If hydrogen is to be used at large scale across transport, industry and stationary power applications, PEM fuel cells will need to operate reliably with hydrogen supplied through real production, storage and distribution chains. Under such realistic scenarios, the fuel quality and air quality play an important role. Contamination of the hydrogen stream or air input may lower the activity of catalysts, damage the membrane, and thus lead to inefficient operations and reduced stack life time. This way, technologies for purifying, detecting, protecting from poisoning, and restoring stack performance are directly related to the general issue of increasing PEMFC life time and commercialization. In summary, hydrogen and proton exchange membrane fuel cells stand at the crossroads of energy policies, industrial progress and technological advancement. According to EU and US policy plans, hydrogen will be an important element in the decarbonization process in various industries, whereas the scientific research policy is focused on decreasing the costs, efficiency and integration of fuel cells. Within this context, the study of patented impurity mitigation technologies can provide useful insight into how companies and research organizations are addressing one of the key practical challenges for PEM fuel cell deployment.

1.5 Hydrogen Purity and Why Impurities Matter

The functioning and longevity of PEM fuel cells are influenced not only by the design of the stack, the catalytic activity and operating conditions, but also by the purity of the reactant streams provided to the cell. Given that hydrogen and air or oxygen are fed to the anode and cathode respectively, impurities can be introduced to the fuel cell from either side and affect the membrane, the catalytic layer, gas diffusion layers and other components. It is therefore crucial to ensure the purity of the hydrogen stream and the quality of air used [10]. The PEM fuel cell is highly susceptible to any contamination as its electrochemical reactions occur in the catalytic sites that are typically made up of platinum or platinum alloys. The availability of such catalytic sites is essential as it enables the process of oxidation of hydrogen at the anode side and reduction of oxygen at the cathode side. If the contaminants penetrate into the system, they might get adsorbed at the catalytic sites and affect the path of reaction and charge transfer in addition to increasing the resistivity of membrane conductivity or transport pathways within the electrodes and gas diffusion layers [10]. The hydrogen input into the PEMFC system can come from various sources. While electrolysis of water can provide fairly pure hydrogen,

there are several cases where the cost-effective choice is hydrocarbon reforming. Nevertheless, the reforming process will create hydrogen-rich gas that contains impurities like carbon monoxide, carbon dioxide, methane, nitrogen, sulfur-containing substances and others. Steam methane reforming yields a syngas, which includes hydrogen and carbon monoxide and needs to be treated by water-gas shift, pressure swing adsorption, methanation, preferential oxidation and membrane separation before the use in a PEM fuel cell [10, 11]. Therefore, hydrogen quality standards have been established to make sure that the hydrogen which is being used in PEM fuel cells has the right amount of impurities that can run the fuel cells. According to ISO hydrogen fuel quality standard found in the literature, the concentration of impurities is extremely low, with extremely strict restrictions on carbon monoxide, ammonia, sulfur compounds, carbon dioxide, water, oxygen, hydrocarbons and halogenated compounds [10]. The reason for such stringent restrictions lies in the sensitivity of PEMFCs to impurities. In reality, having purity higher than 99 percent does not guarantee proper function of fuel cells. Of all the contaminants in the fuel stream, CO is one of the most researched and technologically significant. CO is important since it adsorbs very strongly onto platinum catalysts located at the anode, blocking access of the hydrogen molecules to the surface of the catalyst. This means that less catalytically active surface will be available for hydrogen oxidation and hence low cell voltage and power output.The poisoning mechanism is therefore directly related to the competition between hydrogen and carbon monoxide for adsorption on the catalyst surface [10, 11]. The severity of CO poisoning depends on several factors, including CO concentration, current density, catalyst type, operating temperature, pressure, humidity and anode operating mode. At low-temperature PEMFC operating conditions, even very low concentrations of CO can cause measurable performance loss. The review by Shabani et al. reports that CO concentrations above very low ppm levels may lead to steady-state performance loss, and that 0.2 ppm CO can already produce a measurable voltage reduction under specific automotive PEMFC conditions [10]. This explains why CO removal and CO-tolerant materials are central topics in PEMFC research and patenting activity. High-temperature PEM fuel cells show a different behavior. Das et al.[11] experimentally investigated a high-temperature PEMFC operating between 120 °C and 180 °C with hydrogen streams containing 2 percent and 5 percent CO. Their results show that cell performance degradation is severe at lower temperatures, while CO tolerance improves significantly at 180 °C. At high temperature, the surface coverage of platinum by CO is reduced and electrochemical oxidation of CO becomes more favorable. This indicates that operating temperature can strongly influence impurity tolerance, although higher-temperature operation requires different membranes and system design strategies [11]. Hydrogen sulfide is another severe fuel-side impurity. It may originate from sulfur compounds present in natural gas or other fossil-derived fuels used for hydrogen production. H_2S

has strong affinity for platinum and can occupy catalyst sites, blocking hydrogen adsorption and causing anode poisoning. Unlike CO poisoning, sulfur poisoning is often more difficult to reverse, and in some cases interrupting the contaminant supply does not lead to spontaneous recovery. The hydrogen quality standard reported by Shabani sets a very low limit for total sulfur compounds, this confirm the high toxicity of sulfur species for PEMFC catalysts [10]. Ammonia is also a component to take into consideration for the operation of PEMFCs, especially if hydrogen is obtained via pathways involving nitrogen-containing molecules or if ammonia is used as a hydrogen carrier. Ammonia can have an adverse impact on the operation of PEMFCs since it may give rise to ammonium ions that may be exchanged with protons in the membrane and decrease proton conductivity. This is especially crucial because PEMFCs operate using effective proton migration within the membrane. According to literature examined by Shabani et al.[10], ammonia poisoning may result in an increase in cell resistance and decreased voltage. Even though CO_2 is generally regarded as a less destructive impurity compared to CO, since its main role is serving as a dilution gas in the hydrogen stream, it may be a cause of deterioration in performance as well. In low temperature PEMFC, CO_2 may be involved in chemical reactions leading to formation of CO-like adsorption products on the catalyst at the anode. Hydrogen concentration will be reduced due to hydrogen dilution with non-reacting gases. Therefore, CO_2 should not be considered completely irrelevant in the analysis of real reformate-fed PEMFC systems [10]. Contamination of PEMFCs can also occur through the air flow that reaches the cathode. The problem becomes even more crucial for the mobile applications, because automobiles function in contaminated air with different composition of air in various locations depending on its contamination by industrial processes. Sulfur oxides, nitrogen oxides, ammonia, volatile organic compounds, hydrocarbons, ozone and particulates present in the air can penetrate into the catalyst layer at the cathode and disrupt the oxygen reduction process. Some types of contaminants can be recovered from the PEMFC when clean air is provided, but other types cannot [10]. The issue of cathode side poisoning is technologically relevant because the cathode reaction is already one of the largest contributors to voltage losses in PEM fuel cells. The adsorption of contaminations on platinum surfaces of cathodes results in a decrease in the active surface area for the oxygen reduction reaction and increases kinetic losses. Besides, some contaminations may migrate across the membrane or be dissolved in the product water, which affects both electrodes. Hence, filtration of air and poisoning resistant cathode catalysts are relevant means of mitigating contamination effects, particularly in automotive PEMFCs [10]. Impurities may also originate from inside the system rather than from the external fuel or air feed. Materials used in the balance of plant, assembly aids, seals, plastics, adhesives, lubricants and cleaning agents can release organic or inorganic contaminants during operation. These substances may leach into the

system, reach the membrane electrode assembly and cause performance decay. This aspect shows that fuel cell purity is not only a matter of hydrogen production and air filtration, but also of material compatibility and system-level design [10]. Another relevant category is ionic contamination. Foreign cations and anions may originate from corrosion, catalyst dissolution, membrane degradation, airborne pollutants or balance-of-plant materials. Ionic species can exchange with protons in the membrane, decrease ionic conductivity, block pores in the gas diffusion layer, increase mass-transport losses and promote chemical degradation. In some cases, the damage caused by ionic contamination is difficult to recover because it involves physical changes in the membrane, catalyst layer or gas diffusion layer [10]. Therefore, the effect of contaminants is not confined to only one mechanism of degradation. Depending on the type of contaminant, operating conditions, and the components affected, poisoning can lead to catalytic site poisoning, loss of electrochemical surface area, conductivity decrease of membranes, pore clogging of gas diffusion layer, change in reaction pathway, increase in ohmic resistance, mass transport limitation and permanent material damage. Such complexity accounts for the reason why the investigation of contamination of PEMFCs usually involves electrochemical analysis, polarization curves, impedance spectroscopy, cyclic voltammetry, and durability tests among others [10, 11]. Several mitigation strategies have been proposed to reduce the negative effects of impurities. For fuel-side CO poisoning, the main strategies include upstream hydrogen purification, preferential oxidation, methanation, pressure swing adsorption, purification membranes, oxygen or air bleeding, current pulsing, self-oxidation strategies and CO-tolerant catalysts such as Pt-Ru or other advanced catalyst structures. For cathode-side contaminants, mitigation approaches include air filters, tolerant electrocatalysts and specific recovery procedures. For system-related impurities, material selection and compatibility testing are critical. The significance of impurity mitigation is that ultra-pure hydrogen production can be challenging from both technical and economic standpoints [10, 11].

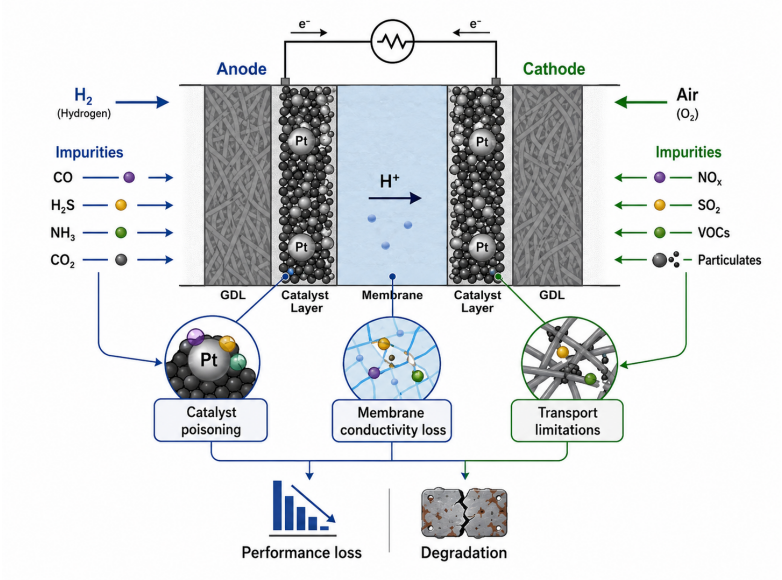


Figura 1.8: Diagram of PEM fuel cell impurites.

The importance of impurity mitigation is further emphasized in practical situations. In transport, PEMFCs are exposed to dynamic load profiles, start-stop cycles, changing humidity, varying temperature and polluted air. In stationary or reformate-fed systems, hydrogen may contain residual CO, CO_2, sulfur compounds or ammonia depending on the fuel processor and purification system. In marine or remote applications, onboard reforming may be attractive, but it increases the need for efficient contaminant removal before the hydrogen-rich stream reaches the stack. Therefore, impurity management is a cross-cutting requirement across PEMFC applications. For the purpose of this thesis, hydrogen purity and impurity effects provide the technological basis for the patent landscape analysis. With the possibility of reducing performance and shortening life time, contamination is an important issue for inventions in this domain since the contamination may increase the cost of systems. The reasons behind the importance of impurities play a crucial role in the selection of the keywords and patent classification codes and the analysis of technology clusters.

Chapter 2

Method

This chapter describes the methodological approach adopted to identify, collect and validate the patent documents used in this thesis. The objective of the patent analysis is to investigate technological solutions related to impurity mitigation in PEM fuel cell systems. More specifically, the analysis aims to identify inventions dealing with the treatment, purification or control of reactant streams in order to reduce the negative impact of contaminants on fuel cell performance and durability. The methodological structure follows a progressive logic. First, patents are introduced as a source of information for technology analysis. This is important because patent documents are not only legal documents, but also rich technical sources that describe inventions, technological problems, proposed solutions, applicants, classification codes and citation relationships. Since the research topic is highly interdisciplinary, the construction of a reliable query required several iterations, combining keyword-based searches and patent classification codes. Therefore, the retrieved results were manually validated in order to evaluate the relevance of each search strategy and to identify the most appropriate query for the subsequent analysis. The need for an iterative approach derives from the complexity of the technological field. The fields of PEM fuel cell technology include electrochemistry, materials engineering, gas purification, hydrogen generation, air delivery, balance of plant equipment, control systems, and degradation processes. Hence, there are numerous ambiguous terms in this context. For instance, *impurities*, *purification*, *poisoning*, *sulfur*, and *ammonia* could either mean contamination of reactants' streams or fabrication of materials, polymers, electrolytes, catalysts, or even different fuels. Therefore, the construction of the search query was not a purely mechanical task, but required a continuous comparison between the intended research scope and the actual content of the retrieved patent documents. The method adopted in this thesis can be summarized in four main steps. The first step consisted in defining the technological scope of the analysis, namely PEM fuel cells and, more broadly, fuel cell systems in which reactant treatment or purification is relevant. The second

step consisted in identifying the most appropriate keywords and classification codes to retrieve patents related to impurity mitigation. The third step involved testing different search queries on Lens.org and manually checking samples of retrieved patents to identify false positives and assess the precision of each query. The fourth step consisted in selecting the final search strategy, which was then used as the basis for the patent landscape analysis.

2.1 Patents as a Data Source

Patents represent a particularly useful source of information for the study of technological change. Unlike scientific publications, which mainly report research findings and theoretical or experimental advances, patent documents are directly connected to inventions that applicants consider potentially valuable from a technical and commercial perspective. For this reason, patent data can provide insight into the direction of industrial research and development, the technological positioning of companies and research institutions, and the evolution of innovation activity within a specific domain. In this thesis, patents are used as technological data rather than as legal instruments. The objective is not to assess infringement, patentability, freedom to operate or the legal strength of individual patents. Instead, patent documents are analyzed to understand which technical solutions have been developed to address impurity-related problems in PEM fuel cell systems. This perspective is consistent with the use of patent landscape analysis, where patent data are collected and organized in order to describe innovation trends, main technological areas, key actors and geographical patterns within a given field. A patent document contains different types of information. Textual components generally consist of the title, abstract, claims, and the description. The title briefly conveys what the invention is all about, while the abstract contains a brief description of the technical problem being addressed and its solution. Claims give the legal definition of the invention, and for this reason, they are rather juridical in nature, but may include useful technical content as well. Description gives the fullest description of the invention, covering the background of the invention, the technical area, embodiments, and any advantages that could be derived from the invention. Searching all fields may increase recall, but it also produces a large amount of noise because terms may appear in long descriptions, examples or peripheral parts of the document. In addition to textual information, patent documents include structured bibliographic data. These data are essential for quantitative analysis. The most relevant fields for this thesis are applicants or assignees, application year, patent jurisdictions, patent classification codes and forward citations. For the temporal analysis, different patent date fields may be considered. Publication date indicates when a patent document becomes publicly available, but it may occur significantly later than

the actual filing of the invention. For this reason, publication-date trends can be affected by time lags and may not accurately represent the moment when inventive activity occurred. Application date is closer to the applicant's decision to seek protection, while priority date generally represents the earliest filing date associated with a patent family. Therefore, priority date is particularly useful in patent landscape analysis because it provides a closer approximation of the timing of invention. In this thesis, the temporal evolution of the selected dataset is therefore interpreted primarily through priority-date or application date trends, rather than publication-date trends. Applicants and assignees make it possible to identify the organizations that are most active in the technological field. In the context of PEM fuel cells, these organizations may include automotive manufacturers, electronics companies, energy companies, component suppliers, universities and research institutes. Application year is useful for analyzing trends over time, while jurisdictions provide information about the geographical scope of patenting activity. Patent

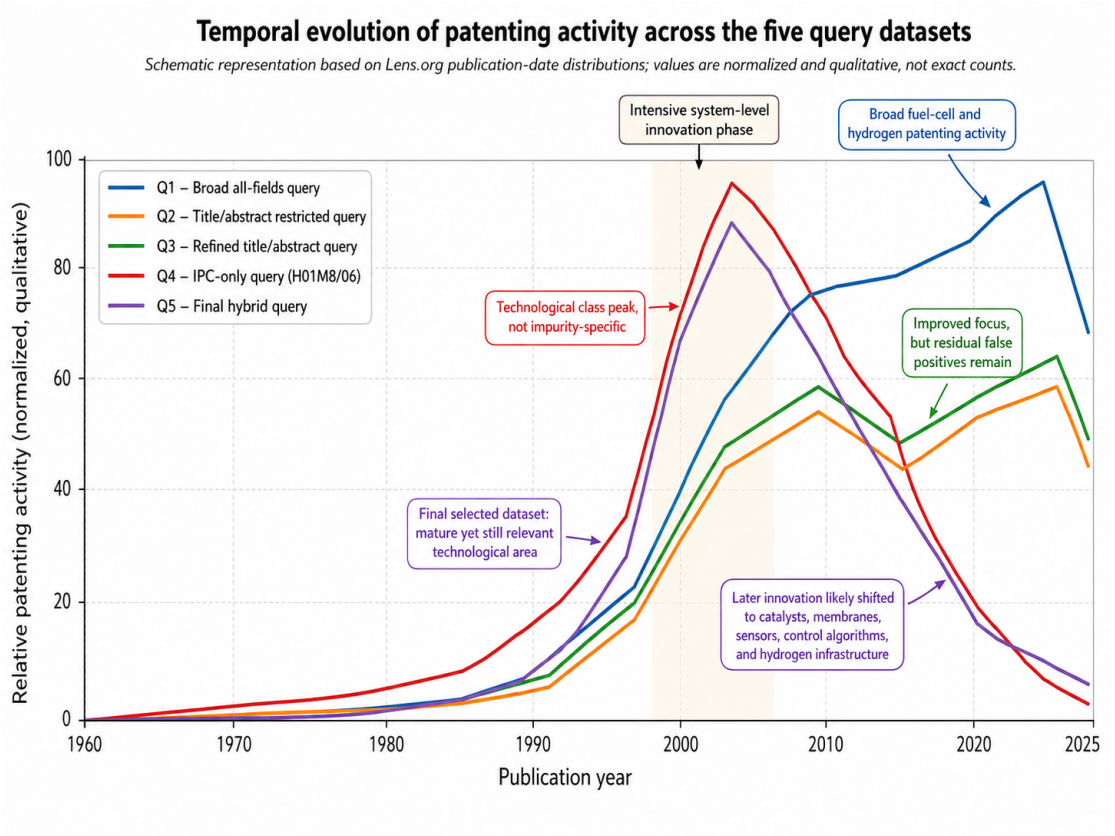


Figura 2.1: Temporal evolution of patenting activity across the five query datasets

classification codes are particularly important for the construction of a search strategy. The International Patent Classification (IPC) system assigns patents to

technological categories according to the technical content of the invention. In principle, classification codes help to reduce ambiguity because they allow the researcher to restrict the search to a specific technological domain. However, IPC codes must be used carefully. A single IPC class may contain a very wide range of inventions and may include documents that are only indirectly related to the research question. This is the reason why the use of classification codes becomes more efficient in conjunction with textual key words that describe the technical problem. In this work, the IPC code H01M8/06 is particularly pertinent as it describes fuel cells provided with means for generating reactants or treating residuals. This classification is connected to systems that manage, treat or condition the reactants involved in fuel cell operation. Therefore, it is conceptually close to technologies such as hydrogen purification, gas treatment, reactant conditioning, fuel processors and balance-of-plant architectures. However, as discussed in the following section, this code alone is too broad and retrieves many patents that do not specifically address impurity mitigation. Its value emerges when it is combined with keywords related to contamination, purification, poisoning and impurities. Another indicator of patents to consider is that of forward citations. A forward citation happens when a patent cites an older patent. Forward citations are a common tool in patent analysis because it is considered as a measure of the technological importance or relevance of an invention. If a patent receives several forward citations from other patents, it can be considered as an important technology that has helped to shape future technologies. However, care should be exercised when using citation indicators because different patents offices and technological sectors use different citation practices. Old patents are likely to have many forward citations than new ones simply because they have been around for a long period of time. Another important aspect is the concept of patent families. The same invention can be patented in different countries, resulting in different patent documents, which pertain to similar technical solutions. An invention may be protected in the US, in Europe, in Japan, in China, and other countries. When each separate document is counted as one invention, the estimation may become incorrect. This is particularly problematic when analyzing time trends, assignee concentration or portfolio size. Therefore, patent family information is important for avoiding duplication and for distinguishing between the number of legal documents and the number of unique inventions. The use of patents as a data source also presents limitations. To begin with, not all innovations are patented. For example, some firms use trade secrets or internal knowledge. The second thing is that the terms used in patenting are often quite broad. Applicants may use general wording in order to obtain wider protection, which can make keyword searches difficult. Third, patent databases may include different legal statuses, duplicate publications and family members. Fourth, patents do not necessarily indicate commercial success. A patented technology may never be industrialized, while an unpatented solution may become widely adopted.

Despite these limitations, patents are highly suitable for the objective of this work. The technological problem of impurity mitigation in PEM fuel cells is directly connected to industrial development, system reliability and long-term commercialization. Companies working on fuel cells, hydrogen production, gas purification and automotive systems are likely to protect technical solutions through patents. Therefore, patent documents can provide valuable evidence of how different actors are addressing contamination, poisoning, reactant purification and system-level protection. For this reason, the patent analysis developed in this thesis focuses on three main dimensions. The first dimension is temporal: the analysis investigates how patenting activity evolves over time. The second dimension is organizational: the analysis identifies the main applicants and compares their patent portfolios. The third dimension is technological: the analysis examines IPC codes and patent content in order to identify the main technological sub-fields. These dimensions make it possible to connect the technical background described in Chapter 1 with the innovation patterns observed in the patent data.

2.2 Building Search Queries

The construction of the patent search query represents a central step in the methodology of this work. The objective of the search strategy was to identify patent documents related to impurity mitigation technologies in PEM fuel cell systems. More specifically, however, the goal was not only to identify all patents relating to fuel cells and contaminants, but also those where the presence of contamination, poisoning or purification processes have something to do with the function or performance of the fuel cell system. This is critical because the technological domain of PEM fuel cells is one of extreme interdisciplinarity, involving electrochemistry, polymer chemistry, catalyst engineering, fuel engineering, gas purification technologies, system controls, balance of plant and degradation studies. Thus, there are several keywords that may seem directly related to the issue at stake but which can actually provide misleading results if used for searching in patent databases. Words like *impurity*, *contamination*, *poisoning*, *sulfur*, *ammonia*, and *purification* can belong to completely different technological domains, being used either to describe the contaminant in the hydrogen or air flow, or the purification of raw materials during the manufacturing process, the synthesis of polymers, the preparation of catalysts, or even an alternative fuel. For this reason, the search strategy was developed iteratively. Each query was tested on Lens.org and then evaluated through manual inspection of a sample of retrieved patents. This validation process became essential for determining if the patents found using the queries matched the intended scope of the thesis. The validation process considered three key criteria, namely: if the document found was indeed related to fuel cells; whether the impurity term indicated an outside contaminant or an irrelevant internal material process; and whether the invention provided any relevant technical solution concerning contamination prevention, gas purification, poisoning resistance, and reactant stream processing.

2.2.1 Query 1

The initial strategy was based on two conceptual blocks. The first block defined the technological domain and included terms related to fuel cells:

```
"fuel cell" OR "PEMFC" OR "proton exchange membrane"
```

The second block defined the problem area and included terms related to contamination, poisoning and purification:

```
contamin* OR impurit* OR poison* OR "CO tolerance"
OR sulfur OR ammonia OR purif*
```

The truncation symbol was used to capture different word forms. For example, *contamin** can retrieve *contaminant*, *contaminants*, *contamination* and *contaminated*. Similarly, *impurit** captures both *impurity* and *impurities*, while *purif** captures *purify*, *purification* and *purified*. This approach was useful for maximizing recall, but it also increased the risk of retrieving false positives. The first query combined the two conceptual blocks across all fields:

```
("fuel cell" OR "PEMFC" OR "proton exchange membrane")
AND
(contamin* OR impurit* OR poison* OR "CO tolerance"
OR sulfur OR ammonia OR purif*)
```

This query retrieved 123,828 records. Although the result set was very large, manual validation showed that the precision was below 5%. Therefore, the query was not suitable for building the final dataset. The primary cause of poor results obtained during this search was that the field of search was too broad and the keywords used were ambiguous in nature. As the search had been carried out on all fields, the keywords could be present in any part of the patent document, which included the description, examples, background and claims of the patent. This resulted in obtaining patents in which the keywords were present but in an insignificant or irrelevant way. One of the key sources of noise was the keyword *ammonia*. While ammonia could indeed be considered as contamination in the case of PEM fuel cells, it frequently pops up as fuel, hydrogen carrier, or ammonia cracking fuel in the patent documents. Consequently, the search retrieved a large number of patents pertaining to ammonia-based fuel cells, hybrid power systems, or hydrogen production via ammonia, and not those describing ammonia as contamination in hydrogen used in PEM fuel cells. A second important source of noise was the keyword *sulfur*. In the context of fuel cell contamination, sulfur may refer to harmful compounds such as H_2S or SO_2. However, in the field of PEM fuel cell materials, sulfur is also strongly connected to the chemistry of proton exchange membranes, especially sulfonated polymers and PFSA-based materials. As a consequence, the query retrieved many patents concerning polymer synthesis, membrane chemistry or sulfonic acid groups, even when these inventions were not related to external sulfur-containing contaminants. The terms *poison**, *impurit** and *purif** also generated false positives. In some documents, *poisoning* referred to internal catalyst degradation or chemical effects not caused by external reactant stream contaminants. In other cases, *impurities* referred to unwanted substances in raw materials during manufacturing, while *purification* referred to chemical purification steps in catalyst, membrane or electrolyte production. These results showed that a broad keyword search could not distinguish between impurity mitigation during fuel cell operation and purification processes occurring during the fabrication of fuel cell components.

2.2.2 Query 2

The second query introduced a field restriction. The fuel cell concept was searched only in the title, while the contamination-related block was searched in the abstract:

```
title:("fuel cell" OR "PEMFC" OR "proton exchange membrane")
AND
abstract:(contamin* OR impurit* OR poison* OR "CO tolerance"
OR sulfur OR ammonia OR purif*)
```

This query retrieved 7,385 records and improved the estimated precision to approximately 20%. The improvement was expected, because requiring the fuel cell concept to appear in the title increased the probability that the patent was actually focused on fuel cell technology. Compared with the first query, this strategy reduced the number of irrelevant documents retrieved only because the words appeared somewhere in the full text. However, this query still produced substantial semantic noise. The presence of *ammonia* continued to retrieve patents where ammonia was used as a primary fuel or as a hydrogen carrier, rather than as an impurity. The presence of *sulfur* continued to capture patents related to sulfonated membranes and sulfur-based chemistry. In addition, the abstract field still contained many terms related to component fabrication, material purification and internal chemical processes. Therefore, although the second query was more selective than the first one, it still did not provide a sufficiently reliable dataset for quantitative analysis. The second query also highlighted the problem of document duplication. Patent databases often contain multiple documents related to the same invention. A single invention may be filed in different jurisdictions or published in different legal forms, such as patent applications, granted patents or utility models. If these documents are counted separately, the analysis may artificially inflate the number of technological solutions. Therefore, this step showed that patent family deduplication would be important in later stages of the analysis, especially when studying time trends and assignee concentration.

2.2.3 Query 3

The third query was developed to improve the semantic precision of the search. In this attempt, the fuel cell block and the impurity block were searched in both title and abstract fields, but the keyword *ammonia* was removed:

```
(title:("fuel cell" OR "PEMFC" OR "proton exchange membrane")
OR abstract:("fuel cell" OR "PEMFC" OR "proton exchange membrane"))
AND
(title:(contamin* OR impurit* OR poison* OR "CO tolerance"
OR sulfur OR purif*)
OR abstract:(contamin* OR impurit* OR poison* OR "CO tolerance"
OR sulfur OR purif*))
```

The above search resulted in the retrieval of 10,126 references and had a precision of 40.7% on average. This search was improved by not searching for the term *ammonia*, as this term would return too many false positive results about the use of ammonia as a possible alternative fuel or hydrogen carrier. In particular, *CO tolerance* and *poison** were useful because they were more directly connected to fuel cell degradation and mitigation strategies. These terms helped retrieve patents related to gas monitoring, contaminant tolerance, purge strategies, filtering systems and other engineering solutions. Nevertheless, the third query also revealed the limits of a purely semantic approach. Even when the search was restricted to title and abstract fields, false positives remained significant. This was not mainly due to a syntax problem, but to the fact that the same vocabulary is used in different sub-domains of PEM fuel cell technology. The term *sulfur*, for instance, can indicate a harmful gas-phase contaminant, but it can also refer to sulfonated materials that are essential for proton conduction. The term *purification* can refer to hydrogen purification before entering the stack, but also to the purification of platinum, membranes or electrolytes during production. The term *impurity* can refer to impurities in the gas stream, but also to impurities in raw materials or metallic alloys. This result demonstrated that a search based only on words cannot fully capture the intended technological meaning. The search engine can verify whether two terms appear in the title or abstract, but it cannot always understand whether the impurity is an external contaminant affecting the fuel cell during operation or an internal substance related to material preparation. Therefore, a more structured approach was needed.

2.2.4 Query 4

The fourth query tested a classification-based strategy using only the IPC code H01M8/06:

```
class_ipcr.symbol:"H01M8/06"
```

The IPC class H01M8/06 refers to fuel cells with means for production of reactants or for treatment of residues. This class is conceptually relevant to the thesis because impurity mitigation often involves reactant treatment, fuel processing, gas conditioning or purification before the reactants enter the fuel cell stack. Therefore, this IPC code was selected as a possible technological filter. However, the query retrieved 51,666 records and showed an estimated precision of only 16.7%. This result confirmed that the IPC code was too broad when used alone. The class H01M8/06 includes several technological areas: reactant production, reforming, fluid management, gas treatment, residue treatment, thermal management and other system-level solutions. Some of these areas are relevant to impurity mitigation, but many are not directly connected to contamination, poisoning or purification. The major drawback of using only IPC in searching is that although the patent classification relates to the technological field covered by the patent, it does not relate to the specific technical problem which the patent solves. The reason for classifying a patent under H01M8/06 is that the patent deals with reactant generation or processing and does not involve any issues related to contamination. It could have to do with reformer configuration optimization, condensate water management, valve setup, heat exchanger, or fuel provision in general. Therefore, the fourth query showed that IPC codes are useful for defining the technological perimeter, but they are not sufficient to identify the intended subset of patents. A classification code can reduce some semantic ambiguity, but without textual keywords it cannot express the research intent. In this case, the intent was to retrieve patents where reactant treatment is explicitly connected to contamination, poisoning, impurities or purification.

2.2.5 Query 5

The fifth and final query combined the strengths of keyword search and IPC classification. It used H01M8/06 as a technological filter and combined it with impurity-related keywords searched in the title and abstract:

```
class_ipcr.symbol:"H01M8/06" AND (title:(contamin* OR impurit*
OR poison* OR purif*) OR abstract:
(contamin* OR impurit* OR poison* OR purif*))
```

This hybrid query retrieved 2,117 records and achieved the best performance among the tested strategies, with an estimated precision of 76.7%. The improvement can be explained by the complementary role of the two parts of the query. The IPC code restricts the dataset to patents related to fuel cells and reactant treatment. The keyword block then selects only those patents where the technical problem is explicitly associated with contamination, impurities, poisoning or purification. In other words, the IPC code defines the technological space, while the keywords define the problem-oriented focus. This strategy was particularly effective because it reduced the material-science noise observed in previous attempts. Patents related only to membrane chemistry, catalyst synthesis, polymer sulfonation or raw material purification were less likely to be retrieved unless they were also classified within the relevant fuel cell reactant-treatment domain and explicitly mentioned impurity-related terms in the title or abstract. As a result, the query was more aligned with the objective of identifying system-level technologies such as gas filters, purification units, electrochemical purifiers, scrubbers, treatment devices, membranes for reactant purification, purge strategies and balance-of-plant architectures. The final query also produced a more manageable dataset. A result set of 123,828 or 51,666 records would have been too large and too noisy for a meaningful manual validation and subsequent analysis. By contrast, 2,117 records represent a more realistic dataset for a patent landscape analysis, while still preserving sufficient breadth to study trends over time, assignees, IPC distributions and geographical patterns.

Tabella 2.1: Iterative Query Development and Precision Results

Query	Search Strategy	Records	Precision	Main Issues Identified
Q1	`("fuel cell" OR "PEMFC" OR "proton exchange membrane") AND (contamin* OR impurit* OR poison* OR "CO tolerance" OR sulfur OR ammonia OR purif*)`	123,828	**< 5%**	Ammonia paradox (fuel vs. contaminant); sulfur chemistry overlap with PFSA membranes; lack of spatial contextualisation
Q2	`title:("fuel cell" OR "PEMFC" OR "proton exchange membrane") AND abstract:(contamin* OR impurit* OR poison* OR "CO tolerance" OR sulfur OR ammonia OR purif*)`	7,385	**20%**	Persistent ammonia interference; sulfur/sulfonic acid ambiguity; high rate of duplicate patent families
Q3	`(title:("fuel cell" OR "PEMFC" OR "proton exchange membrane") OR abstract:("fuel cell" OR "PEMFC" OR "proton exchange membrane")) AND (title:(contamin* OR impurit* OR poison* OR "CO tolerance" OR sulfur OR purif*) OR abstract:(contamin* OR impurit* OR poison* OR "CO tolerance" OR sulfur OR purif*))`	10,126	**40.7%**	Sulfur polysemy (H_2S vs. sulfonic groups); internal poisoning (methanol crossover, phosphoric acid); deduplication needed
Q4	`class_ipcr.symbol:"H01M8/06"`	51,666	**16.7%**	IPC class too broad ("cauldron effect"); captures macro- and micro-engineering indistinctly; no intentional filtering (why, not what)
Q5	`class_ipcr.symbol:"H01M8/06" AND (title:(contamin* OR impurit* OR poison* OR purif*) OR abstract:(contamin* OR impurit* OR poison* OR purif*))`	2,117	**76.8%**	Patent family duplicates (up to 4 copies per invention); grey-zone technologies (flow batteries, metal-air batteries)

Note: Precision estimated on a manual sample of 100 patents per query.

2.3 Final Search Strategy and Dataset Selection

The comparison between the five tests shows that neither a purely keyword-based strategy nor a purely classification-based strategy was sufficient. Keyword-based searches were affected by semantic ambiguity, while the IPC-only search was affected by excessive technological breadth. The hybrid query provided the best compromise because it used classification to define the technological environment and keywords to specify the technical problem. The validation process also showed that the final query is not completely free from limitations. Some false positives remain, especially in adjacent electrochemical fields that share similar vocabulary with fuel cells. For example, redox flow batteries and metal-air batteries may also involve fluid treatment, air purification, impurity removal or electrochemical purification systems. These technologies can occasionally enter the dataset if their patent classification and wording overlap with those of fuel cell systems. Therefore, a later cleaning step may be required before conducting the final quantitative analysis. Another limitation concerns patent family duplication. The final query may retrieve multiple documents belonging to the same invention, especially when a patent family includes filings in several jurisdictions. This issue is particularly important for assignee analysis and trend analysis. If each document is counted separately, a company that files the same invention in many countries may appear more innovative than a company that files fewer international extensions. Therefore, the analysis should distinguish, when possible, between individual patent documents and patent families. Despite these limitations, the final query was selected because it best reflects the technological focus of this work. It captures patents related to the treatment of reactants in fuel cell systems and specifically filters for inventions addressing impurities, contamination, poisoning or purification. This makes it suitable for studying how companies and research organizations have developed solutions to protect PEM fuel cells from impurity-related degradation. The search strategy can therefore be interpreted as the result of a progressive refinement process. The first query maximized recall but produced excessive noise. The second query improved relevance by restricting fields. The third query reduced one major source of false positives by removing ammonia. The fourth query tested the usefulness of IPC classification but showed that classification alone is insufficient. The fifth query integrated classification and keywords, producing the best balance between relevance and dataset size. This final strategy constitutes the basis for the patent landscape analysis developed in the following sections.

Chapter 3

Analysis and Results

This chapter presents the analysis of the selected patent dataset obtained through the final search strategy defined in Chapter 2. The selected dataset corresponds to the hybrid query combining the IPC code H01M8/06 with impurity-related keywords searched in the title and abstract fields. The objective of this chapter is therefore not to compare all the preliminary query attempts, but to examine the patent landscape emerging from the final dataset. The selected query is the following:

```
class_ipcr.symbol:"H01M8/06"
AND
(title:(contamin* OR impurit* OR poison* OR purif*)
OR abstract:(contamin* OR impurit* OR poison* OR purif*))
```

The question selected above was done so due to the presence of both complementary filters. The filter H01M8/06 under IPC classification narrows down the scope of the search to only inventions that have something to do with fuel cells in terms of production, processing, and disposal of reactants. The keywords will be used to find patents mentioning contamination, impurities, or poisoning. As a result, the selected dataset is focused on system-level solutions related to reactant treatment, gas purification, purge regulation, contaminant removal and protection of fuel cell systems from impurity-related degradation. The analysis presented in this chapter is organized around the main dimensions of patent landscape analysis: dataset size, patent families, temporal evolution, legal status, geographical distribution, applicants and citation indicators. These dimensions make it possible to interpret the selected dataset not only in terms of the number of retrieved patent documents, but also in terms of technological maturity, industrial relevance and innovation patterns.

3.1 Overview of the Selected Dataset

The analysis presented in this chapter is based on the selected patent dataset obtained through the final search strategy defined in Chapter 2. The selected dataset corresponds to the hybrid query based on the IPC code H01M8/06 and a set of impurity-related keywords searched in the title and abstract fields. This query was selected because it identifies patent documents located at the intersection between fuel cell reactant treatment and impurity-related technological problems. The selected query retrieved 2,117 patent records on Lens.org. The number of records is in relation to 1,260 simple families of patents and 1,209 extended families of patents. The dataset also consists of 1,133 cited patents, 1,479 patents that cite the retrieved records, and 18,570 citations. These indicators provide an initial overview of the scale, structure and visibility of the selected patent landscape.

Indicator	Value
Patent records	2,117
Simple families	1,260
Extended families	1,209
Cites patents	1,133
Cited by patents	1,479
Patent citations	18,570

Tabella 3.1: Main indicators of the selected patent dataset.

The first relevant aspect of the dataset is the difference between patent records and patent families. Patent records refer to individual patent documents, while patent families group together documents that are connected to the same invention or to closely related filings. This distinction is important because a single invention can generate several patent records when protection is requested in different jurisdictions or when the same invention appears in different publication stages. For this reason, the 2,117 patent records should not be interpreted as 2,117 completely independent inventions. The number of simple families, equal to 1,260, provides a more appropriate approximation of the number of distinct technical solutions included in the dataset. The difference between patent records and simple families indicates that several inventions were protected through more than one patent document. This is typical in technologically and commercially relevant fields, where

applicants may seek protection in multiple countries or regions. The ratio between patent records and simple families is approximately 1.68. This means that, on average, each simple family corresponds to more than one patent record. The value suggests a moderate level of patent family duplication. The dataset is therefore not dominated by excessive duplication, but family-level interpretation remains necessary. Analyses based only on patent records may overestimate the number of independent inventions, while analyses based on patent families provide a more conservative view of technological output. The comparison between simple and extended families also provides useful information. The selected dataset contains 1,260 simple families and 1,209 extended families. The difference between these two values is limited, suggesting that the dataset is relatively coherent from a family-structure perspective. Extended families are generally broader because they may include patent documents connected through indirect priority relationships. The closeness between simple and extended family counts indicates that, for this dataset, the number of broader invention groups does not differ substantially from the number of simple patent families. The citation-related indicators show that the selected dataset is not isolated within the patent system. The number of patents cited and citing the recovered patents is 1,133 and 1,479 respectively. Moreover, the database consists of 18,570 patents citations. This clearly indicates that the patents in the selected database are related to earlier and future technological developments. This does not necessarily mean that all patents in the dataset have high technological quality, since citation practices depend on patent office procedures, technological field and patent age. However, the presence of a substantial number of citations indicates that the dataset belongs to an active and structured technological domain. From a technological perspective, the selected dataset is focused on inventions related to the treatment, conditioning and protection of reactant streams in fuel cell systems. Since the query combines H01M8/06 with keywords such as *contamin**, *impurit**, *poison** and *purif**, the retrieved documents are expected to include technologies such as gas purification units, reactant treatment systems, purge regulation devices, contaminant removal methods, fuel processing components and balance-of-plant solutions. These are all areas directly connected to the mitigation of impurity-related degradation in fuel cell operation. The dataset is therefore suitable for the objective of this thesis because it captures a system-level technological space. Impurity mitigation in PEM fuel cells is not limited to the electrochemical stack itself. It also involves the external systems that supply, clean, monitor and regulate hydrogen and air before and during operation. For this reason, a dataset centered on reactant treatment and purification provides a meaningful basis for studying how companies and research organizations have addressed one of the practical barriers to fuel cell reliability and commercialization. Overall, the selected dataset represents a focused but sufficiently broad patent landscape. It is targeted in that it does not contain many elements of semantic noise that arise as

a result of broader keyword searches. On the other hand, it is broad enough to contain more than two thousand patents as well as more than one thousand patent families. The combination of these features makes the database suitable for the following analysis of the selected patent landscape.

3.2 Temporal Evolution of Patenting Activity

The temporal evolution of the selected dataset provides useful information about the development pattern of impurity mitigation technologies in fuel cell systems. The analysis is based on the earliest priority date associated with the patent records retrieved through the final selected query. Priority date is particularly useful in patent landscape analysis because it is closely connected to the first filing of an invention and therefore provides an appropriate indicator for identifying when inventive activity started to emerge in a technological field. Since the selected dataset is built around the IPC code H01M8/06 and impurity-related keywords in the title and abstract fields, the observed trend mainly reflects patenting activity related to reactant treatment, purification, poisoning prevention and system-level protection of fuel cells. These technologies are strongly connected to the auxiliary systems and balance-of-plant components required to operate PEM fuel cells under practical conditions. The priority-date trend shows that inventive activity in the selected dataset was limited before the 1990s, with only isolated records appearing in earlier decades. Activity then started to increase more visibly during the 1990s, followed by a much stronger growth from the late 1990s and especially after 2000. The most intense phase of patenting activity is concentrated in the early 2000s, with a pronounced peak around the first half of the decade. After this peak, the number of new priority filings decreases progressively, although patenting activity continues in the following years. This temporal pattern suggests that impurity mitigation technologies experienced a major development phase during the early commercialization and system-integration period of fuel cell technologies. The concentration of priority dates in the early 2000s indicates that this was a particularly active period for system-level inventions connected to hydrogen treatment, gas purification, purge regulation, fuel processing, contaminant removal and stack protection. During this phase, many applicants were likely addressing practical problems related to the operation of complete fuel cell systems, rather than focusing only on the electrochemical stack. The timing of the peak is coherent with the nature of the selected dataset. The final query focuses on inventions classified in H01M8/06, a class related to fuel cells with means for reactant production or treatment of residues. Therefore, the retrieved documents are strongly connected to auxiliary systems and balance-of-plant solutions. In fuel cell systems, these components become especially important when research and

development moves from laboratory-scale cells toward integrated and application-oriented systems. Once PEM fuel cells are considered for real applications, the purity and management of reactant streams become critical issues because contaminants can reduce performance, accelerate degradation and shorten stack lifetime. The decrease in new priority filings after the peak should not be interpreted as evidence that impurity mitigation became technologically irrelevant. A more appropriate interpretation is that the field entered a more mature phase. During the earlier phase, many broad system architectures and basic protection strategies were patented. After these foundational solutions had been developed, innovation may have shifted toward more specific improvements, such as advanced catalysts, more durable membranes, sensors, diagnostic systems, control algorithms, hydrogen infrastructure and integrated fuel processing technologies. Some of these later developments may not be fully captured by the selected query if they are classified outside H01M8/06 or if they use terminology different from the impurity-related keywords adopted in this search strategy. The temporal profile of the selected dataset therefore reflects the evolution of a specific subset of fuel cell innovation: system-level technologies for reactant treatment and impurity management. This is important because impurity mitigation is not only a materials problem, but also an operational and architectural problem. The presence of contaminants in hydrogen or air streams must be addressed through a combination of purification devices, filters, purge strategies, monitoring systems and control solutions. The priority-date trend suggests that these aspects became particularly relevant when fuel cell systems were being developed for practical applications.

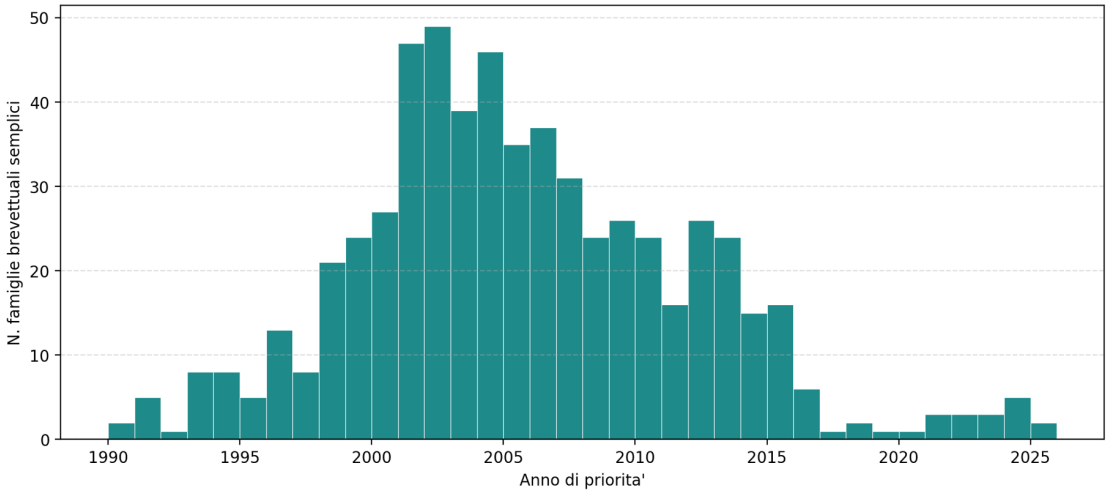


Figura 3.1: Priority-date distribution of the selected patent dataset based on Query 5

The presence of patent records with more recent priority dates indicates that the field has not disappeared. Although the volume of new filings is lower than during the early-2000s peak, continued patenting activity suggests that applicants still consider impurity mitigation and reactant treatment relevant. This is consistent with the technical importance of fuel and air purity for PEM fuel cell durability. Even if the main system architectures are mature, new operating conditions, hydrogen supply chains and application contexts may still create the need for improved purification, monitoring or protection strategies. Overall, the temporal analysis suggests that the selected dataset represents a mature but still relevant technological area. The high concentration of priority filings during the early 2000s marks a phase of intensive development of fuel cell system architectures and protection strategies. The subsequent decrease suggests technological maturation rather than technological abandonment. Therefore, the selected dataset captures an innovation trajectory in which impurity mitigation moved from an expanding system-level innovation area toward a more established component of fuel cell reliability and commercialization.

3.3 Legal Status and Technological Maturity

The legal status distribution of the selected dataset provides useful information about the maturity of impurity mitigation technologies in fuel cell systems. While the temporal analysis based on priority date shows when inventive and filing activity was most intense, legal status helps to understand whether the retrieved patents are still under protection, under examination, abandoned, inactive or already expired. For this reason, legal status can be used as a complementary indicator to interpret the technological stage of the field. In the selected dataset, the largest legal status category is represented by expired patents. This result is consistent with the concentration of priority filings observed between approximately 2000 and 2010. Since many patent families in the dataset have their earliest priority dates in that period, a significant share of the corresponding patents has already reached the end of its legal protection period. This suggests that many technologies related to reactant treatment, purification systems, purge strategies and fuel cell protection were developed during an earlier phase of fuel cell system innovation. The predominance of expired patents does not mean that the technological problem has lost importance. Rather, it indicates that several foundational solutions in this field are no longer protected or have completed their legal life cycle. In a patent landscape analysis, this is an important signal of maturity. Technologies with a high number of expired patents are often fields in which important inventive activity took place in the past and where many basic architectures, devices or methods have already been disclosed. At the same time, the selected dataset also includes pending patent documents. This is a relevant finding because pending patents indicate that new applications are still being filed and examined. Therefore, impurity mitigation cannot be interpreted as a closed or obsolete technological area. Although the strongest concentration of priority filings occurred in the 2000s, the presence of pending documents shows that companies and research organizations still consider reactant treatment, contamination control and purification relevant for fuel cell development. This mixed legal status profile suggests that impurity mitigation technologies are in a mature but still active stage. The expired patents reflect the existence of an established technological base, while the pending and active documents indicate continuing innovation. This understanding is consistent with the characteristics of the problem. The sensitivity of the PEM fuel cell to impurities is a permanent feature since it is related directly to durability and performance. With the development of hydrogen production and distribution technologies, additional operational conditions could emerge, which would generate the need for better purification techniques and protections. The presence of discontinued and inactive documents also provides useful information. These categories may indicate patent applications or rights that were not maintained, abandoned or no longer considered strategically valuable by applicants. This may happen for different reasons, such

as changes in technological priorities, limited commercial exploitation, company strategy, lack of market readiness or the replacement of older solutions by newer technical approaches. In this sense, discontinued and inactive documents should not automatically be interpreted as technically irrelevant. They may still contain useful information about past technological directions and about solutions that were explored during earlier phases of fuel cell development.

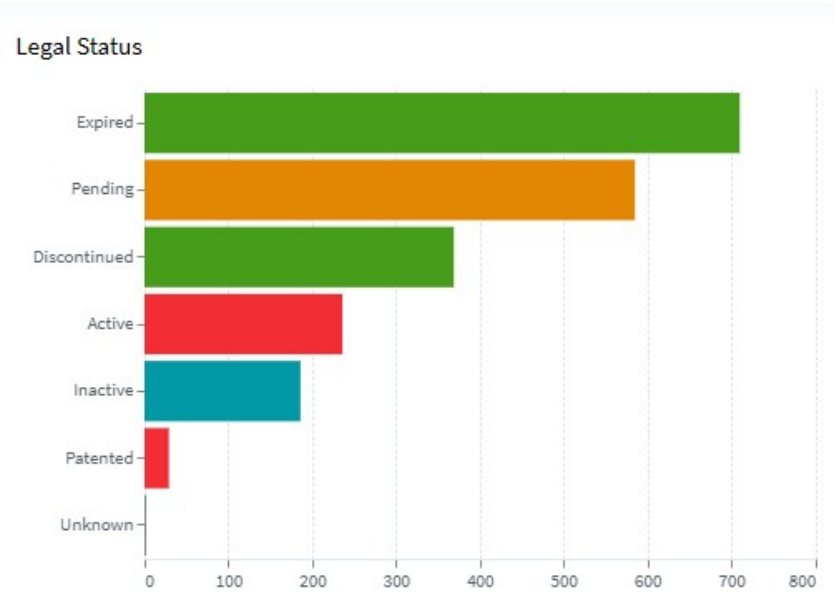


Figura 3.2: Legal status distribution of the selected patent dataset based on Query 5.

The legal status distribution can also be connected to the system-level nature of the selected dataset. The query captures patents related to fuel cell reactant treatment and impurity-related problems, rather than the entire field of PEM fuel cells. Many of these inventions concern auxiliary systems, purification units, purge control devices, fuel processing arrangements or balance-of-plant components. These are technologies that often become important when fuel cells move from laboratory research toward practical applications. The high share of expired patents may therefore reflect a period in which companies were actively trying to solve operational problems connected to system integration and real-world use. From an industrial perspective, the legal status profile indicates that some technologies in the dataset may now belong to the public domain, while others are still protected or under examination. Expired patents may still be relevant because they can represent prior art and reveal the historical development of technical solutions. Pending and active patents, instead, are more closely associated with current strategic interests. Therefore, the coexistence of expired and pending documents

suggests that the field has both a historical foundation and a continuing innovation frontier. This interpretation is important for the purpose of the thesis. If the selected dataset had been dominated only by pending patents, impurity mitigation could have been interpreted as a mainly emerging research area. If it had been composed almost exclusively of expired patents, it could have been interpreted as a field with limited current relevance. Instead, the observed distribution suggests a more balanced situation: impurity mitigation technologies have already gone through an important development phase, but the field remains active because new patent applications continue to appear. Overall, the legal status analysis supports the conclusion that impurity mitigation in fuel cell systems is a mature technological area with continuing industrial relevance. The expired patents indicate that many system-level solutions were developed during previous waves of fuel cell innovation, especially during the period in which priority filings were most concentrated. At the same time, pending and active documents show that the field continues to evolve. This confirms that reactant purity, gas treatment and protection from contamination remain important issues for the reliability and commercialization of PEM fuel cell systems.

3.4 Geographical Distribution and Industrial Context

The geographical distribution of the selected dataset provides insight into the markets and industrial regions in which impurity mitigation technologies for fuel cell systems are considered strategically relevant. The analysis is based on the jurisdiction distribution generated by Lens.org for the final selected query. Since the selected dataset focuses on patents related to reactant treatment, purification, poisoning and impurity control, the geographical distribution does not simply show where patents were filed. It also helps to identify the regions where applicants expected fuel cell system technologies to have commercial, industrial or strategic importance. A first important methodological clarification is necessary. Patent jurisdictions do not necessarily correspond to the country where the invention was originally developed. A jurisdiction indicates the country or regional patent office where the applicant requested legal protection. Therefore, geographical distribution should not be interpreted as a direct map of invention origin. Instead, it reflects a combination of technological activity, expected markets, competitive pressure, industrial policy and intellectual property strategy. Applicants generally seek protection in countries or regions where they expect future commercialization, manufacturing opportunities, public support for hydrogen technologies or strong industrial competition. The jurisdiction map for the selected dataset shows that patent protection is mainly concentrated in the United States, Japan, China and

Europe, with additional filings in other regions. This concentration suggests that impurity mitigation technologies are primarily protected in the major industrial areas involved in fuel cells, hydrogen systems, clean mobility and energy technologies. These regions are also associated with sectors in which PEM fuel cells may have practical relevance, such as road transport, stationary power generation, backup power, distributed energy systems, fuel processing and hydrogen infrastructure. Japan appears as one of the most relevant jurisdictions in the selected dataset. From an industrial perspective, this result is coherent with the importance of fuel cell technologies in Japanese automotive, electronics and residential energy applications. In these sectors, fuel cell reliability is a central requirement. Automotive applications require stacks capable of operating under dynamic loads, start-stop cycles and variable environmental conditions. Residential and distributed power systems require long operating life, stable performance and limited maintenance. In both cases, impurity mitigation becomes an essential system-level function, because contaminants in hydrogen or air can reduce catalyst activity, increase degradation and compromise system durability. The relevance of Japan in the geographical distribution can therefore be connected to the need for reliable and integrated fuel cell systems. The patents captured by the selected query are not only related to the electrochemical stack, but also to external and auxiliary components such as purification devices, fuel processors, purge systems, gas treatment units and control strategies. These technologies are particularly important in industrial contexts where fuel cells must move from laboratory testing to practical operation. The Japanese presence in the dataset therefore reflects a market and innovation environment in which fuel cell reliability and system integration have been strategically important. The United States also represents a central jurisdiction in the selected patent landscape. This can be interpreted in relation to the size and technological relevance of the U.S. market for hydrogen, fuel cell systems, stationary power and clean transport. For applicants working on impurity mitigation, filing patents in the United States may be strategically valuable because the same technological solutions can be applied across several industrial sectors. Reactant purification and contamination control are relevant for fuel cell vehicles, backup power units, distributed generation, fuel processing systems and hydrogen supply infrastructure. In the U.S. context, the selected dataset appears particularly connected to system engineering and balance-of-plant technologies. Fuel cell systems require not only an efficient stack, but also a set of auxiliary subsystems able to supply, condition and regulate the reactants. For this reason, patents dealing with gas purification, contaminant removal, fuel processors or purge control are directly relevant to the industrial deployment of fuel cell technologies. The U.S. presence in the jurisdiction map can therefore be interpreted as evidence of the strategic value of protecting technologies that improve reliability, durability and operational robustness of fuel cell systems. China is also visible in the geographical distribution of the selected

dataset. Its presence reflects the growing role of China in hydrogen and fuel cell patenting activity. However, the interpretation of the Chinese contribution requires caution. In the broader query attempts, several Chinese patent documents were associated with material preparation, membrane chemistry and general fuel cell components. The final selected query reduces part of this noise by combining the IPC code H01M8/06 with impurity-related terms in the title and abstract, but it does not completely eliminate the possibility of overlap with adjacent technological fields. From an industrial perspective, the Chinese presence can be connected to the rapid expansion of fuel cell and hydrogen-related technologies. In this context, impurity mitigation may be relevant for several application areas, including transport, distributed power, hydrogen production and gas treatment. Since fuel cell deployment depends on the quality of hydrogen supply and on the reliability of the system under real operating conditions, technologies for purification and contaminant control can become increasingly important as the market develops. Therefore, the Chinese jurisdictional presence should be understood as part of a broader industrial expansion in hydrogen and fuel cell technologies.

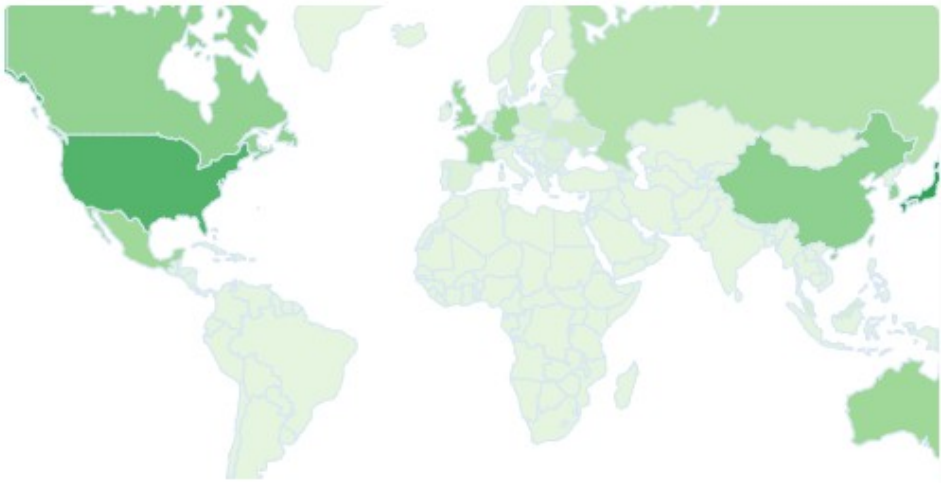


Figura 3.3: Jurisdiction distribution of the selected patent dataset based on Query 5.

Europe is also represented in the chosen set of patents and stands out as yet another significant geographical region in terms of patenting. The relevance of Europe is explained by the fact that hydrogen technologies are linked to the process of industrial decarbonization. Fuel cells may play a role in applications where direct electrification is difficult or less practical, such as heavy-duty transport, backup power, stationary systems and some industrial energy uses. In these application areas, impurity mitigation is relevant because real hydrogen supply chains may

introduce contaminants or quality variations that affect stack performance. The European presence in the patent landscape may therefore indicate that applicants consider Europe a strategic region for the commercialization and protection of fuel cell-related technologies. This is especially important for inventions related to hydrogen production, reformate-fed systems, gas purification and balance-of-plant integration. In Europe, where hydrogen deployment is often connected to transport and industrial decarbonization policies, technologies that improve fuel cell durability and operational reliability can have significant market relevance. The geographical distribution can also be interpreted through the industrial sectors associated with the selected dataset. In the automotive sector, impurity mitigation is linked to hydrogen quality, catalyst protection, purge regulation, stack lifetime and operation under variable load conditions. Fuel cell vehicles require a stable and clean hydrogen supply because even low concentrations of contaminants can affect performance and durability. Therefore, jurisdictions with strong automotive and mobility-related fuel cell activity tend to be relevant for this type of patent protection. Within the energy and gas industries, impurity removal is related to the production of hydrogen, the processing of fuels, gas reforming, and purification. The generation of hydrogen from hydrocarbons or any other chemical means may result in a stream rich in hydrogen but containing some impurities like CO, CO2, or others. Before being supplied to a PEM fuel cell, the gas stream must therefore be treated and conditioned. This explains why patents related to purification units, fuel processors and reactant treatment systems appear in the selected dataset. In stationary and backup power applications, the main requirement is long-term reliability. Fuel cells used for distributed generation or backup systems may operate for long periods and must maintain stable performance with limited maintenance. In this context, contaminant accumulation, fuel quality variations and degradation phenomena can strongly affect system availability. For this reason, technologies for gas treatment, monitoring and protection are relevant not only for vehicles, but also for stationary systems. The geographical pattern observed in the selected dataset therefore confirms that impurity mitigation is not a narrow technical issue limited to the internal chemistry of the stack. It is a system-level requirement that connects different industrial contexts. The same technological problem appears in mobility, energy, gas processing, stationary power and hydrogen infrastructure. Vehicles require clean hydrogen and robust purge strategies; reformate-fed systems require upstream purification; stationary systems require stable long-term operation; hydrogen infrastructure requires quality control and reliable supply. Overall, the jurisdiction analysis supports the interpretation of impurity mitigation as an internationally relevant technological area. The concentration of patent protection in the United States, Japan, China and Europe indicates that the field is associated with major industrial regions active in fuel cells and hydrogen technologies. At the same time, the geographical distribution should be interpreted as a map of strategic

patent protection rather than a direct map of invention origin. This section is therefore complementary to the applicant analysis: while the applicant section identifies the organizations most active in the selected dataset, the geographical analysis shows the main markets and industrial contexts in which these technologies were considered valuable enough to be protected.

3.5 Applicant Structure and Concentration

The applicant structure of the selected dataset provides insight into the organizations that have been most active in patenting technologies related to impurity mitigation, reactant treatment and purification in fuel cell systems. While the geographical analysis identifies the main jurisdictions in which protection was sought, the applicant analysis focuses on the organizations behind the patent documents. In this section, only the selected dataset obtained through Query 5 is considered. The top applicants visible in Lens.org for the selected dataset are reported in Table 3.2. The names are presented as displayed in Lens.org, without manual harmonization. This is important because applicant names may appear under different variants, subsidiaries or historical corporate names. Therefore, the table should be interpreted as a first-level view of the applicant structure rather than as a fully harmonized corporate ranking.

Applicant	Patent Records
Matsushita Electric	125
Toyota Motor	84
Idatech LLC	57
Panasonic	56
Honda Motor	55
Nissan Motor	50
Toyota Motor	42
Osaka Gas	37

Tabella 3.2: Top applicants visible in Lens.org for the selected dataset.

The first element emerging from the applicant distribution is the strong industrial nature of the selected patent landscape. The most visible applicants are not mainly universities or public research institutions, but companies operating in sectors where fuel cell reliability, hydrogen management and system integration are commercially relevant. This is coherent with the technological focus of the selected query, which captures inventions related to reactant treatment, purification, poisoning prevention and balance-of-plant solutions. The presence of automotive manufacturers is particularly significant. Toyota Motor, Honda Motor and Nissan Motor appear among the most visible applicants in the selected dataset. This suggests that impurity mitigation is closely connected to the requirements of fuel cell vehicles and transport applications.PEMFC stacks for automotive applications need to work under dynamic conditions such as variable load profiles, stop-and-start conditions, variations in temperature and humidity, and actual hydrogen availability. In such operating conditions, contamination control plays a key role since the impurities have an adverse effect on the performance of the fuel cells. Impurity mitigation in automotive applications is thus not only a matter of chemistry, but of engineering. Technologies such as purge regulation, hydrogen recirculation, gas purification, contaminant removal and control of reactant flow are directly connected to stack durability and vehicle reliability. The visibility of automotive companies in the selected dataset indicates that these actors considered impurity-related solutions important enough to protect through patents. A second relevant group is represented by companies connected to electronics, compact systems and stationary or distributed fuel cell applications. Matsushita Electric and Panasonic are highly visible in the selected dataset. Their presence suggests that impurity mitigation technologies are relevant not only for vehicles, but also for integrated energy devices, portable systems, residential applications and stationary power solutions. In these contexts, the key requirement is often stable and reliable operation over time. Contaminants in the fuel or oxidant streams can compromise this requirement, making purification and protection strategies important for system performance. The selected dataset also includes applicants connected to specialized fuel cell systems and energy technologies. Idatech LLC and Osaka Gas are particularly relevant in this respect. Their presence indicates that impurity mitigation is not limited to final fuel cell applications, but also concerns fuel processing, hydrogen production, gas treatment and system integration. In reformate-fed or fuel-processor-based systems, hydrogen may contain residual carbon monoxide, carbon dioxide, sulfur compounds or other impurities. Therefore, technologies able to purify or condition the fuel stream before it reaches the stack are essential. This applicant structure confirms the cross-sectoral nature of impurity mitigation in fuel cell systems. Automotive companies are interested in protecting the stack during dynamic vehicle operation. Electronics and system-integration companies are interested in compactness, reliability and long-term operation. Energy and gas-related companies are interested in

fuel processing, hydrogen supply and purification. Specialized fuel cell developers are interested in complete system architectures, where the stack, fuel processor and balance-of-plant components must operate together. The concentration of applicants also provides useful information. The eight visible top applicant entries account for 506 patent records out of 2,117 records in the selected dataset. This corresponds to approximately 23.9% of the total patent records retrieved by Query 5. This percentage suggests a moderate level of concentration. A limited group of organizations accounts for a significant share of the visible patenting activity, but the field is not dominated by a single applicant. The remaining patents are distributed across a wider set of organizations, indicating that impurity mitigation is a relevant topic for multiple industrial actors. However, this concentration value must be interpreted with caution. The applicant names in Lens.org are not fully harmonized in the available data. For example, Toyota Motor appears in two separate entries, and Matsushita Electric and Panasonic may also require careful interpretation because of corporate name changes or related corporate structures. If these entries were consolidated, the share of the main corporate groups would probably increase. Therefore, the raw applicant ranking may underestimate the real concentration of patenting activity. A more rigorous concentration analysis would require the export of the full applicant list and a manual harmonization of applicant names. This would make it possible to calculate more robust indicators, such as the share of the top five, top ten or top twenty applicants. It would also allow the analysis to distinguish between individual legal entities and broader corporate groups. Without this harmonization step, the present analysis should be considered an exploratory but still informative view of applicant concentration. Despite this limitation, the applicant structure supports an important interpretation of the selected patent landscape. Impurity mitigation technologies are mainly associated with organizations that have a practical interest in fuel cell commercialization and system reliability. The involvement of participants in the automotive industry, electronics, energy and fuel cells demonstrates that this issue does not only pertain to academic research or laboratory experimentation but is also related to issues found in industry, including hydrogen purity, fuel conditioning, stack endurance, balance of plant and operation stability. Overall, the applicant analysis confirms that impurity mitigation in fuel cell systems is an industrially relevant technological field. The selected dataset shows a moderate concentration around a group of major applicants, but also a broader distribution of patenting activity across multiple organizations. This suggests that the problem of protecting fuel cells from contaminants has been addressed by different sectors and from different system perspectives, reflecting the role of impurity mitigation as a cross-cutting requirement for the deployment of PEM fuel cell technologies.

3.6 Forward Citations and Portfolio Visibility

Forward citations provide an additional perspective on the technological visibility of the selected patent dataset. In patent analysis, a forward citation occurs when a later patent document cites an earlier patent. For this reason, forward citations are often used as an indicator of how much a patent or a group of patents has been considered relevant by subsequent technological developments. However, citation indicators must be interpreted with caution. These represent indirect metrics regarding the economic or technical value of the patent, as they reflect the visibility of the patent in the patent system. From the data chosen, there are 1,133 cited patents, 1,479 citing patents, and 18,570 patent citations in total. It can thus be observed that the patents selected using the final query have links with other patents. In particular, the presence of 1,479 cited-by patents suggests that later inventions have cited patents belonging to the selected dataset. This means that technologies related to fuel cell reactant treatment, purification, impurity control and poisoning mitigation have contributed to the broader knowledge base of later fuel cell and hydrogen-related patenting activity.

Indicator	Value
Patent records	2,117
Simple families	1,260
Cites patents	1,133
Cited by patents	1,479
Patent citations	18,570
Citations per patent record	8.77
Citations per simple family	14.74

Tabella 3.3: Citation indicators of the selected patent dataset.

The citation density of the selected dataset can be calculated by comparing the total number of patent citations with the number of patent records and simple families. The dataset contains approximately 8.77 citations per patent record and 14.74 citations per simple family. These values suggest that the selected patents have a meaningful degree of visibility within the patent system. The family-level value is particularly useful because patent families provide a better approximation of distinct inventions than individual patent records. The interpretation of these

indicators should take into account the temporal profile of the dataset. As discussed in the previous sections, many patents in the selected dataset were published during the 2000s. This means that a significant portion of the dataset has had enough time to accumulate citations from later patents. Therefore, the observed citation density is partly connected to the maturity of the field. Older patents generally have more opportunities to be cited than very recent patents, even when recent patents are technologically relevant. At the same time, the presence of a relevant number of forward citations supports the idea that impurity mitigation is not a marginal technological issue. If later patents cite documents from the selected dataset, this indicates that subsequent inventions have had to consider previous solutions related to fuel purification, contaminant control, purge regulation, reactant treatment or fuel cell protection. In this sense, forward citations show that the selected dataset is embedded in a broader technological trajectory. The citation profile is also coherent with the system-level nature of the selected dataset. Technologies related to impurity mitigation often affect different parts of the fuel cell system, including the fuel processor, gas purification unit, anode supply line, purge system, air management system, sensors and control devices. Because these solutions are connected to the operation of the complete system, they may become relevant prior art for later inventions in several adjacent domains. For example, a patent on hydrogen purification before the stack may be cited by later patents on reformate-fed fuel cells, fuel processors, gas treatment systems or balance-of-plant architectures. From the perspective of portfolio visibility, the citation indicators suggest that the selected patent landscape contains technologies that have been visible to later applicants. This does not mean that every applicant in the dataset has the same technological influence. A more detailed portfolio-level analysis would require the export of citation data by applicant and the harmonization of applicant names. This would make it possible to identify which companies have the most cited patent families and whether citation visibility is concentrated among a limited group of actors or distributed across the field. Nevertheless, the aggregate citation indicators are useful for interpreting the selected dataset. The combination of more than two thousand patent records, more than one thousand simple families and a meaningful citation density indicates that impurity mitigation technologies form a structured and recognizable patent landscape. The field is not composed only of isolated documents, but of inventions that interact with previous and subsequent patenting activity. Forward citations also reinforce the interpretation of technological maturity. A mature patent landscape is often characterized by a body of prior inventions that later applicants must cite, build upon or differentiate from. In the case of the selected dataset, the citation profile suggests that many impurity mitigation technologies have become part of the prior art surrounding fuel cell system design and reactant treatment. This is consistent with the legal status analysis, which showed the presence of many expired patents together with pending and active

documents. Overall, the citation analysis indicates that the selected dataset has significant visibility within the patent system. The retrieved patents are connected to later technological developments and appear to form part of the knowledge base for fuel cell reactant treatment, purification and impurity management. Although citation indicators should not be interpreted as direct measures of technological quality, they support the conclusion that impurity mitigation is an established and industrially relevant area within the broader development of PEM fuel cell systems.

3.7 Discussion of the Selected Patent Landscape

The analysis of the selected patent dataset provides a comprehensive view of impurity mitigation technologies in fuel cell systems. The dataset obtained through the final query includes 2,117 patent records, 1,260 simple families and 1,209 extended families. This confirms that the selected technological area is sufficiently broad to support a patent landscape analysis, while remaining more focused than the preliminary datasets generated during the query development process. The first important result is that the selected dataset captures a system-level technological field. The query was designed to identify patents located at the intersection between fuel cell reactant treatment and impurity-related problems. Therefore, the retrieved documents are not limited to the electrochemical stack itself, but also include technologies related to hydrogen purification, gas treatment, purge regulation, fuel processing, contaminant removal, system control and balance-of-plant architectures. Indeed, this corresponds to the technological nature of impurities reduction since it cannot be seen only from the perspective of catalyst or membrane and needs to be examined as an operationally-related issue. According to the priority-date, or application-date, trend, the period with the highest intensity of patenting activity was concentrated between approximately 2000 and 2010, with a peak in the mid-2000s. It indicates that the technologies of impurities reduction and reactants purifying played an especially important role when the fuel cells were actively developing. In that phase, many industrial actors were likely attempting to move fuel cells from laboratory research toward practical applications, where fuel quality, air quality, stack protection and system reliability became critical requirements. This decline in patent applications that followed is not indicative of any abandonment of technology but of a maturity. A lot of system-wide applications had already been patented, and perhaps later research was focused on smaller, more specialized components and their integration. The legal status distribution supports this interpretation. The predominance of expired patents indicates that a significant part of the selected dataset belongs to an earlier wave of technological development. Many inventions related to reactant treatment, purification systems and protection strategies have therefore completed their legal

life cycle. However, the presence of pending and active documents shows that the field has not disappeared. Instead, impurity mitigation appears as a mature but still active technological area, where foundational solutions coexist with more recent patent applications. The geographical distribution further confirms the industrial relevance of the field. Patent protection is mainly concentrated in the United States, Japan, China and Europe. These jurisdictions are associated with major markets and industrial regions for fuel cells, hydrogen systems, clean mobility, stationary power and energy technologies. The geographical pattern should not be interpreted as a direct measure of invention origin, because patent jurisdictions indicate where legal protection was requested. However, it does show where applicants considered these technologies strategically valuable. This suggests that impurity mitigation is relevant in regions where fuel cell commercialization, hydrogen infrastructure and clean energy policies have industrial importance. The applicant analysis shows that the selected dataset is strongly connected to industrial actors. Automotive companies, electronics firms, energy-related companies and specialized fuel cell system developers all appear among the most visible applicants. This confirms that impurity mitigation is not only an academic or laboratory research topic, but a practical industrial problem. Automotive applications require durable stacks, stable hydrogen supply and robust operation under dynamic conditions. Stationary and backup power applications require long-term reliability. Reformate-fed systems require upstream purification and fuel processing. These different industrial needs explain why the same technological issue appears across multiple sectors. The technological field and IPC analysis also reinforces the system-level interpretation of the dataset. Since the selected query is based on H01M8/06, the dataset is naturally oriented toward fuel cells with means for producing reactants or treating residues. However, the additional technological areas associated with the retrieved patents show that impurity mitigation involves several interconnected fields. These include gas purification, reactant conditioning, fuel processing, electrochemical components, purge strategies, monitoring and control systems. The patent landscape therefore reflects the interdisciplinary nature of PEM fuel cell reliability, where chemistry, electrochemistry, mechanical design and system engineering interact. The citation profile provides further evidence of the visibility of the selected patent landscape. In the data set there are 18,570 citations, which correspond to 8.77 citations for each patent and 14.74 citations for each simple family. This shows that the retrieved patents do not exist in isolation but as part of a larger technological development process. Later patents have cited inventions related to purification, contaminant control, reactant treatment and fuel cell protection. Although citations should not be interpreted as a direct measure of technological quality, they indicate that the selected dataset has visibility within the patent system and contributes to the knowledge base of fuel cell system innovation. Taken together, these results suggest that impurity mitigation in fuel cell systems represents a mature and industrially

relevant technological field. Its relevance derives from the fact that PEM fuel cells are highly sensitive to the quality of the reactant streams. Contaminants in hydrogen or air can affect catalyst activity, membrane behavior, voltage stability and stack durability. Therefore, technologies that purify, monitor, regulate or protect the reactant streams are essential for the practical deployment of fuel cell systems. At the same time, the selected patent landscape should be interpreted with methodological caution. The dataset is more precise than the preliminary search results, but it is not completely free from limitations. Patent family duplication can inflate the apparent volume of patenting activity if individual records are counted as independent inventions. Applicant name variation can also affect the interpretation of portfolio concentration, especially when the same corporate group appears under different names. Moreover, some grey-zone technologies may still be included because adjacent electrochemical systems, such as flow batteries or metal-air batteries, can share terminology and classification features with fuel cell technologies. Despite these limitations, the final dataset provides a coherent basis for understanding how patented technologies have addressed impurity-related problems in fuel cell systems. The results show that the field is characterized by an early phase of strong system-level development, a mature legal status profile, international patent protection, significant industrial participation and meaningful citation visibility. This confirms that impurity mitigation is not a secondary issue, but one of the practical technological areas supporting the reliability, durability and commercialization of PEM fuel cell systems. Overall, the selected patent landscape shows that the mitigation of impurities is positioned at the interface between fuel cell chemistry and system engineering. It connects the internal sensitivity of PEM fuel cells to contaminants with the external need to supply clean, controlled and reliable reactant streams. For this reason, the patent activity observed in the selected dataset provides useful evidence of how industrial actors have tried to solve one of the key operational challenges limiting the large-scale deployment of PEM fuel cell technologies.

Chapter 4

Conclusion

This work investigated impurity mitigation technologies in proton exchange membrane fuel cell systems through a patent landscape analysis. The research began with the technological background of fuel cells and hydrogen systems, with particular attention to proton exchange membrane fuel cells and their application in clean transportation, stationary energy production and distributed energy systems. As explained in the initial chapter, PEM fuel cells have advantages that include low operating temperatures, rapid start-ups, high energy density, and being suited to dynamic operations. Nevertheless, mass production faces several challenges such as high cost, durability problems, water management, heat management, dependence on platinum catalysts, and sensitivity to contaminants. The issue of impurities was identified as a particularly relevant technological problem. Functioning of PEM fuel cell relies on the delivery of hydrogen gas into the anode side and oxygen/air into the cathode side. Impurities found in these fuel streams can lead to adverse effects on the electrochemical reaction, catalyst efficiency, membrane conductance, and even stack durability. Carbon monoxide, sulfur compounds, ammonia, carbon dioxide, volatile organic compounds, and even pollutants in the air stream can thus have impact on the performance and durability of PEM fuel cells. This shows that not only does the issue of impurity elimination involve the chemical or material sciences, but it is also a system-level issue. The research question addressed by the thesis was that of establishing an efficient database based on patents. It was found during the development phase that a basic keyword search would not be enough. Keywords such as *contamin**, *impurit**, *poison**, *sulfur*, *ammonia* and *purif** were yielding far too many false positives as the same language is employed in other areas such as membrane chemistry, catalyst production, purification of materials and fuels. On the other hand, the usage of the patent class H01M8/06 by itself was too wide as it contained patents not dealing with impurities but rather the production of reactants. The final selected query combined the IPC code H01M8/06 with impurity-related keywords searched in the title and abstract

fields. This hybrid strategy represented the best compromise between technological scope and semantic precision. The IPC code defined the technological perimeter of fuel cell reactant treatment, while the keywords introduced the problem-oriented focus on contamination, impurities, poisoning and purification. As a result, the selected query retrieved a dataset aligned with the objective of the work, focusing on system-level solutions such as purification units, gas filters, fuel processors, purge strategies, contaminant removal devices and balance-of-plant architectures. The selected dataset contained 2,117 patent records, corresponding to 1,260 simple families and 1,209 extended families. This confirms that impurity mitigation in fuel cell systems is not a marginal topic, but a recognizable area of patented technological activity. The difference between patent records and patent families also highlighted the importance of considering patent family duplication. Since the same invention may be filed in multiple jurisdictions, patent records are useful for analysing legal coverage, while patent families provide a more appropriate approximation of distinct technical solutions. The temporal analysis, based on earliest priority date, showed that patenting activity in the selected dataset was mainly concentrated between approximately 2000 and 2010, with a pronounced peak in the early 2000s. This indicates that impurity mitigation technologies underwent a period of intensive development during a phase in which fuel cell systems were moving toward more practical and application-oriented configurations. During this period, companies and other applicants were likely addressing issues related to hydrogen quality, reactant treatment, system operation under real conditions and stack protection. The subsequent decrease in new priority filings does not imply that the topic lost technological relevance. Rather, it suggests that the field progressively entered a more mature stage after many broad system architectures and protection strategies had already been developed. Later innovation may have shifted toward more specific technologies, such as sensors, catalysts, control systems, durable membranes, hydrogen infrastructure and integrated fuel processing solutions. The legal status analysis supported this interpretation. The selected dataset was characterized by a significant presence of expired patents, indicating that many inventions belong to an earlier wave of fuel cell system development. This result is coherent with the concentration of priority filings in the 2000s. However, the presence of pending and active documents shows that the field has not disappeared. Instead, impurity mitigation appears to be a mature but still active technological area. This is consistent with the continuing relevance of reactant purity for PEMFC durability, reliability and commercialization. According to geographical assessment, patent protection was observed to have been highly concentrated in the major industrial zones like the United States, Japan, China, and Europe. These zones do not always indicate the origin point of invention, but only the market zones in which the applicants perceived patent protection as strategically essential. This kind of geographical concentration can be attributed to the importance of fuel

cell and hydrogen technology within the industrial sector, especially within clean transportation and energy sectors. It also confirms that impurity mitigation is relevant in markets where reliable fuel cell operation is a key requirement. The applicant analysis further confirmed the industrial nature of the selected patent landscape. The most visible applicants include companies connected to automotive applications, electronics, energy systems and specialized fuel cell development. Automotive companies are particularly relevant because fuel cell vehicles require stack durability, hydrogen quality control and robust operation under dynamic load conditions. Electronics and stationary system companies are connected to compactness, reliability and long-term operation. Energy and gas-related companies are relevant because fuel processing and hydrogen purification are essential when the fuel stream is not supplied as ultra-pure compressed hydrogen. This applicant structure shows that impurity mitigation is a cross-sectoral technological issue. The analysis of technological fields and IPC distribution reinforced the idea that impurity mitigation is positioned between electrochemistry and system engineering. The selected patents are connected to reactant treatment, gas purification, fuel processing, purge regulation, control systems, monitoring devices, catalysts, membranes and other auxiliary technologies. This confirms that the protection of PEM fuel cells from contaminants cannot be addressed only inside the stack. It also requires external and integrated system solutions able to supply clean and controlled reactant streams. The citation analysis showed that the selected dataset has meaningful visibility within the patent system. The dataset contained 18,570 patent citations, corresponding to approximately 8.77 citations per patent record and 14.74 citations per simple family. Although citations should not be interpreted as direct measures of technological quality or commercial success, they indicate that patents related to impurity mitigation have been considered relevant by later patent documents. This supports the interpretation of the selected patent landscape as an established technological domain within fuel cell system innovation. Overall, the findings obtained in this thesis demonstrate that impurity mitigation technologies in PEM fuel cell systems represent an established, industry-oriented and internationally protected field of innovation. This topic is directly connected to the technical problems outlined in the first chapter: PEM fuel cells are a promising technology for clean energy conversion, but their successful implementation requires reliable operation with realistic hydrogen and air supplies. Impurities may affect catalyst efficiency, membrane behaviour, voltage stability and stack lifetime. Therefore, technologies able to purify, monitor, regulate and protect the reactant streams are essential for improving system durability and reliability. The thesis also highlights the usefulness of patent landscape analysis for studying technological development. Patent data make it possible to observe not only individual inventions, but also broader patterns related to time, geography, applicants, technological fields and citations. At the same time, the analysis has some limitations. Patent

documents do not capture all innovation, because some knowledge may remain protected as trade secrets or internal know-how. Patent citations are influenced by patent age, patent office practices and applicant strategies. Jurisdictions reflect protection strategies rather than invention origin. Applicant rankings may be affected by name variations, and patent family duplication can distort quantitative indicators if not properly considered. Finally, despite the improved precision of the selected query, some grey-zone technologies may still be present due to overlaps with adjacent electrochemical systems. Despite these limitations, the selected dataset provides a coherent view of how industrial actors have patented solutions for impurity-related problems in fuel cell systems. The evidence collected in this work suggests that impurity mitigation should be understood as a key enabling area for PEMFC deployment. It links the electrochemical sensitivity of the stack to the practical requirements of hydrogen supply, fuel processing, air management and balance-of-plant integration. For this reason, the development of technologies able to purify, control and protect the reactant streams remains central to improving the reliability, durability and commercialization potential of PEM fuel cell systems.

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