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Green hydrogen development: An analysis of the Brazilian innovation system

by

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Abstract: Brazil has received international attention and investment for renewable energy production, including investments to produce low-carbon hydrogen: green hydrogen. However, green hydrogen requires relatively new technology and inputs are still expensive when compared to fossil fuels. The diffusion of this technology depends on the fulfillment of seven innovation functions. This study therefore seeks to analyse the evolution of these functions in the context of Brazil to understand how policies and strategies can improve in order to enable the hydrogen economy to reach the level of *socio-technical regime*.

Keywords: green hydrogen, hydrogen economy, innovation system.

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List of Acronyms

ABH$_2$ – *Associação Brasileira do Hidrogênio* – Brazilian Hydrogen Association

ABNT – *Agencia Brasileira de Norma Tecnica* – Technical Normazation Brazilian Agency

ANEEL – *Agencia Nacional de Energia Eletrica* – Electric Energy National Agency

BNDES – *Banco Nacional de Desenvolvimento Ecnomico e Social* – Social and Economic Development Bank

CCS – Carbon capture and storage

CCU – Carbon capture and utilisation

CCUS – Carbon capture utlisation and storage

CEMIG – *Companhia Eletrica de Minas Gerais* – Minas Gerais Electric Company

CGEE – *Centro de Gerenciamento e Estudos Estrategicos*: Center for Management and Strategic Studies

CNPq – *Companhia Nacional de Pesquisa* – Research National Comapny

CO$_2$ – Carbon dioxide

EPE – *Empresa de Pesquisa Energetica* – Energy Research Company

FAPESP – *Fundação de Apoio a Pesquisa do Estado de São Paulo* – Foundation for Research Support of São Paulo State

GIZ – *Deustche Gesellchaft für Internationale Zusammenarbeit* - German Society for International Cooperation

H$_2$O – water molecule

IPEA – *Instituto de Pesquisa Economicas Avançadas:* Advanced Economic Research Institute

IS – Innovation System

LABH$_2$ – *Laboratório do Hidrogênio* – Hydrogen Lab

MCT – *Ministerio da Ciência e Tecnologia* – Science and Technology Ministry

MLP – Multi-Level Perspective

UNEP – United Nation Environment Programme

1 Introduction

At the risk of not reaching the goal of limiting global warming to 1.5ºC, the United Nations report, named The Closing Window (2022), warns global society about the need to rapidly implement changes in electricity supply, industry, transportation, and buildings. To increase energy performance and move towards a low carbon emission energy source, the same report suggests that transitioning to hydrogen economy has the potential to promote full decarbonisation of industrial sectors and put the emissions on track of reaching the Paris Agreement targets (Amirthan & Perera, 2022; Dawood, Anda & Shafiullah, 2020; Khan & Al-Ghamdi, 2023; UNEP, 2022). Depending on the production way, hydrogen fuel gets different classifications based on colors. Grey hydrogen is the most produced and consumed, its production process uses natural gas and emits CO_2. In order to achieve zero emissions, producers and consumers have to focus on *green hydrogen*, which uses electricity from renewable sources to separate water molecules (H_2O), in a process called electrolysis. Green hydrogen, also called the fuel of the future, is claimed to have great potential to transform polluting industries, such as steel and cement (IPEA, 2022; Oliveira, Beswick & Yan, 2021).

Since 2021, several companies in the energy sector in Australia, the Netherlands, France, Portugal, Spain, and Germany have announced investments of at least 39 billion dollars in Brazil to produce hydrogen in the coming years (IPEA, 2021). With that said, this work explores the development of the hydrogen innovation system (IS) in Brazil to enable the energy transition toward the hydrogen economy.

1.1 Research gap, relevance and importance

Governments, academia, research institute, and industry have been investigating the Brazilian potential to contribute to the energy transition. Chantre et al. (2022) explore stakeholders' perceptions according to their experiences and expectations for the development of the hydrogen economy in Brazil. Through interviews, they mapped Brazilian players, barriers to technological development, and internal market potential.

The Brazilian Institute of Applied Economic Research (IPEA, 2022) carried out a study in which it analyses the evolution of investments in the hydrogen sector and identified the hydrogen production routes in Brazil and the potential for international cooperation. A descriptive research methodology was used, with information obtained from bibliographic surveys, documents, and statistical databases.

In 2021, the German International Cooperation Agency (GIZ), released the study "*Mapeamento do Setor de Hidrogênio Brasileiro*" (Mapping of the Brazilian hydrogen sector). The study deeply describes the current scenario of Brazilian hydrogen, going through some historical aspects, institutional policy and interviews with relevant actors.

Kelman et al., (2020) assess the economic feasibility of green hydrogen o production in Brazil through a financial model using linear regression. Nadaleti, de Souza and de Souza (2022) explore the potential of using the surplus of solar and nuclear production plants to produce green and purple hydrogen. Raffi, Massuquetti and Alves (2013) analyse the investments policy in hydrogen generation in Brazil since 2002 onwards. They used bibliographic research.

The preliminary bibliographical research revealed the lack of a systematic analysis of the evolution of the hydrogen system in the last 20 years. Thus, this research aims to fill this gap by offering a holistic view of the creation of Brazilian IS. Using a systemic approach where the actions of relevant actors and the impacts they have on the system are considered, those actions are manifested in the form of functions. The *functions of the innovation system* approach suggests a framework with seven functions: *entrepreneurial activity*, *knowledge development*, *knowledge diffusion*, *guidance of the search*, *market formation*, *resource mobilisation* and *creation of legitimacy* (Hekkert et al., 2007; Hekkert & Negro, 2009; Negro, Hekkert & Smits, 2007).

Another contribution of this study is to use the Multilevel Perspective (MLP) as a theoretical framework to explain how the *landscape level* has influenced the performance of some functions of the innovation system. The author, therefore, hopes that by understanding the fulfillment of those functions, policymakers, industry, and society can take actions that can influence the speed and the trajectory by which a novelty can rise from the *niche* to the *socio-technical regime* and put us on track for carbon emission reduction.

1.2 Research questions

This research is guided by the main research question:

Q1 – How did the hydrogen technical system evolve in Brazil between 2002 and 2022?

And as secondary question,

Q2 – How have the functions of the green hydrogen innovation system been fulfilled in Brazil?

To answer the first question, an analysis focused on government policies and sectoral technical studies will be carried out aiming to build the historical line of the system's evolution. As for the second question, a methodology developed by researchers at the Minnesota University, and was adapted and applied by Hekkert and his colleagues at Utrecht University will be used to assess the performance of each of the seven functions.

1.3 Thesis outline

In addition to this introductory chapter, this thesis is divided into 6 other question chapters described below.

- The *Chapter 2* provides an overview of the hydrogen economics discussion. This chapter presents content and technical terms from the field of chemistry that may be difficult for scholars of economic history field, however, understanding the main barriers to hydrogen economy are given by its physical characteristics. So, the possibility to reach a production model based on hydrogen will depend on the capability to overcome these barriers.
- The *Chapter 3* briefly describes Brazilian energy contexts and renewable electricity production.
- In the *Chapter 4,* the theoretical approach is presented as a combination of the Multilevel Perspective and the Innovation Functions.
- *Chapter 5* describes the methodological approach and data.
- *Chapter 6* brings the results, analysis and discussions divided into parts: the first one shows the events description and the second one shows the functions fulfillment.
- The conclusions are presented in the chapter 7.
- Finally, in the last part there are the appendices.

2 Overview of hydrogen economy development

During the first industrial revolution, coal worked as propeller of economic production. In the following years, from 1820 to 1910, the coal consumption in England and Wales, France, Germany, Italy, Netherlands, Portugal, Spain, and Sweden increased from 28,9% to 83,5% compared to other energy sources (Kander, Malanima & Warde, 2013). The second industrial revolution reinforced the role of oil as energy carrier (Kander, Malanima & Warde, 2013), both sources are recognised as great emitters of CO_2, main responsible of global warming. Here lies the reason why it is important to academia, industry, government, and society work together to find greener solutions without compromising energy security necessary to economic development.

First coined by the Professor John Bockris in 1970 (Brandon & Kurban, 2017), the term "hydrogen economy" might be self-explanatory. However, it is necessary to refine its conceptualization to better understand the pathway of breaking the fossil fuel path dependency in our society and propose solutions towards the replacement of fossil fuel based productive model to a low carbon energy source. When reviewing the role of hydrogen storage technology development, Amirthan and Perera (2022, p. 2) referred to hydrogen economy as the "hypothesis of having hydrogen as primary energy carrier". According to Center for Management and Strategic Studies (CGEE, 2010), hydrogen economy is used to describe a new economic paradigm less dependent on non-renewable resources focusing on energy security and environmental impact attenuation. In this work, it is not only considered both concepts, but, in terms of theoretical approach, hydrogen economy is seen as the consolidation of this technology as main participant in the socio-technical regime level. This concept is further elaborated in the section three.

When analysing the academic literature about hydrogen production, Dawood, Anda and Shafiullah's (2020, p. 3849) showed that a hydrogen-based production system comprehend four main stages: production, storage, safety and utilisation or, as they call, "corners of hydrogen square" (figure 1).

Based on four corners of the hydrogen square, this section will present the main characteristics and challenges for the development of the hydrogen economy, both in Brazil and abroad. This chapter is divided into two sub-sessions, the first one is dedicated to understanding the development of hydrogen as fuel, presenting its characteristics, classification, and application in economy. The second part presents an overview of the Brazilian energy context focusing on the sustainable energy production which is necessary to produce green hydrogen.

2.1 Characteristics of hydrogen and the four corners approach

2.1.1 Hydrogen properties

Hydrogen is the most abundant element in the universe and the third most prevalent on Earth's surface, making it widely available (Dawood, Anda & Shafiullah, 2020). The gas is, at the same time, a primary fuel and energy vector or energy carrier (GIZ, 2021). As a primary fuel source, hydrogen can be found naturally in certain geological environments either in its pure form or mixed with other gases, in this case, its application is similar to fossil fuels (GIZ, 2021). However, its extraction from geological sources is not widely used. The most common way is to obtain hydrogen is as an energy carrier, like electricity, and can be produced from various sources without emitting greenhouse gases or other pollutants (GIZ, 2021). The main difference between hydrogen and electricity is that hydrogen can be used as chemical energy carrier, composed also by molecules and not only electrons like electricity (GIZ, 2021).

Due to its low density (0,089888 g/L), low boiling point (-252,34ºC) and low fusion point (-259,34ºC) manipulating hydrogen is a challenging task (Armaroli & Balzani, 2011). Comparing hydrogen with other fuels, chemical engineers show that liquid and gas hydrogen have 33,3 kWh Kg^{-1} which is the most energy comparing weight-for-weight among all substances, on the other hand, hydrogen is the lightest chemical element, as a consequence, when compared to the volumes of other elements, it has low energy density per unit volume (table 1) (Edwards, Kuznetsov & David, 2007).

Table 1 Gravimetric and volumetric energy content of fuels, hydrogen storage options and energy sources

Fuel	**specific energy ($kWh\ kg^{-1}$)**	**energy density ($kWh\ dm^{-3}$)**
liquid hydrogen	33,3	2,37
hydrogen (200 bar)	33,3	0,53
liquid natural gas	13,9	5,6
natural gas (200 bar)	13,9	2,3
petroleum	12,8	9,5
diesel	12,6	10,6
coal	8,2	7,6
methanol	5,5	4,4
wood	4,2	3
electricity (Li-on battery)	0,55	1,69

Source: Edwards, Kuznetsov & David (2007)

As a chemical energy carrier, hydrogen allows stable storage and transport similar to traditional sources like oil, coal, and natural gas. This makes it a promising candidate for balancing energy supply and demand in countries electrical system. In Brazil, for instance, the stability of national electrical system is currently done inefficiently through the reduction or increase in electricity generation by thermoelectric and hydroelectric plants (IPEA, 2022). Researchers of the Brazilian Institute of Applied Economics Research advocates that Hydrogen can be redirected to electrolysers during excess generation and used to generate electricity through a fuel cell during moments of high demand (IPEA, 2022).

2.1.2 First corner: production

The hydrogen production uses other energy source to isolate its molecule. According to Dawood, Anda and Shafiullah (2020), there are several ways and technical procedures to obtain hydrogen (appendix A), each of them with specific level of cleanness, cost and efficacy. The definition of which method will depend on the feedstock (water, brine, algae, biomass, coal, fuels), energy source (electric, photonic, bioenergy, heat), catalyst material, and scale (Dawood, Anda & Shafiullah, 2020).

Even though, there is no worldwide hydrogen classification accepted yet, the color system is most known way to do so. The table 2 summarizes the color-based hydrogen classification according to its production method. When the CO_2 released during the generation of hydrogen is captured and stored (CCS), utilized in other industrial processes (CCU), or even both (CCUS), the resulting hydrogen is referred to as blue hydrogen. The carbon neutrality of blue hydrogen happens due the CO_2 capturing. However, blue hydrogen does not address the issue of significant greenhouse gas emissions during the pre-chain phase. Blue hydrogen is frequently regarded as an interim solution for transitioning from gray hydrogen to green hydrogen (GIZ, 2021; Khan & Al-Ghamdi, 2023).

Table 2 Hydrogen classification

Classification	**Production processes**
Brown hydrogen	produced from lignite gasification without CCUS (carbon capture, use and sequestration of carbon).
Black hydrogen	produced from coal or anthracite gasification without CCUS
Gray hydrogen	produced from natural gas by means of steam methane reforming, or using electrolysis, powered by non-renewable energy source and without CCUS.
Blue hydrogen	produced from fossil fuel (mainly by reforming) with CCUS
Green hydrogen	produced via electrolysis of water with energy from variable renewable sources (particularly hydro, wind, solar energy, and biomass).

Source: IPEA, 2022

The International Energy Agency’s (IEA) report presented that in 2021 was produced 94 million tonnes of hydrogen with more than 900 million tonnes of CO_2 emitted (IEA, 2022). Despite being the most widely used method worldwide (approximately 95%), gray hydrogen, which is produced by steam reforming of methane, has significant environmental drawbacks. For instance, the production of 1 ton of hydrogen through this method generates around 10 tons of CO_2 emissions (IEA, 2022). Electricity can also be used to produce hydrogen. In this case, the emission of gases that impact global warming will depend on the electricity matrix of the producing country.

Hydrogen that uses electricity from a renewable source produced via water electrolysis, therefore with no CO_2 emissions, is known as green hydrogen (table 2). Due to its low carbon footprint, green hydrogen is considered a key technology for countries committed to decarbonization goals outlined in the Paris Agreement under the UNFCCC (GIZ, 2022). With that said, the biggest challenge for our society is not just to migrate to a hydrogen economy model, but to a low carbon hydrogen economy. This objective can be achieved through the production of blue hydrogen or green hydrogen (Kelman et al., 2020) .

In 2019, the IEA’s hydrogen analysis claimed that depending on the cost of natural gas, the cost of producing gray hydrogen varies between US$ 0.5/kg and US$ 1.7/kg. In the case of blue hydrogen, the cost is between US$ 1/kg and US$ 2 kg. For green hydrogen the cost is high to US$3/kg and US$8/kg, caused specifically by the cost of producing renewable energy.

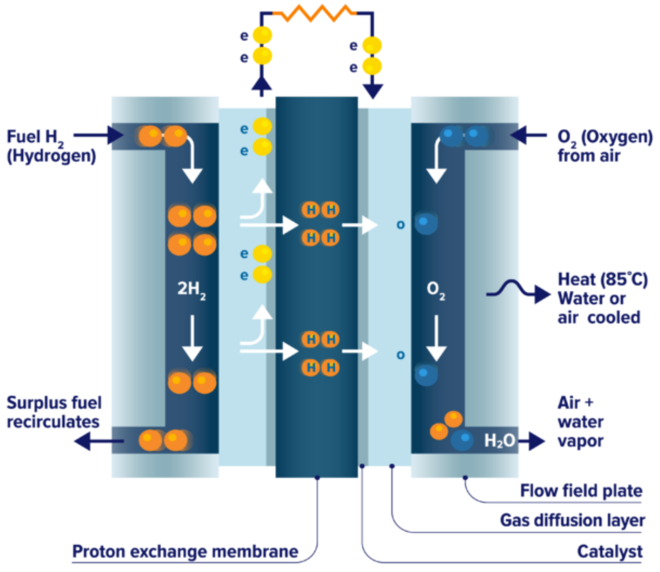
The drivers behind the progress of an innovation depend on the development of its complementarities which are interconnected and influence each other interdependently, these are the development blocks (Taalbi, 2017; Dahmén, 1984). Thus, to produce green hydrogen, through water electrolysis, on a large scale, it is necessary to increase the production and reduce the cost of electricity from renewable sources and advances in fuel cell technology (Kelman et al., 2020; Zhou et al., 2022).

2.1.2.1 Fuel cell development

Invented in 1839 by William Grove (Fuel Cell Today, 2023), the fuel cells work like regular batteries. The latter, however, have their reagents stored inside, undergoing oxidation-reduction reactions and the transforming chemical energy into electrical energy, while the former does not have chemical energy stored. As long as there is reagent injection, fuel cells continuously produce electricity (Fogaça, 2023).

There are several types of fuel cells, but they all work in a similar way. It consists of a unity of electrolyte and two electrodes. Based on the electrolyte used within, the fuel cells receive the following typification: PEM (proton exchange membrane), DMFC (direct methanol fuel cell), MCFC (molton carbonate fuel cell), PAFC (phosphoric acid fuel cell), SOFC (solid oxide fuel cell) and AFC (alkaline fuel cell) (Armaroli & Balzani, 2011; Dawood, Anda & Shafiullah, 2020; Zhou et al., 2022; CHFCA, 2023). Oxygen collected from the air passes by one electrode and the hydrogen, from an external source, passes over the other electrode. those atoms movements generate electricity in one side. As the ions move through the electrolyte towards the cathode, they combine with oxygen atoms, facilitated by another catalyst, resulting in the formation of water (Armaroli & Balzani, 2011; CHFCA, 2023). When the fuel cell receives water and electricity, the electrolytes work on the opposite way, separating the water molecule creating hydrogen and oxygen gases.

Figure 1 PEM fuel cell



SOURCE: Wikipedia Membrane electrode assembly

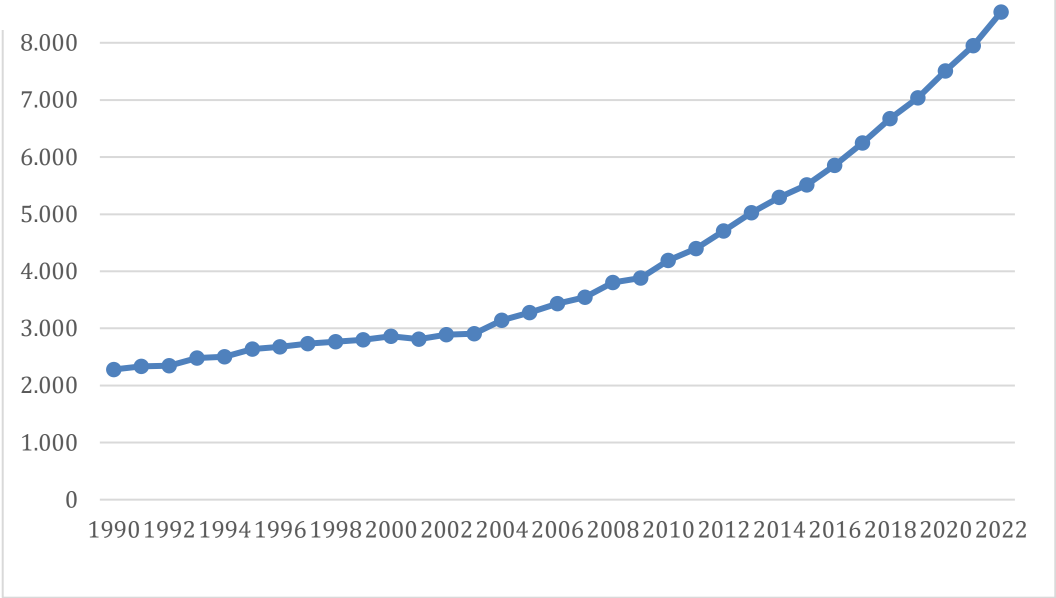
Source: CFFCA, 2023

Using fuel cell to produce electricity has several advantages: reduction of GHG and petrol consumption, promoting the use of renewable energies, silent operation, low maintenance and high reliability (Armaroli & Balzani, 2011). On the other hand, the technology of fuel cells presents the following bottlenecks: the costs associated with fuel cells for stationary electrical generation are still significantly high and are not viable as substitutes for technologies based on fossil fuels (Rodrigues, Souza & Tambor, 2019). Furthermore, the lifecycle and degradation time of many fuel cell technologies, especially those high temperature ones that are ideal for generating electrical energy, are still not completely understood (Dawood, Anda & Shafiullah, 2020). Another challenge is the cost of hydrogen, which is one of the main fuels for fuel cell technologies. Hydrogen is currently expensive and there is also no developed infrastructure for its large-scale production and distribution (Rodrigues, Souza & Tambor, 2019).

2.1.2.2 Renewable electricity production

Renewable electricity is the energy source necessary to produce green hydrogen and it is obtained from a renewable energy source, such as: wind, solar, hydropower, waves and tidal, and biomass. The figure 2 shows the evolution of renewable energy source production, the rising curve shows that from 1990 and 2022 the production increased 74%. The IEA (2022) states that, in terms of global renewable capacity additions they are going to stay the same in 2023, however, the capacity of wind and solar energy capacity will increase while hydro power capacity will decrease. In any case, the increase in investment in solar and wind energy contributes to reducing its cost, which has an impact on the final price of green hydrogen (McKinsey, 2021).

Figure 2 Evolution of electricity production from RE sources between 1990 and 2022 (Terawatt hour - TWh)

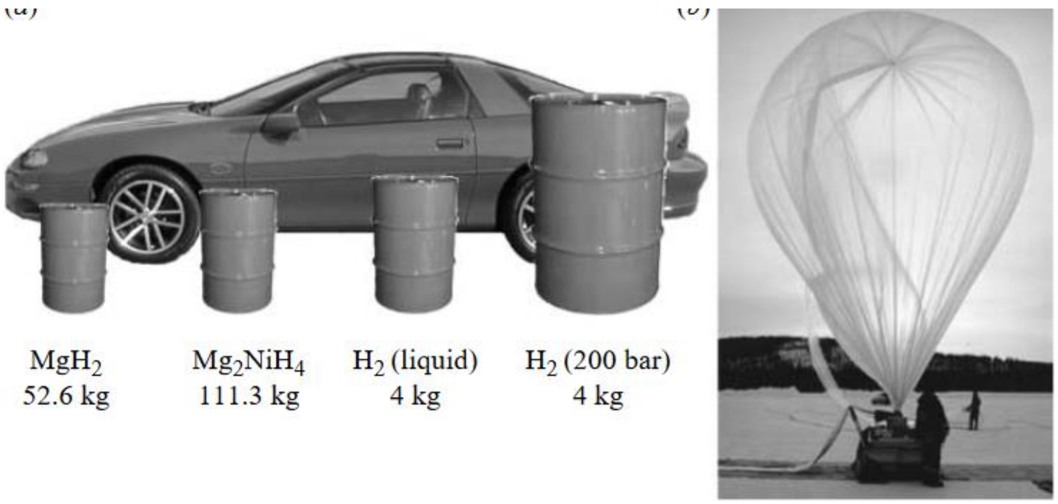


Source: own calculation using data from Ritchie, Roser & Rosado, 2022.

2.1.3 Second corner: storage

In order to evolve to hydrogen based economy, advancements in storage technology are also needed (Dawood, Anda & Shafiullah, 2020). The challenge of storing hydrogen is related to its physical properties and applicability. In stationary applications, such as industrial and household use, hydrogen storage systems may occupy a relatively sizable area, with weight not being a significant concern. However, when it comes to transportation, like in cars, the storage of hydrogen is constrained by both volume and weight limitations (Abe et al., 2019).

Figure 3 Volume of 4 kg of compressed hydrogen



Source: Edwards, Kuznetsov & David, 2007, p. 1050

In the figure 3 (a), the authors illustrate the issue about balancing weight and volume of 4kg of hydrogen. In the first container, four kilogram of hydrogen is obtained by separating the magnesium hydride molecule (MgH_2), in this case it is necessary 52,6kg of that chemical compound. In the second barrel, it is shown the volume of magnesium nickel hydride (Mg_2NiH_4), and it necessary 111,3kg. The last two containers show hydrogen in its pure form liquid and compressed air. In normal conditions, 4kg of hydrogen occupy the space of a mid-size balloon (figure 3-b) (Edwards, Kuznetsov & David, 2007).

Currently there are several techniques that enable producers to storage and transport hydrogen, making it available for commercial use (appendix B). These methods include combining hydrogen with metal hydrides, using additives or catalysts for chemical hydrides. Furthermore, hydrogen adsorption, liquefaction and compression are also viable alternatives (Andersson & Grönkvist, 2019).

2.1.4 Third corner: safety

The largest dirigible ever constructed was the Hindenburg, proudly labeled "Made in Germany", It boasted an impressive length of 245 meters and could reach speeds of up to 135 km/h (Andrade, 2022). The dirigible's framework consisted of metal covered in cotton, and it utilized hydrogen instead of helium. On May 3, 1937, the Hindenburg embarked on its journey from Frankfurt, Germany, with a destination set for the United States. The airship carried 36 passengers and 61 crew members, and its return trip was planned to accommodate 72 passengers for the coronation of King George VI of England (Andrade, 2022). Tragically, three days later, as the Hindenburg attempted to dock at the New Jersey Station, a disaster struck when it caught fire and plummeted from a height of 78 meters. It is widely believed that the early release of the ropes caused sparks, igniting the hydrogen and leading to the catastrophic fire that destroyed the airship in less than thirty seconds . (Andrade, 2022). The images of the Hindenburg's tragedy illustrate how flammable hydrogen can be. However, it does not require any more safety precaution than other fuels, that is, with proper handling and a system of use designed for safety, hydrogen can be consumed safely (Edwards, Kuznetsov & David, 2007). Edwards et al (2007, p. 1054) also mention that "safety is not only a technological issue", which means that hydrogen needs to be perceived as safe, this fact highlights the psychological character of adopting a new fuels or other devices in early introductory phase.

To guarantee the safety standards in the hydrogen market, standardization entities are setting the safety criteria to operate. The International Standardization Organization (ISO) has already released 11 standardization norms related to hydrogen and its technologies (GIZ, 2021). In the national level, the Brazilian Association of Technical Standards (ABNT) has a special study commission, with members of industry, government, academia, putting efforts on the standardization in hydrogen technology extends across various aspects, encompassing systems and devices involved in hydrogen production, storage, transport, measurement, and utilisation.

2.1.5 Fourth corner: utilisation

In terms of usage, hydrogen can be applied to the production of diverse goods and in numerous industrial procedures, including those not related to energy. According to IEA, the worldwide demand for hydrogen has increased more than three times since the mid-1970s and exceeded 70 Mt in 2018. Some of hydrogen applications are described below.

Within a hydrogen economic system, the gas would be widely used in industry. Currently, the gray hydrogen is already used in the industries of refining crude oil, ammonia production, reducing agents in the steel and glass industry, hydrogenation of hydrocarbons, hydrogenation of fat in margarine manufacture process, refrigeration and cryogenics (GIZ, 2021). The replacement of gray hydrogen by sustainable hydrogen would result in the non-emission of 900 million tons of CO_2 (IEA, 2022). The potential for new applications of green hydrogen is even more promising. Green hydrogen production can play an integrative role between electrical power generation and other uses *Power-to-X* (Edwards, Kuznetsov & David, 2007; GIZ, 2021). In this way, hydrogen becomes a chemical form of electrical energy storage for various purposes, especially in industries that are known to have a large carbon footprint. Such as, the cement industry, mining industry, steel industry, glass industry, transportation and household heating system, for instance (GIZ, 2021; Chantre et al., 2022).

The use of hydrogen on a large scale presents an important obstacle related to logistics and transport. The transportation usually occurs in its gas and liquid forms, the former uses high pressure tanks (from 500 to 700 atm) and the latter reducing the gas to its boiling point which increases costs and complexity (GIZ, 2021). Finding economically viable and efficient means of separating the hydrogen molecule from other elements, storing, and transporting it, has been the biggest challenge to the diffusion of this type of technology (Edwards, Kuznetsov & David, 2007).

Wrap up this sub-section, the table 3 summarizes the main obstacles to the development of the hydrogen economy and consequently impact on the technological advance of green hydrogen.

Table 3 Necessary improvements in hydrogen technology

First corner – production
• High cost of fuel cells for stationary electrical generation. • Lack of understanding of the life cycle of fuel cells. • High cost of renewable energy.
Second corner – storage
• Difficulty finding a viable way to compress the gas. • High cost and high energy consumption for hydrogen liquefaction. • Turn green ammonia competitive price.
Third corner – safety
• Lack of universal standardization.
Fourth corner – utilisation
• Lack of distribution network and pipelines.

Source: Dawood, Anda & Shafiullah, 2020*; GIZ, 2021; IPEA, 2022; IEA, 2019.*

2.2 Context of energy in Brazil

According to the Energy Research Company of Brazil (EPE, 2022), energy matrix is the set of sources used in a country, or in the world, to meet the need (demand) for energy. In other words, it is the portfolio of energy supply available to be used and moves all sectors of a country’s economy.

With the surface area of 8.5 million km², Brazil is the largest country in Latin America and the fifth largest in the world. Thanks to its size, geographical location and natural resources, Brazil has been able to develop a diverse energy matrix that places it in a prominent situation in terms of production and consumption.

In this chapter, the profile of the Brazilian energy matrix will be presented, focusing on renewable sources that make it an attractive country for investments in the production of green hydrogen.

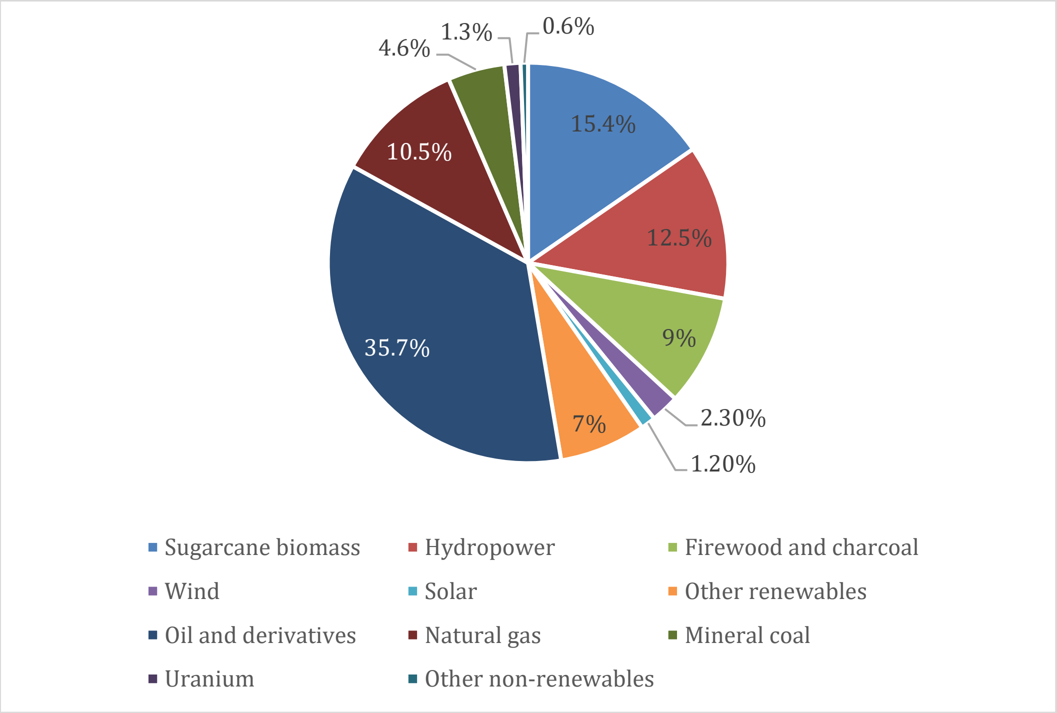
2.3 Brazilian energy matrix

Brazil has diverse energy matrix; this diversity is represented in the figure 4. The energy source can be divided into renewable (47.4%) and non-renewable (52.6%). According to EPE (2023), the renewable energy sources present in Brazil are sugarcane biomass, hydropower, firewood and charcoal, wind, solar and other renewables which are biodiesel, biogas, other biomasses, industrial gas from charcoal and lixivia. The non-renewable energies are oil and derivatives, natural gas, mineral coal, uranium, and other non-renewables.

The more diverse a country's energy matrix the more immune it will be energy to supply disruptions, especially, the one with natural causes. In Brazil, for example, when it does not rain enough to generate energy in the hydroelectric plants, the National Electric Energy Agency (ANEEL) authorizes the use of thermoelectric plants to supply the demand. This measure, however, increased the cost of production since hydroelectric energy is cheaper in Brazil (GIZ, 2021).

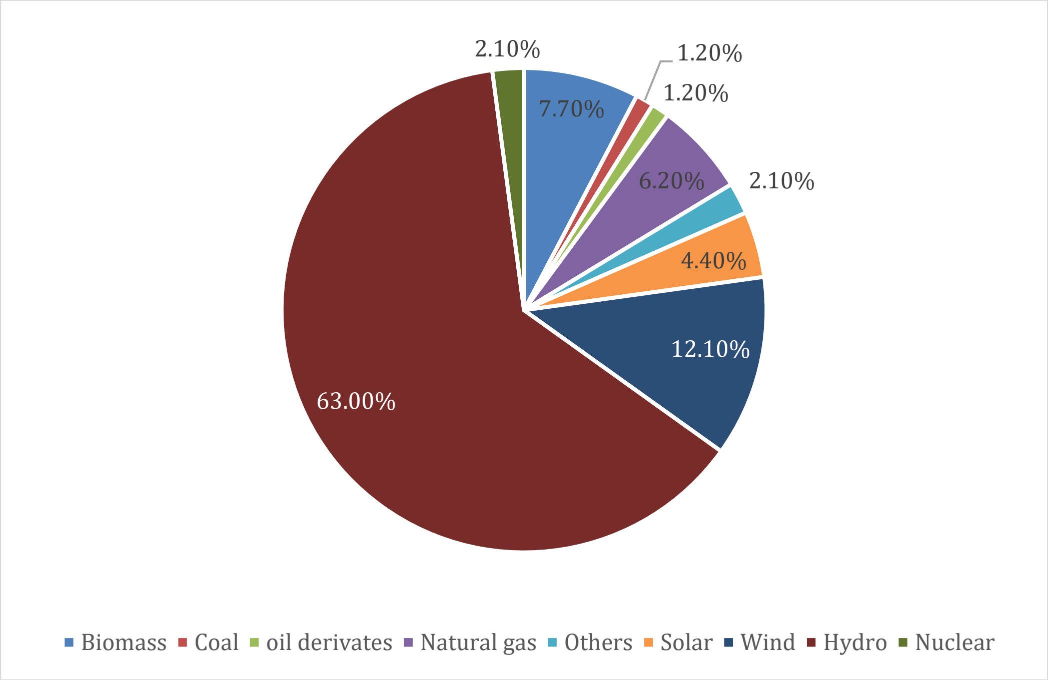
In terms of electricity supply, in 2022, the installed capacity reached 189.1 GW. According to EPE's Statistical Yearbook of Electrical Energy report (2022), the main renewable electricity sources present in the Brazilian are hydropower, wind power, sugarcane, biomass, and solar. Together, the renewable sources have 87.9% of participation in the electricity generation (EPE, 2022). The non-renewable electricity sources in Brazil are coal, petroleum products, and natural gas with 12.1% share (figure 5).

Figure 4 - Percentage of energy domestic offer in Brazil by source (2022)



Source: EPE, 2023.

Figure 5 - Brazilian total electricity installed capacity in by source (2021)



Source: EPE, 2023.

As shown in the graphs, Brazil has great potential for hydrogen production through electrolysis. However, for the expansion of hydroelectric energy production, it reached the production limit due to the non-prioritization of construction of new hydroelectric plants. At the same time, the implementation of photovoltaic plants and wind turbines has increasingly supplied the country's electricity demand, enabling a decrease in the consumption of electricity from non-renewable sources (table 4).

In addition to the natural aspects that favor the production of renewable energy, the increase in this energy source is also due to the institutional structure that has been developed over the last few years that have made renewable energy competitive in Brazil. Chantre et al. (2022) highlight the normative resolution number 482/2012, which made it possible to compensate the electrical surplus produced by small private photovoltaic systems. This strategy caused a considerable increase in the installation of micro and small producers that consume electricity on a stationary basis and the surplus is supplied to the national electrical system, generating extra savings in electricity consumption.

Table 4 - Comparison of electricity generation by source (GWh)

Source	2021	2022	Δ 22/21
Hydropower	362,818	427,114	17.7%
Natural gas	86,957	42,110	-51.6%
Wind	72,286	81,632	12.9%
Biomass	52,416	52,223	-0.4%
Nuclear	14,705	14,559	-0.1%
Coal steam	17,585	7,988	-54.6%
Oil derivates	17,327	7,056	-59.3%
Solar	16,752	30,126	79.8%
Others	15,263	14,364	-5.9%
Total	656,109	677,173	3.2%

Source: EPE, 2023.

The National Program for Incentive to Renewable Electric Sources (PROINFA) in addition to promoting the renewal of the Brazilian energy matrix, it also sought to develop the national industry for the production of components for wind turbines (GIZ, 2021). In addition to the onshore wind power potential of 500GW, which is still not fully utilized, a roadmap for the production of offshore wind energy in Brazil is in the study phase (EPE, 2020). Preliminary studies point to a generation capacity of 700GW in places with a depth of up to 50m in the sea (GIZ, 2021).

Solar energy has the lowest production among renewable sources, however, its growth has had considerable growth year after year. States in the Northeast region have stood out for their high solarimetric index. The increase in supply has generated a drop in the price of solar energy. The GIZ report (2021) points out that in the 2013 auction the average price of photovoltaic solar energy was $103/MWh, while in 2019 the average price offered was $20.3/MWh.

The current production of renewable energies in Brazil and the prospect of an increase in the future, places the country in a prominent position. The countries that traditionally produces renewable energy have great chance of becoming a green hydrogen power producer (IEA, 2019).

3 Theoretical approach for understanding sustainable innovation diffusion.

As it was evidenced in the previous chapter, given the various applications of hydrogen as a low-carbon energy source, hydrogen economy is pointed as an efficient alternative to continue economic growth without jeopardizing the planetary frontier related to climate change. But why then has this energy transition not happened yet? The answer lies in the carbon lock-in and path dependence of fossil fuel technologies that are part of the current socio-technical regime. Theorists have dedicated themselves to understanding how the academy, businessmen, policy makers and society, in a systemic relation, can indicate the trajectory of the necessary energy transitions and sustainable development.

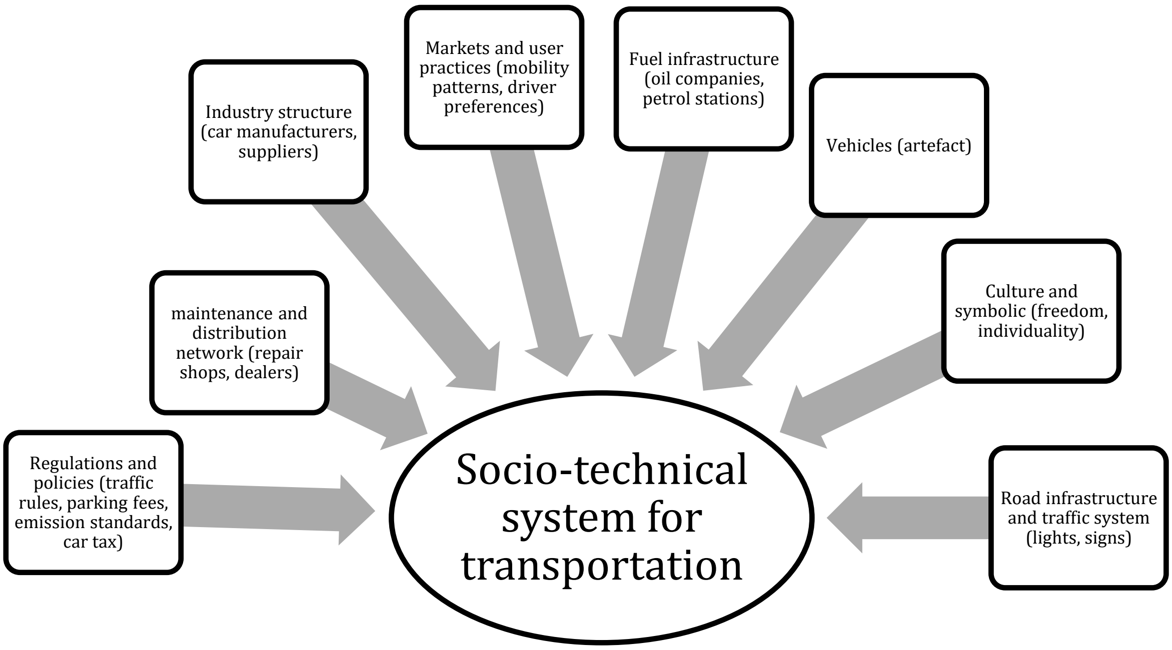
In this chapter, this work seeks to explain the concepts used in the multi-level perspective (MLP) theory and functions of innovation system framework to present the theoretical approach used to analyse the innovation system interaction within Brazilian context.

3.1 Multi-level perspective

Our society is made up on socio-technical systems which is the interaction between people and technology for our daily life activities. Eric Trist (1981) uses the concept of socio-technical system applied for a better understanding of the relationship between British mine workers and their workplace with all the norms and technical structure embedded in the social environment. In the MLP, socio-technical is related to all the parts required perform a societal function (Geels, 2020). In the figure 6, the elements of transportation socio-technical system are exemplified, similarly, other social activities have their own socio-technical system with specific cluster of elements, such as regulations and policies, maintenance and distribution network and so on.

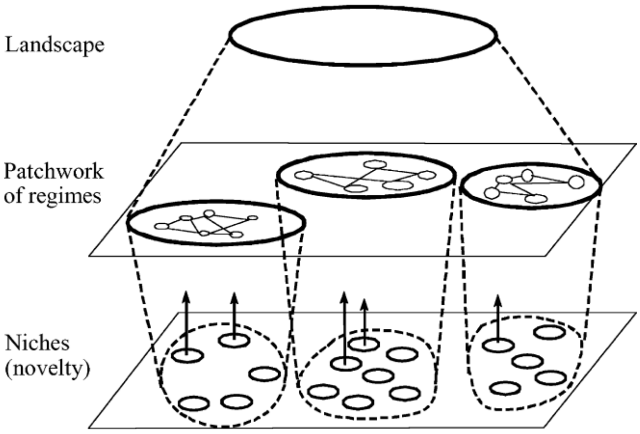
Since the Industrial Revolution, centuries of investments in a production model based on fossil fuels have strengthened the clusters towards to socio-technical systems that created the current the technological carbon lock-in have been responsible for the current socio-environmental issues, for instance global warming, pollution, and health issues. The carbon lock-in is the main challenge in terms of transitioning to green social-technical regime (Chen et al., 2023). Notwithstanding, in the MLP approach, society can switch from a socio-technical regime to another by interaction of three analytical levels: niches, regimes and landscapes (El Bilali, 2019; Geels, 2002, 2010, 2011, 2020).

Figure 6 Socio-technical system for transportation scheme



Source: Geels, 2020.

Figure 7 Multiple levels as a nested hierarchy



Source: Geels (2002)

The niche level is where radical innovations take place, the socio-technical regime is formed by the combination of socio-technical systems, and landscape is the highest structure and tends to be more stable (Figure 7). It is important to note that this categorization in the positioning of the levels does not mean that there is a hierarchy between them, on the contrary, on the contrary, the interaction and influence between the layers happen in a mutual and non-hierarchical way (Geels, 2011). In the following subchapters we will address each level presented by the MLP.

3.1.1 Socio-technical regime

Socio-technical regimes are in the center of MLP analyses (Markard & Truffer, 2008). According to Geels (2011, p. 1260), regimes are the "semi-coherent set of rules carried by different social groups". The regime rules are both the medium and outcome of action, meaning that actors use and create rules through their actions. Examples of regime rules include cognitive routines, shared beliefs, capabilities, lifestyles, user practices, institutional arrangements, regulations, and contracts (Geels, 2011).

At the level of the regimes, technology lock-in is found, which tends to perpetuate itself as a productive model, showing its path dependency and resistance to change (Geels, 2020). In the energy sector, there is carbon lock-in, as the production model is based on fossil fuels, which were widely used since the beginning of the industrial revolution in the 18th century (Sato et al., 2021). Therefore, innovation in existing regimes occurs incrementally, resulting in stable trajectories that encompass technology, culture, politics, science, markets, and industry (Geels, 2002). While, in a smaller level, sub-regimes have their own dynamics, they also interact and co-evolve with each other. The socio-technical regime concept aims to capture the coordination between different sub-regimes and provide additional stability, although it can also lead to tensions (El Bilali, 2019; Geels, 2010, 2011; Markard & Truffer, 2008).

The transition to a hydrogen economy, based on green hydrogen, depends on the diffusion of technology production innovation, which at the moment, not only faces barriers presented by the socio-technical regime of fossil fuel, but also depends on the capability of the actors overcome the challenges presented in the hydrogen economy development corners (figure 1), incrementally moving towards socio-technical system of hydrogen (Conte, 2009; Dawood, Anda & Shafiullah, 2020; Hacking, Pearson & Eames, 2019).

The technological improvements necessary to increase hydrogen availability is linked to the niche (novelty) level of MLP.

3.1.2 Niches

Geels (2011, p., 27) defines niches as "protected spaces" where companies, universities and other research institutes perform R&D activities and discover new technology that can tackle sustainable issues, in order to fulfill a specific market demand. Entrepreneurs act on the niche level producing innovations that can be adopted and complement the current regime or create total disruptive innovation that can even replace the existing regime (Geels, 2010; Hekkert & Negro, 2009). El Bilali (2019) states that transition happen when the novel technology reaches enough level of robustness and maturity able to challenge the *status quo* socio-technical system.

The main object of this work is centered on the niches level. Applying another theoretical framework based on the functions of the innovation system. When the actors in the area perform their function satisfactorily, hydrogen will be able to overcome the barriers to the lack of infrastructure, regulation, and consumer habits.

3.1.3 Landscape

In this work, it is used the following conceptualization the socio-technical landscape is the widest level in which socio-technical transition operates, has an impact on the dynamics of both niche and regime (Rip & Kemp, 1998). Markard & Truffer (2008, p., 606) define the landscape level as the “residual” of innovation influential elements that are not influenced by the outcome of the innovation process on the other levels. El Bilali (2019, p. 10) states that landscape is used as a “garbage can” where theorists fit all the rest they could not fit on the other categories. Typically, the landscape level changes slowly, although there is a debate about whether it can be considered flat or hierarchical (Geels, 2011).

We can cite the Paris agreement as part of the landscape level that influences the development of new technologies to reach the global warming goal and creates an opening in the current regime for the possibility of new technologies. The development of green hydrogen in Brazil has been heavily influenced by elements of geopolitics beyond climate change, for example (Biogradlija, 2022; BMWK, 2023). The government of Germany has actively participated in international agreements and international technical cooperation between different countries (Biogradlija, 2022). This strategy of German international relations was intensified after Russia's invasion of Ukraine, which led countries in the global north to impose sanctions against Russia, having a direct impact on Germany's energy supply, which depended on Russian gas supplies (BMWK, 2023).

3.2 Functions of the Innovation System

According to Hekkert et al. (2007, p. 415), Innovation System (IS) is defined as “all institutions and economic structures that affect both on rate and direction of technological change in society”. This concept is consequence of the combination of evolutionary and institutional theories and its main prerogative is that innovation and diffusion does not happen only because the individual, but it is also an outcome of the collective acts (Hekkert et al., 2007; Nelson & Nelson, 2002). In other words, the technological changes, innovation diffusion and, consequently, socio-technical regime transition are not determined only by the potential that certain innovation have to solve specific environmental problem. With that said, the fact that hydrogen has more energy than diesel and gas (table 1) have not been sufficient to guarantee its production in large scale nor the replacement of fossil fuels. In this sense, to understand the trajectory, success and/or failures of certain innovation become part of the mainstream, also called socio-technical regime, or not, scholars should look at the system in which the innovation is embedded.

In different studies, scholars have dedicated themselves to apply a set of innovation functions, by which compose the framework of functions of innovation system. By focusing on the fulfillment of specific functions, the framework provides a better understanding of the dynamics within the IS (Hekkert et al., 2007; Hekkert & Negro, 2009; Negro, Alkemade & Hekkert, 2012; Negro, Hekkert & Smits, 2007). The suggested set are of functions are (1) *entrepreneurial activity*, (2) *knowledge development*, (3) *knowledge diffusion through network*, (4) *guidance of the search*, (5) *market formation*, (6) *resource mobilisation*, and (7) *creation of legitimacy/counteract resistance to change* (Hekkert et al., 2007; Hekkert & Negro, 2009; Markard & Truffer, 2008; Negro, Alkemade & Hekkert, 2012; Negro, Hekkert & Smits, 2007).

3.2.1 Function 1: entrepreneurial activity

Entrepreneurial activity is considered the most important function of the innovation system (Hekkert & Negro, 2009). Indeed, without entrepreneurs willing to take the risks, little or no innovation could ascend and spread. This is why little individual innovation took place within the Union of Soviet Socialist Republics regime (Bulaj, 2022).

In order to perform entrepreneurial activities, investors consider the potential of profit generation. It is true, though, that many companies are currently willing transition to a greener business model, but it is less likely they are going to do that if there is no incentive to innovate. Carlsson and Stankiewicz (1991, p. 105) said that “there must be not only an embryo (core) but also a fertile environment” for entrepreneurial activity rise. In this case, institutions can set a new “rules of the game” to propel sustainable innovation (North, 1991, p. 98). With that said, the amount of new entrant companies in a market can be a way to analyse the IS environment. Studies on innovation should focus on entrepreneurial activity as a consequence of the infrastructure for entrepreneurship at the macro-industrial level (Van De Ven, 1993). Consequently, when a marked delay in the development of business activities is noticed, the reasons can be found in other functions (Hekkert et al., 2007).

The evolution of this function can be analysed by quantifying the number of new entrants (Hekkert & Negro, 2009). New entrants can be companies that already develop a certain economic activity and decide to expand their business by investing in other areas, or completely new companies that are created specifically due to the glimpse of a business opportunity (Hekkert et al., 2007; Negro, Hekkert & Smits, 2007).

3.2.2 Function 2: knowledge development

Knowledge development function is characterized by the learning process. In fact, information and knowledge are crucial elements for innovation and development (Lundvall, 2007). Knowledge within the economy is mainly generated through R&D projects that take place within companies, research laboratories and/or academia (learning by searching) (Negro, Hekkert & Smits, 2007). Companies can also generate knowledge through trial and error (learning by doing).

This function can be mapped through the quantification of R&D projects, patents, and R&D investments (Hekkert et al., 2007; Hekkert & Negro, 2009).

3.2.3 Function 3: knowledge diffusion through networks

Carlsson and Stankiewicz (1991) argue that information exchange is a crucial feature of the innovation system. For Belmonte and Scandelari (2005), networks aim to promote and preserve cooperation among companies, businesses and R&D organizations to obtain access to ideas, share skills, resources, information and expertise.

Knowledge diffusion through networks it requires not only engagement between R&D in the cluster but promotes the strengthening of the sector in search of overcoming common problems, for which the relationship goes beyond the productive cluster and reaches government sectors, competitors, and the market itself (Hekkert & Negro, 2009). Networks enable policymakers to make decisions based on the most up-to-date technological insights and information, and the exchange of information can lead to alterations in R&D agendas influenced by changing norms and values (learn by interacting and learning by using) (Carlsson & Stankiewicz, 1991).

To determine the degree of knowledge exchange within the digestion network, the number of events such as workshops, conferences, and symposia dedicated to technology should be mapped out (Hekkert et al., 2007; Negro, Hekkert & Smits, 2007).

3.2.4 Function 4: guidance of the search

Due to the limited nature of the resources, companies arrange budgets to invest in R&D projects. They g*uidance of search* is related to the guidance function involves activities that enhance the clarity and visibility of particular needs among technology users (Hekkert & Negro, 2009). In the government, policy makers can set specific goals of certain innovation consumption, green hydrogen production for instance. The perspective of attending the future demand for this renewable energy source, can determine the allocation of resources for the development of more efficient ways for its production (Negro, Hekkert & Smits, 2007). However, not only governments can fulfill this function, in fact industry and market can indicate whether there is or not a profitable investment strategy.

Negro, Hekkert & Smits, (2007) point two ways to measure the fulfillment of this function. The first is based on the analysis of specific targets stablished by stakeholders for using a technology, the second method consists in analysing the debate about the innovation. The number of articles that bring positive impacts can propel development investments, at the same time, negative papers can impede the new technology development (Hekkert et al., 2007).

3.2.5 Function 5: market formation

In many cases, new technologies, especially sustainable ones, face difficulties in competing with established ones, compromising the *market formation* and suppressing the demand for renewable solutions and perpetuating the carbon lock-in (Chen et al., 2023). As result, it is crucial that new technologies take advantage of policies that can enhance its use and diffusion along the market. One example is the tax rebates and purchase subsidies implemented by Norway government to increase the market for electric vehicles (European Commission, 2023).

Hekkert et al., (2007) suggested that a way to analyze this function is by mapping out specific tax regimes for new technologies, or other political strategies that focus on improving the new technology chances to diffuse.

3.2.6 Function 6: resources mobilisation

Without financial and human capital, the activities within the innovation are unfeasible, consequently, adequate resource allocation is crucial for knowledge production in a specific technology (Hekkert & Negro, 2009).

Measuring the fulfillment of this function over time using specific indicators is challenging, states Hekkert et al (2007). Instead, the best way to assess whether this function is being fulfilled is through interviews with inner core actors to determine if they perceive a lack of access to sufficient resources as a problem (Hekkert et al., 2007).

3.2.7 Function 7: creation of legitimacy/counteract resistance to change

The fulfillment of other functions does not guarantee the immediate socio-technical regime replacement. One can still expect that the mainstream regime will react and gather strategies to persist (Hekkert et al., 2007).

The *creation of legitimacy* is also as part of lobby activities that pressure governments for policies to support industry with new technology development either with *resource mobilisation*, taxes subsidies or purchase quotas as *market formation*, and *guidance of search* (Hekkert & Negro, 2009; Suurs, Hekkert & Smits, 2009). However, the niche technology actors can make pressure asking for support and the regime technology can also reunite political power to maintain its influence, creating and strengthening its resistance to change – *counteract resistance to change* (Geels, 2002; Hekkert et al., 2007).

Negro, Hekkert and Smits (2007, p. 928) suggest, as a measurement method, map out the “statement in the literature separated by interest groups”.

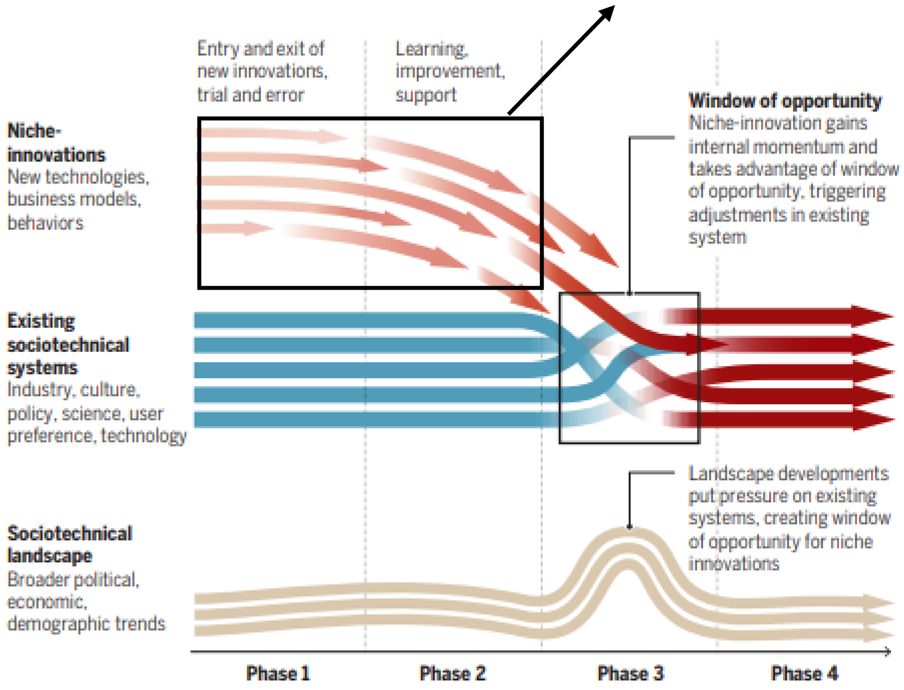
3.3 This research placement in the theoretical framework

This framework was chosen to analyse the green hydrogen IS in Brazil, due the fact it can show the IS formation focusing on the social dynamics of actor’s interaction by mutual influence within the system (Negro, Hekkert & Smits, 2007). In fact, innovation does not happen just by the introducing new technology, more than that, innovation is the result of the ability to create a new (Hekkert, 2020).

The figure 8 shows the positioning of this analysis. On the niche-innovations layer of the MLP, sustainable technology is represented in lighter-red arrows, in this case, green hydrogen production technologies. In the phases I and II, in the rectangle area, lies the object of this thesis. The constant improvement and fulfillment of the functions in virtuous loops, combined with the pressure created by the landscape on the existing social-technical regime, creates a window of opportunity where the hydrogen can become part of the energy regime (Hekkert, 2020; Negro, Hekkert & Smits, 2007).

Figure 8 Research placement in the MLP

Area where the seven innovation system functions take place and object of this analysis.



Source: adapted from Geels et al., 2017 and Hekkert, 2020.

In any case, interactions can be classified as positive or negative (Suurs, Hekkert & Smits, 2009). We have a positive interaction when it reinforces a virtuous circle that leads to the diffusion of new technology. On the opposite side, negative fulfillments of innovation function can lead to a vicious circle that slows down innovative diffusion (Suurs, Hekkert & Smits, 2009).

4 Approach and data

4.1 Approach

According to Hekkert et al. (2007, p. 427), the change in a technology is reached "when the functions interact and lead to a virtuous cycles". So, the relations, integration and fulfilment of the functions are important to understand the systemic evolution of different innovation system. Over the past 20 years, government and private entities, banks, cooperation agencies and ministries have released technical studies and reports on hydrogen development in Brazil, however, these documents fail to provide a systemic analysis. With that said, in order to answer the research question *How has the hydrogen innovation system evolved in Brazil in the last two decades?* This study applies an approach extensively used to analyse the fulfillment of innovation system functions related to sustainable energy transitions, such as, the biomass failure of biomass in the Netherlands (Negro, Alkemade & Hekkert, 2012). Similarly, this research is a descriptive study which covers qualitative and quantitative aspects of the systemic function's interactions.

4.1.1 Historical event analysis

5.1.1.1 Minnesota Innovation Research Programme's approach (MIRP)

When analysing innovation at the firm level, MIRP developed the sequence analysis approach. In 1983, its researchers engaged in longitudinal field studies of different innovations in public and private sectors (Van de Ven & Poole, 1990). They started off by collecting historical data in 1984. This core data was repeatedly measured to capture its evolution.

For a better understanding of MIRP's methodology, it is necessary to understand the concepts of *incident* and *event*. The former is the occurrence as it is, simply, a qualitative indicator of the occurrence with no theorization, and the latter is "a theoretical construct" (Van de Ven & Poole, 1990, p. 319). For instance, if a given company fail the application for funds for its R&D department, it can have influence on the project development and layoff of innovation staff. The application failure is the incident and the theorization of the resource cut, personnel layoff, and any other consequences, are the events. The events can have positive, negative or mixed impact to the innovation process, according to their classification the MIRP's researchers coded each event into Bit Maps for Time Series Analysis (Van de Ven & Poole, 1990).

5.1.1.2 Utrecht University's approach adaptation

Scholars from the Copernicus Institute for Sustainable Development and Innovation have dedicated themselves to apply MIRP's method evaluate the evolution of each Function of Innovation System, however they call it *process analysis* or *historical event analysis* (Hekkert et al., 2007; Hekkert & Negro, 2009; Negro, Alkemade & Hekkert, 2012; Negro, Hekkert & Smits, 2007). They

As the Minnesota scholars were more focused on the micro-level, the Utrecht University's researchers apply this approach to the system level. Unlike the application at the firm level, the system analysis implies a broader view of the research scope (Hekkert et al., 2007). Instead of conducting interviews, observing meetings between employees of the researche company, data collection at the systemic level takes place through newspaper archives and professional journals (Hekkert et al., 2007).

5.1.1.3 Approach application in this research

The application of this approach in this study consists of mapping out as many historical facts as possible related to green hydrogen technology development in Brazilian innovation system of hydrogen. Firstly, these facts are extracted from professional journals, newspapers, sectorial reports, news websites, government web pages, and government technical studies. Secondly, the relevant events are stored in a database, classified, and placed within a specific system function area. This method is intended to track functional patterns and the results presented as a coherent sequence of facts and systemic trends that can explain the interaction between functions over time (Negro, Hekkert & Smits, 2007). Each event is assigned a value with the same weight. However, some events might have a negative consequence on the fulfillment of a specific system function, in this case, these events are assigned a negative score (Negro, Hekkert & Smits, 2007). The table 4 shows which indicators were reported within each function and the value assigned to each of them.

As a result, the event description is displayed as storyline corroborated by quantitative indicators showing how the function changed over time. In this research, it will be focused the connections and drivers that has origin in one function and leads to another, or several others (Hekkert et al, 2007). The collected data is demonstrated in graphs to indicate the trajectory of the function fulfillment. The positive line represents the total amount of positive events within that year in that function, and the negative line represents events that contributed negatively for that function fulfillment. However, the graphs are used to illustrate the development of a function in the period and cannot be taken as the absolute result of how the actors performed their function (Negro, Hekkert & Smits, 2007).

Table 5 Indicators for measuring system functions

Function	Indicator	Sign/Value
Function 1: entrepeneurial activities	signed/project announced or started. withdrawal/project stopped	+1 -1
Function 2: knowledge development	Patents applications	+1
Function 3: knowledge diffusion	Workshops, conferences, webinars	+1
Function 4: guidance of the search	Positive expectations on Green H2 Regulations by government Negative expectations on Green H2 Expressed deficit of regulation	+1 -1
Function 5: market formation	Specific favorable tax regimes and environmental standards Expressed lack of favorable tax regimes or favorable environmental standards	+1 - 1
Function 6: resources mobilisation	Subsidies, investments Expressed lack of subsidies, investments	+1 -1
Function 7: Creation of legitimacy	Support by government, industry Expressed lack of support by government, industry	+1 -1

Source: Negro, Hekkert & Smits, 2007.

4.2 Data source and treatment

This study uses qualitative data collected from two main reliable reports, complemented with data retrieved from government official sources, associations, and institutions. The first association is The Overview of Hydrogen in Brazil report which was released in 2022 by the Brazilian Institute of Applied Economics Research (IPEA). IPEA’s focus is to identify investments and the main sustainable hydrogen production areas in the country (IPEA, 2022). The other secondary source is the report Map of the Brazilian Hydrogen Sector released in 2021, from the *Deutsche Gesellschaft für Internationale Zusammenarbeit* which is the German international cooperation agency (GIZ). This study maps some actors of hydrogen IS, industry, academia, and institutions (GIZ, 2021). Both reports are important and rich in relevant information, however, they fail in presenting the dynamics of interactions along time. This is why both reports are used as starting point for data collection and the gaps in data and improvements were fulfilled according to the considerations below.

- *Function 1-entrepreneurial activity*: IPEA's report (2022) presents three main states that have attracted investments in projects for production of green hydrogen, they are Pecém port in Ceará state, Suape port in Pernambuco state and Açu port in Rio de Janeiro. Due the lack of data base of all entrants' companies in the hydrogen production business in the past twenty years, to measure the performance of entrepreneurial activity, this work considers, as well, the announcement of investment, in the three states mentioned before, disclosed in news channels or news portals of the respective state governments.
- *Function 2 - knowledge development*: Negro, Hekkert and Smits (2007) suggest that this function can be measured by the number of R&D projects, amounts invested in R&D and registered patents. Although the cited reports bring information about R&D in the hydrogen industry, they do not offer a comprehensive view, bringing only mentions of the biggest projects. Therefore, to corroborate the analysis of this function, this study investigates the data base of patents deposited in the Brazilian National Institute of Industrial Property (INPI) of technologies related to green hydrogen production (INPI, 2023). INPI could not provide data for the whole period investigated, but it consolidates data from the whole country providing a whole systemic understanding.
- *Function 3 - knowledge diffusion through networks*: To quantify the events, workshop, and webinars, firstly, searches were carried out on search engines separated by year using the key words *"hidrogênio verde workshop no Brasil"*, *"hidrogênio verde eventos no Brasil"* and *"hidrogênio verde webinars no Brasil"*, however, the method did not show results. In this way, to map the events was used information about 1. events organized by the Brazilian hydrogen association (ABH$_2$) and 2. events promoted by the Brazil Green Hydrogen initiative.
- *Function 4 – guidance of the search*: further search was made in technical studies issued by the Ministry of Mines and Energy, Ministry of Science, Technology, and Innovation, and National Electricity Agency.
- *Function 6 – resource mobilisation:* in addition to searching on government websites and on the reports, a search was carried out on the websites of *Banco do Brasil*, *Banco do Nordeste*, and *Banco Nacional de Desenvolvimento Econômico e Social*.

Function 7 – creation of legitimacy: to investigate the existence of help and support from the Brazilian government to the development of the hydrogen economy, searches were carried out on websites of the National Congress in order to find bills of law to support this industry.

Furthermore, the data presented in the results of these reports do not mention the specific date when the event took place, so, to understand the evolution through time, the database was completed with the dates presented on news websites or/and government websites. Articles and scientific publications are also source of data for this thesis. They were collected from reports references, search on the internet and on institutional pages and other sectorial information channel.

5 Events description and system function development

In this chapter, the result of the research is presented in a description chronological sequence, and it is divided into sections. The first one describes governmental and institutions actions to promote hydrogen IS and the second section presents the fulfillment evolution of the seven functions.

5.1 Twenty years of hydrogen development in Brazil

5.1.1 Brazilian fuel cell program: attempt to organize research

In 2001, the Ministry of Science and Technology of Brazil hired the international consultant Doctor Helena Li Chum, from the National Renewable Energy Laboratory in the United States. The main purpose was to identify the Brazilian potential and ongoing actions related to R&D in fuel cells and hydrogen Technologies (de Matos & Junior, 2009; CGEE, 2002). The main result of Doctor Chum's diagnosis was the foundations to create, in 2002, the Brazilian Fuel Cell Program, also called Procac (de Matos & Junior, 2009).

In the document, the CGEE (2002) listed the main initiatives happening in the country since the end of the 1990's. Back then, (1) funding agencies such as MCT/FINEP, CNPq, FAPESP, and others responded to the interests expressed by researchers and leaders within these organizations providing incentives to R&D projects in fuel cell field; (2) the existence of interest of energy companies, associated institutions, and ANEEL in evaluating the role of hydrogen or other alternative fuels in the country's energy mix; (3) the Brazilian state oil company, Petrobras, and the National Agency of Gas and Petroleum had the interest to increase the use of natural gas in producing hydrogen; (4) the CT-PETRO and CT-ENERG are RD&I federal sectoral funds had projects fund by them; (5) financial support provided to small companies through FAPESP's PIPE program; (6) FAPESP's investments in electrochemistry and fuel cell research in the state of São Paulo, and similar initiatives in other states, focusing on catalysis; (7) establishment of university incubators for start-up companies; (8) previous funding allocated to centers of excellence in heterogeneous catalysis, natural oil and gas, established by Petrobras through CENPES; (9) previous investments in material analysis centers; (10) investments in demonstration projects using internal resources from COPEL, Petrobras, CEMIG, AES of Brazil. Even though all those initiatives were identified by Chum's research group until 2001, those were not coordinated movements due the lack of centralized policy or strategy (CGEE, 2002).

In 2002, the Brazilian Ministry of Science and Technology, for the first time, created the Fuel Cell Programme (Procac). Its objectives were promoting integrated and cooperative actions to make the national development of technologies related to hydrogen and fuel cell systems feasible (GIZ, 2021). The Program was structured in five research and development networks: proton exchange membrane fuel cell network; solid oxide fuel cell network; fuel and hydrogen network; integration network and systems, and user network (de Matos & Junior, 2009; CGEE, 2002). The purpose of implementing the networks was to coordinate R&D efforts and avoid resource dispersion. The programme also focused on training human capital with postgraduate programmes in Brazilian universities (CGEE, 2002). Between 2002 and 2004 very little was made, mostly due the party transition that switched to the center left-wing after 12 years of center right-wing administration in the presidency (de Matos & Junior, 2009).

In 2003, the member countries of the International Energy Agency (IEA) met to discuss the formation of an international group to develop Research and Development (R&D) programs and strategic policies in hydrogen technologies (de Matos & Junior, 2009). At the end of the meeting, the International Partnership for Hydrogen Economy (Iphe) was created (Andrade & Lorenzi, 2015). The organization currently has 24 members, including Brazil (IPHE, 2023). Its main goal is to stimulate public and private policies and research for the development of technologies related to the energy use of hydrogen and the hydrogen economy, as well as their regulations (Andrade & Lorenzi, 2015).

6.1.2 Hydrogen R&D persistence

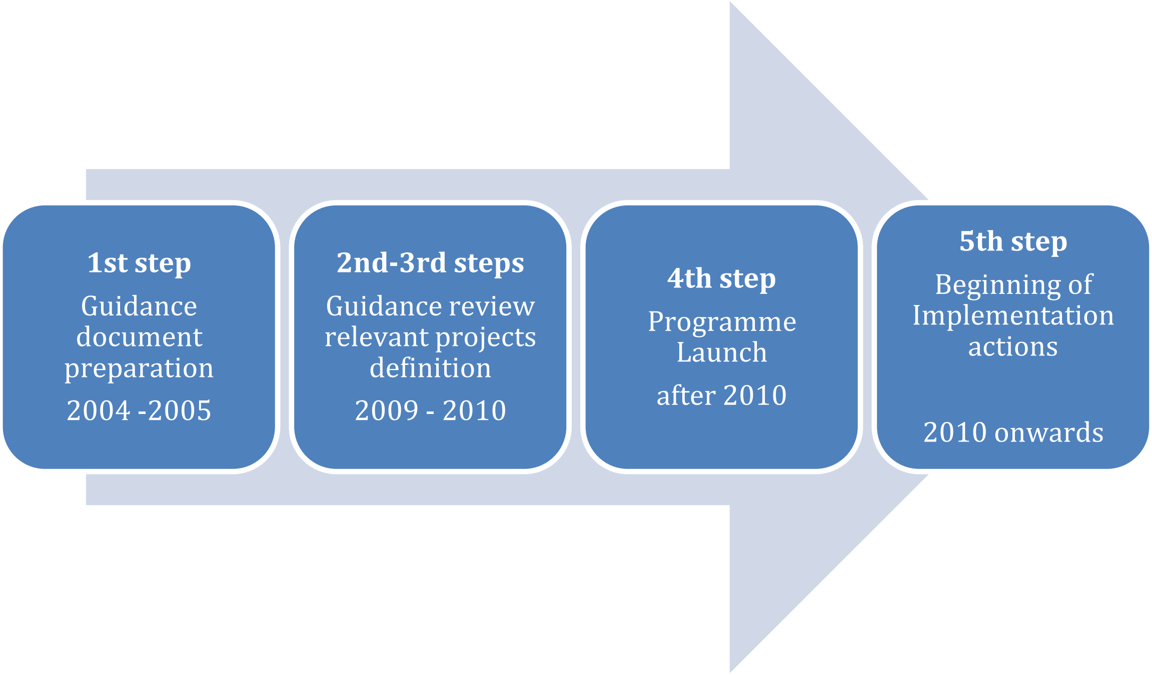
In fact, Brazil is at the forefront of research in hydrogen technology in South America (Raffi, Massuquetti & Alves, 2013). During the period from 1999 to 2007, Brazilian investments in fuel cell, originated from private and public sectors, totaled about $46 million (Raffi, Massuquetti & Alves, 2013). However, when compared to other developing countries investments, this amount represents 25% to 35% of the investments in Russia, India, China, or South Korea in the same sector. And it is equivalent to 3% to 5% of the investments in Japan, the European Union, or the United States (CGEE, 2010). Although research into this technology had increased considerably, the funds allocated by the federal government were relatively low compared to other countries (Raffi, Massuquetti & Alves, 2013).

Even though, in the first years the Procac showed ineffective in directing research in hydrogen, state research promotion institutes carried out their own projects. For instance, in São Paulo, the state power company invested $350,000 to develop its own fuel cell in 2003 (FAPESP, 2004). The project was executed by the company Eletrocell which was responsible for developing and assembling the prototype using sectoral fund from CT-ENERG (FAPESP, 2004).

6.1.3 Procac's new name and another delay

Later in 2005, the Procac was renamed to Science, Technology and Innovation Programme for the Hydrogen Economy or simply ProH_2. This time, the programme integrated the roadmap for structuring the hydrogen economy in Brazil of the Ministry of Mines and Energy (GIZ, 2021). The roadmap introduced the guidelines to the hydrogen economy transitions, focusing on "1) diversification of the Brazilian energy matrix with a growing share of renewable fuels; 2) reduction of environmental impacts, mainly those arising from atmospheric pollution in large urban centers; 3) reduction of external dependence on fossil fuels; 4) hydrogen production from natural gas, in the next ten years; 5) Production of hydrogen from renewable energy sources, with emphasis on the use of ethanol; 6) Development of a technological base to provide reliability to consumers, and; 7) Planning the participation of the national goods and services industry in the development of the new economy" (CGEE, 2010, p. 15-16).

Figure 9 Hydrogen Economy steps in Brazil



Source: EPE, 2021, p. 20.

In terms of RD&I, the ProH_2 suggested the following goals:

- the creation and maintenance of a collaborative research, development, and innovation which include universities, research institutes, research centers, incubators, and companies (CGEE, 2010).
- Support for the modernization and improvement of the research infrastructure of the institutions enrolled in the programme (Raffi, Massuquetti & Alves, 2013; CGEE, 2010).

- Encourage the training and qualification of human resources, with emphasis on postgraduate programmes in Brazil and improvement in centers of excellence in the country and abroad (CGEE, 2010).
- Implement demonstration projects involving various fuel cell systems and hydrogen production technologies, with priority given to technologies developed by ProH2 (CGEE, 2010).
- Integrate projects to implement the use of domestic renewable fuels, especially the reform of ethanol (CGEE, 2010).
- Promote the establishment of norms and standards for the certification of products, processes and services related to hydrogen and fuel cell technologies (CGEE, 2010).
- Finally, generate and share information on research groups, infrastructure, projects, and companies involved in hydrogen technologies in Brazil (CGEE, 2010).

Despite the ambitious goals of producing and using hydrogen by 2010, in 2006, Petrobras found the deep-water oil reservoir (pre-salt), this discovery delayed the programme launching (Chantre et al., 2022).

6.1.4 Subsidies for competitiveness policies and a unique result

In 2010, CGEE and the Ministry of Science, Technology and Innovation launched the document Energy Hydrogen in Brazil: Subsidies for competitiveness policies – 2010-2015 (EPE, 2021). This document seeks to complement the public policies initiated in 2005, providing support for the definition of concrete actions for academia, governments, and industry to overcome specific bottlenecks identified within four recommendation groups: 1) general recommendations for encouraging hydrogen economy; 2) recommendations for encouraging hydrogen production; 3) recommendations for encouraging the development of hydrogen logistics; and 4) recommendations for encouraging systems using hydrogen (CGEE, 2010; GIZ, 2021; EPE, 2021). The document also determines the roadmap indicating the priority by which different government institutions need to put effort in executing it within short-term (0 to 5 years), mid-term (5 to 10 years) and long-term (10 to 15 years) (CGEE, 2010).

The Global Environment Facilities (GEF), in 2000, chose Brazil and China to implement the hydrogen fuel cell bus project (GIZ, 2021). The objective was not only to provide sustainable public transport, but also to develop the national industry from the initial phases of the project (GEF, 2000; GIZ, 2021). With partnership of the Federal University of Rio de Janeiro, in 2012 the project delivered the prototype of hydrogen propelled buses and generated the know- how to the following Brazilian companies: Marcopolo (bus manufacturer), Petrobras (state oil company), *Tuttotrasporti* (Rio Grande do Sul state transport company) and AES Eletropaulo (São Paulo state's energy distributer) (GIZ, 2021).

In 2012, the test phase of the hydrogen bus began in Rio de Janeiro. Brazil was chosen, along with China, Mexico, Egypt and India, in the year 2000 by the Global Environment Facility to receive support to carry out the development project of the hydrogen bus. To carry out the project, a partnership was created with companies from Brazil, the United States, Canada and Germany (GIZ, 2012).

Another guide for RD&I was released by the same entity in 2017. Using a specific methodology, the Strategic Agenda for ST&I in the Brazilian electricity sector sought to meet Aneel's need to establish proposals for actions that could contribute to the R&D program regulated by Aneel and ensure effective allocation of resources guaranteed by law (CGEE, 2017). Also in 2007, the Brazilian Hydrogen Association (ABH2) was created. Its objective is to promote the chain of production, conditioning, storage, distribution, and use of hydrogen for energy purposes in Brazil (ABH2, 2023). The association acts through the representation of the industry's interest before public bodies; elaboration of codes and norms; event promotion; incentive to CT&I research; promotion of national and international cooperation; finally, the production and dissemination of new knowledge and innovations related to hydrogen (ABH2, 2023).

In 2018, the Science, Technology and Innovation Plan for Renewable and biofuels between 2018-2022 highlighted that their goal is not only to guarantee energy security in Brazil, but also consider the goal of reducing greenhouse gases in the country (GIZ, 2021). Once again, hydrogen production is seen as an alternative technology for the renewable energy sector (Brazil, 2018). The Plan presents recommendations for promoting research, technological development, and innovation in hydrogen production chains, strengthening competitiveness, and increasing the diversification of the energy matrix in a safe and efficient manner (Brazil, 2018). In this sense, the plan recommends the use of hydrogen mainly for vehicular and stationary use for energy generation and for fuel production (GIZ, 2021; Brazil, 2018).

In 2020, the Brazilian government returned its attention to hydrogen, including it in the "Disruptive Technologies" chapter of the 2050 National Energy Plan which mentions the government's intention to create a specific action plan on the subject (EPE, 2020).

In August 2020, the Brazil-Germany Chamber of Commerce, in São Paulo and Rio de Janeiro, created the Brazil-Germany Alliance for Green Hydrogen to promote partnerships and business opportunities between Brazilian and German companies and institutions (Aliança Brasil-Alemanha, 2021). The alliance created and supports an information web portal that aims to encourage the exchange of information and strategic cooperation, through networking, a business opportunity aimed at making Brazil a strategic partner for exporting green hydrogen to the European country in the near future (Aliança Brasil-Alemanha, 2021).

The National Energy Policy Board (NEPB) has the Minister of Mines and Energy as chairperson, it is an advisory body to the President of the Republic of Brazil for the formulation of energy policies and guidelines (GIZ, 2021). In 2021, the board approved two resolutions related that directly impacted the RD&I in the energy sector including the hydrogen sector (GIZ, 2021). The Resolution n. 2, of February 10, 2021, establishes the prioritization of resources and funds for research on hydrogen, nuclear energy, biofuel, energy storage, technologies for sustainable thermoelectric generation, digital transformation, and strategic minerals for the energy sector (IPEA, 2022). The NEPB’s Resolution n. 6, of April 20, 2021, determined the study to propose guidelines for a new hydrogen programme (IPEA, 2022).

In July 2021, the Brazilian federal government released the National Hydrogen Programme (PNH$_2$). The PNH$_2$ stresses the significance of acknowledging and prioritizing the nation's energy resources' potential in obtaining hydrogen, regardless of whether they are renewable or not, and its varied applications across sectors like transport, energy, steel, and mining (Brazil, 2021).

Table 6 Summary of Innovation System of Hydrogen events in Brazil

YEAR	**EVENT**	**PROPOSING INSTITUTION**
2002	Creation of PROCAC/ProH$_2$ support R&D and creation technical regulation for a hydrogen economy.	Ministry of Science, Technology, and Innovation
2003	Brazil integrates the International Partnership for the Hydrogen Economy.	Ministry of Mines and Energy
2005	Roadmap for structuring the hydrogen economy in Brazil.	Ministry of Mines and Energy
2010	Energy hydrogen in Brazil - subsidies for competitiveness policies: 2010-2025.	Ministry of Science and Technology
2012	Prototype of the first hydrogen propelled bus.	Federal University of Rio de Janeiro
2017	ST&I strategic agenda in the Brazilian electricity sector.	Electric Energy National Agency
2017	Brazilian Hydrogen Association (ABH2) creation.	Companies and academia
2018	Science, technology, and innovation plan for Renewable and biofuels between 2018-2022.	Ministry of Science, Technology, and Innovation
2020	National Energy Plan 2050.	Ministry of Mines and Energy
2020	Brazil-Germany Alliance for Green Hydrogen	Chamber of Commerce Brazil-Germany
2021	Hydrogen National Program.	Ministry of Mines and Energy

Source: CGEE (2010) and GIZ (2021)

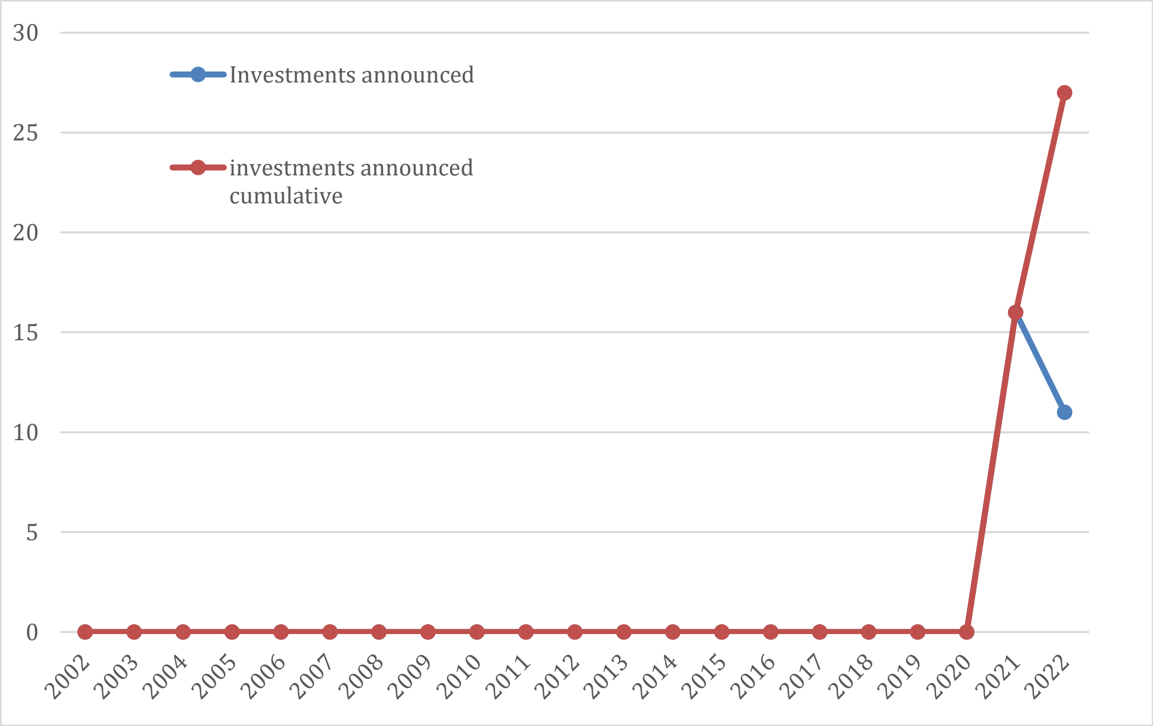
5.2 Innovation systems functions fulfillment

This section is more focused on answering the question "how the functions of the green hydrogen innovation system have been fulfilled in Brazil?" observing the seven innovation functions fulfillment suggested by Utrecht University's scholars.

6.2.1 Function 1 – Entrepreneurial activity in the green hydrogen field

The data show that due to little political articulation and failures to implement the hydrogen development strategies in Brazil, between 2002 and 2020 there was no entry of companies in the green hydrogen market (figure 10). The first entrepreneurial activities were announced in 2021 and 2022, when state governments signed pre-contracts with companies that envision Brazil's potential to become a strong player in the green hydrogen sector (Appendix C). The explosion of investments announced in Brazil, therefore, can be explained by two reasons, one is the sociotechnical landscape and the other is the development of RE production in Brazil.

Figure 10 Function 1 - Entrepreneurial activities



Source: IPEA, 2022

The MLP can explain why, despite uncoordinated actions, Brazil managed to trigger the interest several companies that expressed their will to producing hydrogen in the Latin American country. The s*ociotechnical landscape* pressures European governments and companies to meet the goals of Paris Agreement to find ways to cut off CO2 emissions and continue developing their economies. The invasion of Ukraine by Russia in 2022, the embargoes on the Kremlin also accelerated the search for sustainable energy solutions this is also part of the landscape level. Brazil is an attractive candidate due to its history of renewable energy production and with great room for growth in wind and solar energy production. The expansion RE production will make the green hydrogen produced in Brazil competitive. According consulting company (McKinsey, 2021), the levelized cost of Brazilian green hydrogen (LCOH) would be around ~1.50 USD/kg of H2 in 2030, which is in line with the best locations in the US, Australia, Spain and Saudi Arabia, and ~1 .25 USD/kg of H2 in 2040. The combination of these two scenarios led 14 foreign companies to announce investments to produce green hydrogen in Brazil.

Another explanation for the growth of business activities resides in other levels of public administration in the Brazilian state. The Brazilian Federative Pact allows state governments creating their own independent economic development policies with or without the support of the federal government. The governments of Pernambuco, Ceará and Rio de Janeiro states, for example, have adopted policies to attract investments to the green hydrogen sector, granting tax incentives and benefits to companies to set up production plants in port areas whose hydrogen production focuses mainly on export.

There are three main hydrogen production hubs, two of them are in the Northeast region of the country, the other hub is in the Southeast region, in Rio de Janeiro state (IPEA, 2022). These hubs are strategically located in regions close to areas of wind and solar energy production, export logistics, proximity to industrial centers and have received the highest number of international and domestic investments (IPEA, 2022). As an example, the main hydrogen hub is in the Special trade zone of the Pecém Port in Ceará state which, in addition to guaranteeing a special tax regime, has a connection to the port of Rotterdam and availability of renewable energy (IPEA, 2022).

It is important to mention that even though companies such as Linde, Air Liquide, Air Products, Messer, and Petrobras operate in hydrogen production before 2021, none of them produce green hydrogen for commercial purposes, which is why they were not considered in these results (GIZ, 2021).

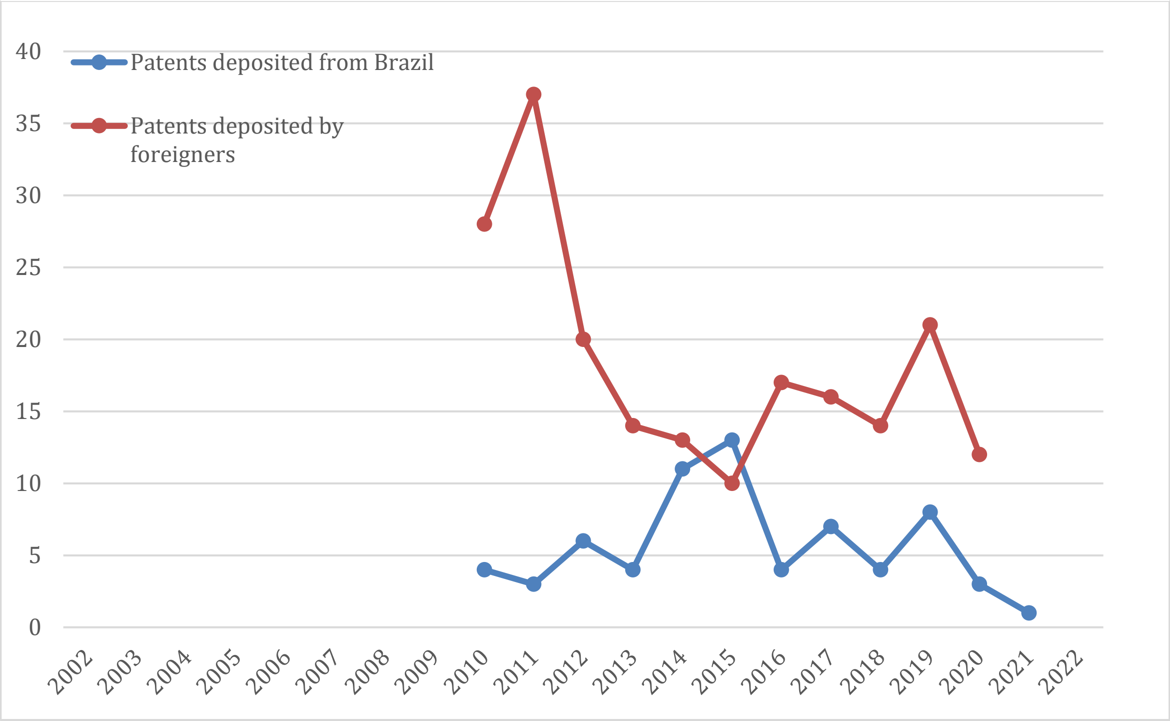
6.2.2 Function 2 – Knowledge development

The knowledge development function is analysed through the number of patents deposited at the INPI related to green hydrogen production technologies. The data show that in terms of green hydrogen, foreign applicants have a greater number than Brazilian ones, with the exception of 2015 when Brazil filed 13 patent applications and the other applicants, 10 applications. For the other periods, patent deposits were between 1 in 2021 and 11 in 2014. The figure 11 reveals that despite there being no record of industrial activity in green hydrogen during 2010 and 2020, the production of knowledge was somewhat relevant.

To analyse the development of this function, it is important to note that since the year 2000, companies in the electricity production, transmission and distribution sector must invest 0.75% of their operating revenue in R&D projects. This contribution constitutes a fund managed by ANEEL responsible for financing several research projects (GIZ, 2021). This regulation was not captured in this research time scope, and it is not possible to identify the origins of the financial resources of each patent deposit, one can that the ANEEL fund has been behind the innovations generated in university laboratories and research institutes, since the federal government's attempts at Procac, ProH2 were frustrated in its implementation.

Even though the INPI could not provide data of patents application between 2002 and 2009, the fact that most national applicants, 15 green hydrogen applicants, are public administration entities: universities and research centers (INPI, 2023), this is indicative that the *learning by searching* process managed to generate knowledge despite the lack of clear development strategy. The implementation of better-defined policies with clear objectives and availability of resources can generate even more R&D. The trend is that new entrants in the Brazilian market can generate the guidance of the search movement to fulfill the market demand.

Figure 11 Function 2 – knowledge development

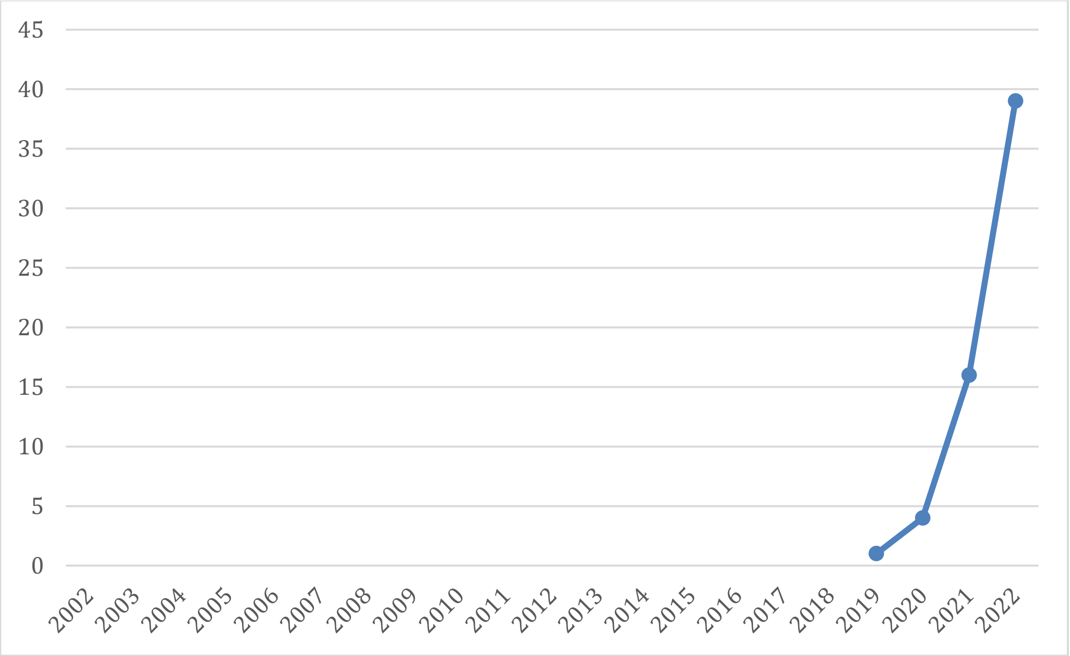


Source: INPI, 2023.

6.2.3 Function 3 – Knowledge diffusion through network

This study was able to map two national level knowledge exchange networks. The first of the is Brazilian Association of Hydrogen (ABH2), created in 2017, this association has been dedicated to representing Brazil at international events, in addition to organise the National Hydrogen Congress, which within the period of this study had two editions. As ABH2 emerged as an extension of Hydrogen Lab (LABH2) at the University of Rio de Janeiro, the association brings together industry, government, and academia to discuss the developments in the technology and research. The second network is the Brazil-Germany Alliance for Green Hydrogen, in addition to organising its own events, is also a platform for promoting events, workshops and webinars. Since the beginning of the activities of both organisations, it has been possible to map a growing evolution of exchanging events and information (figure 12). Given the impossibility of mapping all the events within the proposed period, this study sought to compile the events that were national in scope and exclusively related to hydrogen. With that said, although the graph does not show any events between 2002 and 2019, it means that events have not occurred. On the contrary, Brazilian universities have investigated RE in several research centers and laboratories, it is very likely that they have organized their own events on a smaller scale addressing different sources of renewable energy.

Figure 12 function 3 – Knowledge diffusion through networks



Source: author's compilation from internet data

The increase in the curve on the graph can be explained by the fact that the Brazil-Germany Alliance for Green Hydrogen alone has promoted and fostered an increasing number of events since its inception (Appendix E). Using the MLP again, this is yet another indication of the influence of the landscape on innovation systems, through the chamber of commerce between Brazil and Germany, companies in the European country seek to facilitate the creation and strengthening of the Brazilian knowledge network that in the future may impact their business in a sustainable way.

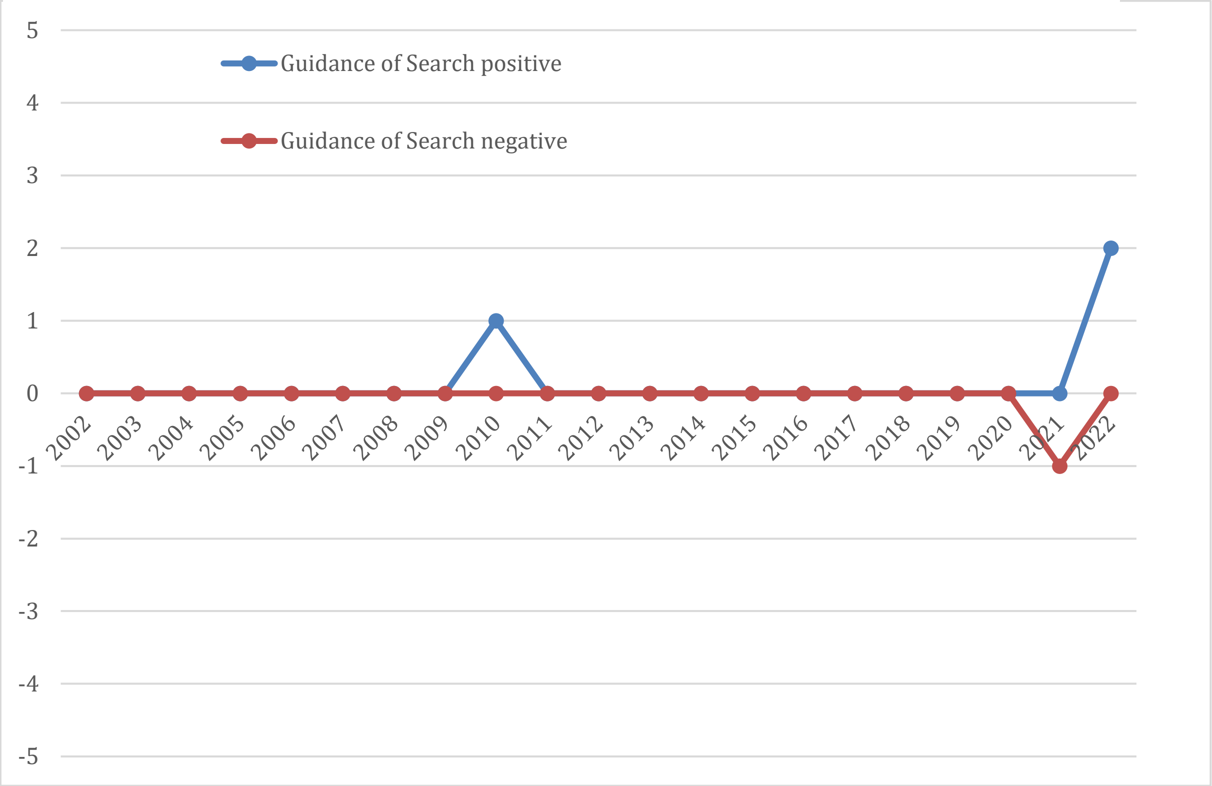
6.2.4 Function 4 – Guidance of the search

In terms of guidance of the search, the data shows three events in 2010, 2021 and 2022 (Figure 13). In 2010, when the Ministry of Science and Technology released the technical document Energy hydrogen in Brazil - subsidies for competitiveness policies: 2010-2025 (CGEE, 2010), the agency suggests that the incentive policy to be adopted should be similar to the policy adopted when promoting ethanol. For the first time it is mentioned a specific goal in green hydrogen consumption, which is the addition of 1% to 10 % of hydrogen produced from renewable energies per cubic meter of natural gas used in Brazil (CGEE, 2010). The indication of the consumption quota for green hydrogen recommended in this period positively influences the guidance of search function, which may explain the number of patent applications registered in the function 2 (figure 11).

In 2021, under Bolsonaro's term, Federal government released the Hydrogen National Program (table 5). Despite the document indicating the promotion of R&D, training of human resources, energy planning, creation of the legal and regulatory framework, and opening and growth of the market, it fails to determine practical and specific objectives, even leaving ambiguous the possibility of hydrogen production using methods polluters (Brazil, 2021). This event was computed as negative; however, it is still not possible to assess the impact of the ambiguity of this program for the development of the hydrogen economy. It definitely goes against the global trend of having specific goals and policies for the reduction of GHG emissions, but the fact that the National Congress is debating two law bill which are more committed to the Paris Agreement (curve increase in 2022, figure 12), nullifies the gap in understanding that non-sustainable hydrogen could also be produced in Brazil.

The two law bills are currently being discussed in the Senate. The first foresees the inclusion of hydrogen in the composition of the natural gas consumed in Brazil from 2035 onwards. The second foresees the promotion of the development of fuel cell technology. This event was computed as negative; however, it is still not possible to assess the impact of the ambiguity of this program for the development of the hydrogen economy. It definitely goes against the global trend of having specific goals and policies for the reduction of GHG emissions, but the fact that the national congress is debating laws that are more committed to the Paris agreement, nullifies the gap in understanding that non-sustainable hydrogen could also be produced in Brazil.

Figure 13 function 4 – Guidance of the search



Source: Source: author's compilation.

6.2.5 Function 5 – Market formation

This research did not find any existing evidence of competitive advantage to hydrogen consumption. However, there is the prospect of approval of law 275 which ensures the addition of 5% hydrogen to natural gas in 2035 and 10% in 2050.

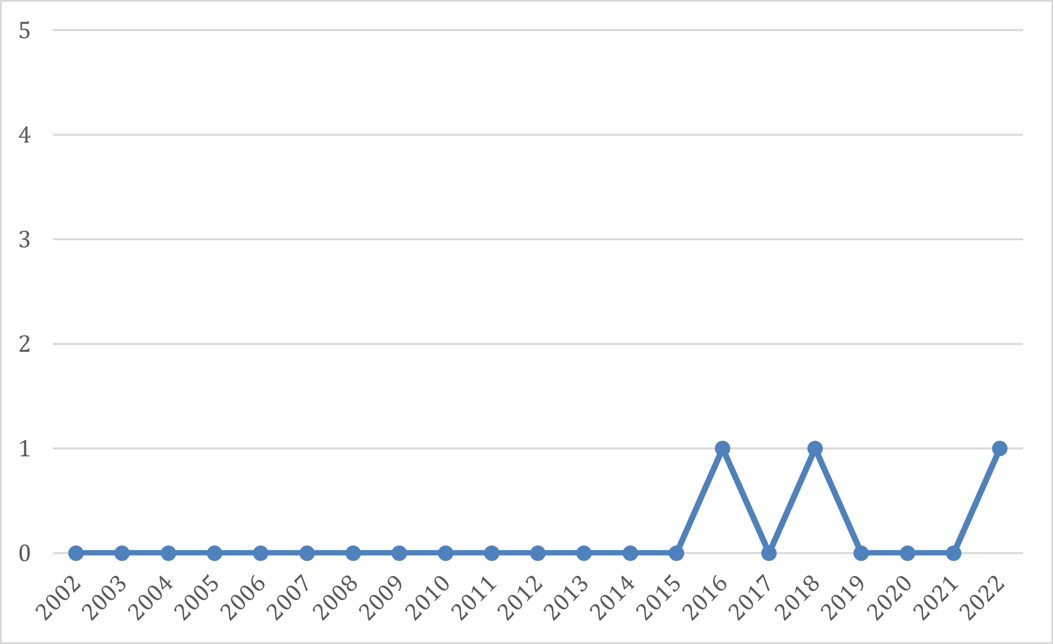
Hydrogen for export, however, can benefit from production incentives when it takes place in the Special Export Processing Zone located in some ports in Brazil.

6.2.6 Function 6 – Resources mobilisation

In terms of resource mobilisation, during the first 14 years, no mobilization of financial resources was observed, or the absence of resources was expressed (Figure 14). In 2016 and 2018, ANEEL launched two project financing calls and in 2022 the National Bank for Economic and Social Development of Brazil (BNDES) created a specific financing line for investors in green hydrogen (BNDES, 2022; GIZ, 2021). The BNDES funding for green hydrogen is a model project that aims to finance low carbon hydrogen producers, especially the ones focused on exporting it (BNDES, 2022).

The indication of only 3 events of allocation of specific financial resources for the development of green hydrogen by ANEEL and BNDES contrasted with the advances that happened in the last two decades, which means that they are directly unrelated. This phenomenon indicates that companies, research institutes and universities relied on financial resources that may came from their own source, international entities or even from sources of incentives that are not necessarily for the promotion of green hydrogen. To clarify, it would be necessary to assess the sources of funds used by beneficiaries. Thus, the fact that there are specific financing lines for green hydrogen indicates a positive trajectory in resource mobilisation.

Figure 14 function 6 – Resources mobilisation



Source: author's compilation from internet data

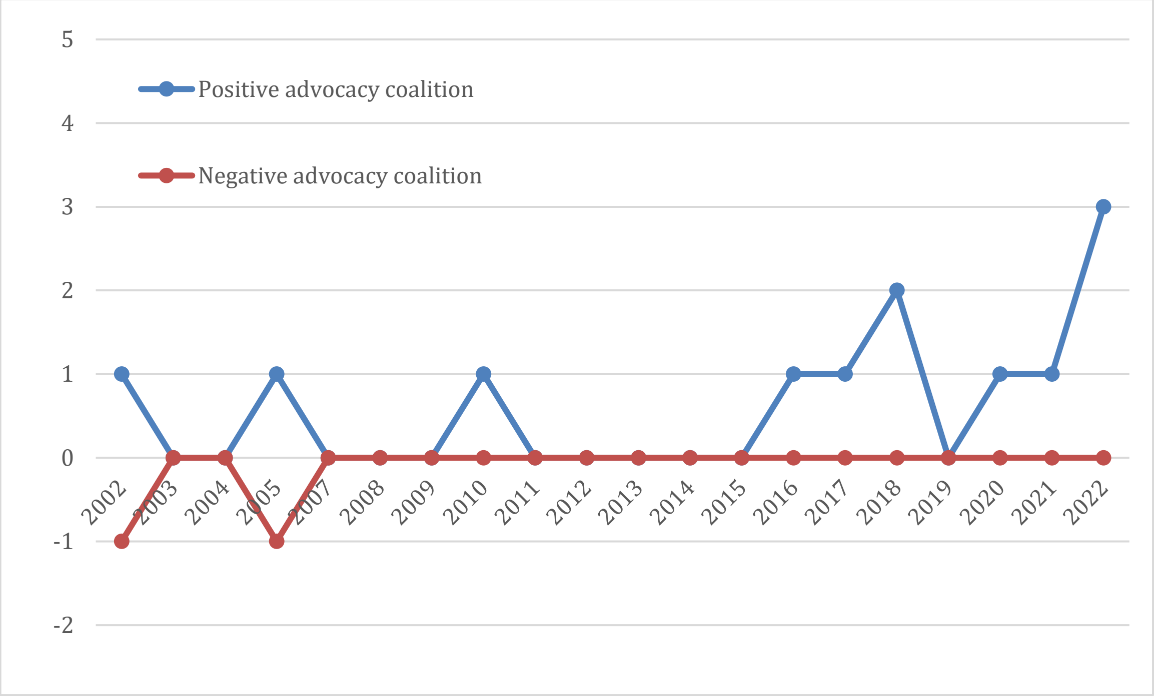
6.2.7 Function 7 – Creation of legitimacy

The policies and studies that indicates the government support to the hydrogen research in Brazil have been relatively balanced up to 2015 (figure 15). Procac, for example, was launched in 2002, however with the transition of the government, academics assess it as ineffective (de Matos & Junior, 2009). In 2005, once again the program did not get off the ground due to the discovery of pre-salt oil. Although we do not have data to support this finding, Chantre (2022) states that this has delayed advances in hydrogen research.

After 2017, other supporting policy technical publications issued by the federal government highlighted and placed hydrogen as an object of research and development, such as the Science, technology, and innovation plan for Renewable and biofuels between 2018-2022 (Brazil, 2018), National Energy Plan 2050 (ANEEL, 2020) and Hydrogen National Program (Brazil, 2021).

The positive rise of creation of legitimacy peaked in 2022, when the senate started discussing 3 bills, two of them were already mentioned in the guidance of the search section, and the third creates the Policy that regulates the production and uses of Green Hydrogen for energy purposes.

Figure 15 Creation of legitimacy



Source: author's compilation from official documents available on the internet

5.3 Other considerations

- In terms of limitation, this research focused on country level actions, taking as main political actor the central government in Brazil capital city. However, in Brazil states and municipalities are independent entities and, as long as they do not break any constitutional law, they can legislate and implement their own policies to encourage research, attract investment, encourage consumption, so their actions were not registered limiting the scope of the results. However, this issue does not invalidate this research, which presents a systemic relationship of the actions, differently from reports used as foundation for this thesis.

- The results relates to Markard and Truffer (2008), the concept of National Innovation System (NIS) does not hold the explanation of the phenomenon mentioned above. NIS is constrained by the geographical boundaries. On the other hand, the object of this research is impacted by an overseas influence within the technological sector (Hekkert et al., 2007). The entrepreneurial activity and knowledge diffusion through networks are functions which are influenced by the international players.
- In line with Hekkert et al., (2007) and Hekkert & Negro (2009), entrepreneurial activity is the main function of the innovation system. In the same year or after the announcement of the intention to invest in hydrogen hubs, it is possible to notice an increase in functions 3, 4 and 7. With the approval law 725, the market creation (function 5) will take place. This can be considered the first virtuous cycle of the hydrogen innovation system in Brazil.

6 Conclusions

While some studies are limited to exposed facts and figures without relating cause and effect of actions taken within the IS of hydrogen in Brazil. The approach used here addresses the gap of systemic analysis on the object. The contribution lays on the fact that this work can help decision makers to have better understand where to focus energy so that hydrogen reaches the level of Socio-technical Regime.

To achieve its the goal, this research answered two research questions:

Q1 – How the hydrogen technical system evolved in Brazil between 2002 and 2022?

Q2 - How the functions of the green hydrogen innovation system have been fulfilled in Brazil?

After in-depth bibliographical research in reports, official documents, academic articles, and technical studies of the Brazilian government's energy sector, the evolution of the innovation system has gone through several promotion policies that offer an overview of the objectives but do not establish specific goals. which highlights the distance between policy makers and hydrogen innovation centers. Despite this, it was possible to perceive that academia and industry are capable of carrying out research and generating innovations in fuel cell technology and hydrogen production through electrolysis.

To answer the second question, a more quantitative approach was chosen. The results for the functions can be divided between two phases, the first between 2002 and 2020 and the second after 2021. In this division, it is clear that in the first phase none of the functions showed stable and consistent growth, which is a reflection of the lack of political coordination and strategy corroborated in the previous section. In the phase starting in 2021, some functions are beginning to demonstrate positive iteractions that are being mainly driven by the increase in the entrepreneurial activity function. It is still early to indicate whether this is the beginning of a positive cycle in the formation of a hydrogen innovation system in Brazil, however, it indicates that government entities must direct efforts to fill in the gaps and take advantage of the moment.

6.1 Recommendations

Based on the data analysis, the following recommendations can be drawn.

- Create a favorable business environment for investors to promote the strengthening of the hydrogen value chain.

- Approve bills pending in the federal senate, mainly Law 725, which establishes the addition of hydrogen to natural gas. The approval of this law guarantees greater normative stability and may initiate the formation of the national consumer market.
- Define more specific objectives for the hydrogen programs and policies already created in recent years.
- Encourage the creation of cooperation networks and research exchange between Brazilian universities and companies entering the national market.
- Make more resources available from ANEEL, or create new funds, to finance specific research on green hydrogen.
- Foster the manufacture of fuel cells within the country, reducing the cost of production and importation in other countries.
- Implement tax reduction policies for companies that consume green hydrogen produced in Brazil.
- Create a centralized database or repository with relevant content so researchers can access it and create more knowledge about the IS and technology itself.

6.2 Future research

This study only considers the actions of some actors in the national innovation system. A complementary mapping would need to consider the actors of the infra-national system, state governments and city halls, for example. Although it is a difficult task to compile data and information from the three administrative levels in Brazil, research centers spread across the country could work in a network in order to draw a more accurate picture, serving as a basis for other states and municipalities to create their policies to encourage green hydrogen.

Further research should consider:

1. other administrative levels mapping the functions in the state and municipalities that have been impacted directly by the hydrogen clusters.
2. the difficulty of joining the data, in this way the partnership with government entities that can pass on the aggregated data.
3. the observation of the trajectory of the functions after the first virtuous circle of hydrogen.

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Appendix A – hydrogen storage methods

2.1.3.1 Metal hydrides

The chemical bonding between hydrogen and metal hydrides (magnesium hydride and magnesium nickel hydride) is stronger compared to the bonds involved in hydrogen adsorption, enabling effective storage (Edwards, Kuznetsov & David, 2007). The release of hydrogen from metal hydrides can be achieved through either thermolysis (heating) or hydrolysis (reaction with water). However, the latter method has shown limited success in previous tests and presents the challenge of capturing water (Andersson & Grönkvist, 2019).

The use of metal hydrides offers a solid-state storage solution for hydrogen, a technology initially developed in the United States. This approach has also driven the development of hydrogen-absorbing alloys, like nickel-metal hydride batteries, commonly used in electronics such as cell phones and digital cameras (Lacerda, 2021).

2.1.3.2 Chemical hydrides

When compared to metal hydrides, the chemical hydrides are significantly different. The main difference is that, under normal conditions, chemical hydrides are in the liquid state (Lacerda, 2021). The association of hydrogen with chemical hydrides also occurs in a liquid state, which simplifies the transport and storage of hydrogen. Therefore, chemical hydrides proposed for hydrogen storage are chemical compounds often obtained from natural gas, such as methanol and ammonia (Lacerda, 2021).

2.1.3.3 Adsorption

The adsorption method consists of linking the hydrogen molecule to a secondary material, often liquid nitrogen (Lacerda, 2021). This approach is still under development and in preliminary research stages. So far, the most promising adsorbents include some activated carbons and metal-organic structures (Andersson & Grönkvist, 2019; Lacerda, 2021).

2.1.3.4 Liquefaction

Liquefying hydrogen brings notable advantages. The main benefit is the fact that is increases substantially its density. Nonetheless, this procedure demands a considerable amount of energy to reach hydrogen's extremely low boiling point (Edwards, Kuznetsov & David, 2007). Gas hydrogen needs to reach the -253^{o}C to liquefy. Storing liquefied hydrogen requires complex cryogenic tanks to minimize evaporation (Andersson & Grönkvist, 2019; Armaroli & Balzani, 2011).

2.1.3.5 Compression

According to Larcerda (2021), the storage system for compressed hydrogen gas demands significant capital investment, as it involves increasing its density and compressing the gas to a sufficient pressure for safe storage in cylinders or underground facilities. Compression serves as an alternative with characteristics similar to natural gas, making it suitable for road transportation and as a vehicle tank. Moreover, underground storage employs the same principles used for storing natural gas, enabling large-scale fuel storage (Lacerda, 2021).

Another important method of hydrogen compression uses compressors for injection into gas pipelines, particularly for storing and transporting large quantities. It's possible to store up to 12 tons of hydrogen per km of gas pipelines. However, due to safety issues, constructing dedicated hydrogen infrastructure is costlier compared to other gases like natural (Armaroli & Balzani, 2011; Lacerda, 2021).

Appendix B – entrepreneurial activity database

Date	Company	Company origin	Incident	Index
02/02/2021	Energix Energy	Australia	Investment anouncement	1
13/03/2021	Fortescue	Australia	Investment project started	1
22/04/2021	White Martins/Linde	Germany	Investment anouncement	1
10/06/2021	Neoenergia	Spain	Investment project started	1
07/07/2021	Fortescue Future Industry	Australia	Investment anouncement	1
07/07/2021	Qair – CE	France	Investment anouncement	1
02/09/2021	EDP	Portugal	Investment anouncement	1
20/09/2021	Neoenergia	Spain	Investment anouncement	1
13/10/2021	Eneva	Brazil	Investment anouncement	1
13/10/2021	Diferencial Energia	Brazil	Investment anouncement	1
13/10/2021	Hytron	Germany	Investment anouncement	1
13/10/2021	H2Helium Energia	Brazil	Investment anouncement	1
15/10/2021	Engie	France	Investment anouncement	1
28/10/2021	Qair – PE	France	Investment anouncement	1
08/12/2021	Total Energies	France	Investment anouncement	1
13/12/2021	AES	Brazil	Investment anouncement	1
02/01/2022	Abreu e Lima (RNEST)	Brazil	Investment anouncement	1
04/02/2022	Equatorial Energia S.A.	Brazil	Investment project started	1
04/02/2022	Distrito Industrial Verde	Brazil	Investment project started	1
04/02/2022	Parque Tecnologico Itaipu	Brazil	Investment project started	1
17/03/2022	H2 Green Power	Brazil/Spain	Investment anouncement	1
02/05/2022	Nexway	Brazil	Investment anouncement	1
02/05/2022	Comerc Eficiencia		Investment anouncement	1

02/05/2022	Casa dos Ventos	Brazil	Investment anouncement	1
22/10/2022	Alupar		Investment anouncement	1
12/12/2022	ABB		Investment anouncement	1
15/12/2022	Transhydrogen Alliance	Netherlands	Investment anouncement	1

Appendix C – knowledge development database

Applicant	Origin country	Application date	Index
TECHNION RESEARCH & DEVELOPMENT FOUNDATION-[IL]	IL	05/01/2010	1
PERLEMAX LIMITED-[GB]	GB	06/01/2010	1
COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES-[FR]	FR	06/01/2010	1
PALMIR-[BE]	BE	18/01/2010	1
AUTRALIAN BIOREFINING PTY LTD.-[AU]	AU	20/01/2010	1
EGEN LLC-[US]	US	22/01/2010	1
HWANG, BOO-SUNG-[KR]	KR	01/02/2010	1
HWANG, BOO-SUNG-[KR]	KR	01/02/2010	1
MIZ CO., LTD-[JP]	JP	15/02/2010	1
MCALISTER TECHNOLOGIES, LLC-[US]	US	17/02/2010	1
MCALISTER TECHNOLOGIES, LLC-[US]	US	17/02/2010	1
MCALISTER TECHNOLOGIES, LLC-[US]	US	17/02/2010	1
UNIVERSIDADE FEDERAL DE MINAS GERAIS-[BR]	BR	23/02/2010	1
HIROFUMI FUKUTOME-[JP]	JP	20/04/2010	1
ACCIONA ENERGÍA, S.A.-[ES]; INGETEAM POWER TECHNOLOGY, S. A.-[ES]	ES	28/04/2010	1
KIVERDI, INC.-[US]	US	12/05/2010	1
	BR	28/05/2010	1
SHARP KABUSHIKI KAISHA-[JP]	JP	25/06/2010	1
HALDOR TOPSOE A/S-[DK]	DK	09/07/2010	1
CRAFT HOLDINGS WA PTY LTD-[AU]	AU	03/08/2010	1
CARLOS ROBERTO DIAS DA SILVA-[BR]	BR	11/08/2010	1
MCALISTER TECHNOLOGIES, LLC-[US]	US	16/08/2010	1
MIOXIDE MINING (PTY) LTD-[ZA]	ZA	16/08/2010	1
ANTECY B.V.-[NL]	NL	17/08/2010	1
FAHS STAGEMYER LLC-[US]	US	23/08/2010	1
INDUSTRIE DE NORA S.P.A.-[IT]	IT	23/09/2010	1
NEW ENERGY AG-[AT]	AT	29/09/2010	1
GEORGE ALBERTO GERALDO DE LIMA-[BR]; GEORGE HUGO LIRA LIMA-[BR]; GEORGE VICTOR LIRA LIMA-[BR]	BR	05/10/2010	1
INDUSTRIE DE NORA S.P.A.-[IT]	IT	07/10/2010	1
BATTELLE ENERGY ALLIANCE, LLC-[US]	US	10/11/2010	1
SHARP KABUSHIKI KAISAHA-[JP]	JP	20/12/2010	1
ASAHI KASEI CHEMICALS CORPORATION-[JP]	JP	24/12/2010	1
GLEISON LUIZ OBERLEITNER-[BR]; MARCO ANTONIO TAVARES MUZI-[BR]	BR	07/01/2011	1

MOLYCORP MINERALS, L.L.C.-[US]	US	21/01/2011	1
RAMOT AT TEL-AVIV UNIVERSITY LTD.-[IL]	IL	24/01/2011	1
ELECTRO POWER SYSTEMS S.P.A.-[IT]	IT	27/01/2011	1
EVEREADY BATTERY COMPANY, INC.-[US]	US	01/02/2011	1
MCALISTER TECHNOLOGIES, LLC-[US]	US	14/02/2011	1
MCALISTER TECHNOLOGIES, LLC-[US]	US	14/02/2011	1
MCALISTER TECHNOLOGIES, LLC-[US]	US	14/02/2011	1
MCALISTER TECHNOLOGIES, LLC-[US]	US	14/02/2011	1
MCALISTER TECHNOLOGIES, LLC-[US]	US	14/02/2011	1
MCALISTER TECHNOLOGIES, LLC-[US]	US	14/02/2011	1
INDUSTRIE DE NORA S.P.A.-[IT]	IT	21/02/2011	1
COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES-[FR]	FR	11/03/2011	1
COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES-[FR]	FR	11/03/2011	1
COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES-[FR]	FR	11/03/2011	1
BOARD OF CONTROL OF MICHIGAN TECHNOLOGICAL UNIVERSITY-[US]	US	17/03/2011	1
OHIO UNIVERSITY-[US]	US	31/03/2011	1
HELION-[FR]	FR	18/04/2011	1
KIVERDI, INC.-[US]	US	27/04/2011	1
AMALIO GARRIDO ESCUDERO-[ES]	ES	09/05/2011	1
COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ÉNERGIES ALTERNATIVES-[FR]; SOCIETE BIC-[FR]	FR	21/06/2011	1
COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ÉNERGIES ALTERNATIVES-[FR]; SOCIETE BIC-[FR]	FR	21/06/2011	1
HYDROX HOLDINGS LIMITED-[ZA]	ZA	08/07/2011	1
UNIVERSITEIT TWENTE-[NL]	NL	15/07/2011	1
RAFAEL REZENDE -[BR]	BR	19/07/2011	1
LIQUID LIGHT, INC.-[US]; PRINCETON UNIVERSITY-[US]	US	27/07/2011	1
SHIONO CHEMICAL CO., LTD.-[JP]	JP	16/08/2011	1
JOÃO BATISTA GERAIS DE CAMARGO RANGEL-[BR]	BR	19/08/2011	1
OHIO UNIVERSITY-[US]	US	23/08/2011	1
COMMISSARIAT À L'ÉNERGIE ATOMIQUE ET AUX ÉNERGIES ALTERNATIVES-[FR]	FR	31/08/2011	1
ACAL ENERGY LIMITED-[GB]	GB	11/10/2011	1
POLYNT COMPOSITES FRANCE-[FR]	FR	03/11/2011	1
MITSUBISHI HEAVY INDUSTRIES ENVIRONMENTAL & CHEMICAL ENGINEERING CO., LTD.-[JP]	JP	17/11/2011	1
NARWA TECHNOLOGIES AG-[CH]	CH	30/11/2011	1
EADS DEUTSCHLAND GMBH-[DE]	DE	05/12/2011	1

TOYOTA JIDOSHA KABUSHIKI KAISHA-[JP]	JP	07/12/2011	1
AQUAHYDREX PTY LTD-[AU]	AU	09/12/2011	1
SIEMENS AKTIENGESELLSCHAFT-[DE]	DE	14/12/2011	1
COMMISSARIAT À L'ÉNERGIE ATOMIQUE ET AUX ÉNERGIES ALTERNATIVES-[FR]	FR	16/12/2011	1
UNIVERSITY OF FLORIDA RESEARCH FOUNDATION, INC.-[US]	US	16/12/2011	1
VITO NV-[BE]	BE	28/02/2012	1
CASSIDIAN SAS-[FR]	FR	06/03/2012	1
BLACKLIGHT POWER, INC.-[US]	US	30/03/2012	1
MARCELO ACOSTA ESTRADA-[EC]	EC	05/04/2012	1
ANTECY B.V.-[NL]	NL	11/04/2012	1
COMMISSARIAT À L'ÉNERGIE ATOMIQUE ET AUX ÉNERGIES ALTERNATIVES-[FR]	FR	19/04/2012	1
HYDRORIPP LLC-[US]	US	01/05/2012	1
COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES-[FR]	FR	02/05/2012	1
INDUSTRIE DE NORA S.P.A-[IT]	IT	03/05/2012	1
NATIONAL UNIVERSITY CORPORATION KUMAMOTO UNIVERSITY-[JP]; TOYOTA JIDOSHA KABUSHIKI KAISHA-[JP]	JP	18/05/2012	1
ADVANCED COMBUSTION TECHNOLOGIES, INC.-[US]	US	23/05/2012	1
AQUAHYDREX PTY LTD-[AU]	AU	12/06/2012	1
COMMISSARIAT Á L`ÉNERGIE ATOMIQUE ET AUX ÉNERGIES ALTERNATIVES-[FR]	FR	12/06/2012	1
COMMISSARIAT À L' ÉNERGIE ATOMIQUE ET AUX ÉNERGIES ALTERNATIVES (FR)-[FR]	FR	12/06/2012	1
JOSÉ FRANCISCO GONÇALVES NETO-[BR]	BR	06/07/2012	1
ITALO WAGNER DOS REIS-[BR]	BR	11/07/2012	1
FERNANDO GONÇALVES SILVA-[BR]	BR	05/09/2012	1
UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG-[OA]	OA	19/09/2012	1
SIDNEY BUENO DA SILVEIRA-[BR]	BR	04/10/2012	1
AREVA-[FR]	FR	11/10/2012	1
UNIVERSIDADE ESTADUAL DO CENTRO OESTE - UNICENTRO-[BR]	BR	16/10/2012	1
WUHAN KAIDI ENGINEERING TECHNOLOGY RESEARCH INSTITUTE CO., LTD.-[CN]	CN	26/10/2012	1
NAUCHNO-PROEKTNOE PROIZVODSTVENNO-STROITELNOE OBEDINENIE GRANTSTROI-[RU]	RU	16/11/2012	1
WOBBEN PROPERTIES GMBH-[DE]	DE	10/12/2012	1
EXERGY POWER SYSTEMS, INC.-[JP]; THE UNIVERSITY OF TOKYO-[JP]	JP	18/12/2012	1
ECONODIESEL COMERCIAL LTDA. - ME-[BR]	BR	18/12/2012	1
COMMISSARIAT A L' ENERGIE ATOMIQUE ET AUX ÉNERGIES ALTERNATIVES-[FR]	FR	09/01/2013	1

HYDROX HOLDINGS LIMITED-[ZA]	ZA	11/02/2013	1
CHRISTIAN TRISCHLER-[AT]	AT	14/03/2013	1
OUTOTEC (FINLAND) OY-[FI]	FI	26/03/2013	1
CRISTHIANE XAVIER IMAMURA-[BR]; DANILO IMAMURA-[BR]	BR	04/04/2013	1
WUHAN KAIDI ENGINEERING TECHNOLOGY RESEARCH INSTITUTE CO., LTD.-[CN]	CN	16/04/2013	1
AQUAHYDREX PTY LTD-[AU]	AU	11/06/2013	1
AQUAHYDREX PTY LTD-[AU]	AU	11/06/2013	1
NUVERA FUEL CELLS, INC.-[US]	US	12/06/2013	1
MAX ROGÉRIO VIEIRA FARIAS-[BR]	BR	14/06/2013	1
KONINKLIJKE PHILIPS N.V.-[NL]	NL	18/06/2013	1
UHDENORA S.P.A-[IT]	IT	12/07/2013	1
LIQUID LIGHT, INC.-[US]	US	05/08/2013	1
GAMIKON PTY LTD-[AU]	AU	05/09/2013	1
NUVERA FUEL CELLS, INC.-[US]	US	30/09/2013	1
PAULO CESAR DE OLIVEIRA-[BR]	BR	08/10/2013	1
UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL-[BR]	BR	01/11/2013	1
INDUSTRIE DE NORA S.P.A-[IT]	IT	11/11/2013	1
SERGE V. MONROS-[US]	US	30/01/2014	1
UNIVERSIDADE DE SÃO PAULO - USP-[BR]	BR	13/02/2014	1
JOSÉ ROBERTO FERNANDES BERALDO-[BR]	BR	17/02/2014	1
HALDOR TOPSØE A/S-[DK]	DK	03/03/2014	1
SAUDI BASIC INDUSTRIES CORPORATION-[SA]	SA	05/03/2014	1
COMPANHIA ESTADUAL DE DISTRIBUIÇÃO DE ENERGIA ELÉTRICA -CEEE-D-[BR]; UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL-[BR]	BR	28/03/2014	1
BRILLIANT LIGHT POWER, INC.-[US]	US	01/04/2014	1
ALEX OLIVEIRA KAMMERER-[BR]	BR	14/04/2014	1
CARLOS ROBERTO DE ALMEIDA-[BR]; JOSE BENEDITO DOS SANTOS-[BR]	BR	28/04/2014	1
MITSUBISHI POWER EUROPE GMBH-[DE]	DE	08/07/2014	1
MITSUBISHI POWER EUROPE GMBH-[DE]	DE	08/07/2014	1
INDUSTRIE DE NORA S.P.A.-[IT]	IT	24/07/2014	1
MARCOS ZIOBER-[BR]	BR	24/07/2014	1
JOSÉ ROBERTO FERNANDES BERALDO-[BR]	BR	25/07/2014	1
AQUAHYDREX PTY LTD-[AU]	AU	30/07/2014	1
AQUAHYDREX PTY LTD-[AU]	AU	30/07/2014	1
WELLINGTON RICARDO DO NASCIMENTO-[BR]	BR	11/08/2014	1
UNIVERSIDADE ESTADUAL DO CENTRO-OESTE, UNICENTRO-PR-[BR]; UNIVERSIDADE TECNOLÓGICA FEDERAL DO PARANÁ - UTFPR-[BR]	BR	12/09/2014	1
GDF SUEZ-[FR]	FR	28/10/2014	1
THYSSENKRUPP AG-[DE]	DE	11/12/2014	1

THYSSENKRUPP AG-[DE]	DE	11/12/2014	1
THYSSENKRUPP AG-[DE]	DE	11/12/2014	1
HIDROGAS LTDA-[BR]	BR	15/12/2014	1
HIDROGAS LTDA-[BR]	BR	15/12/2014	1
EXERGY POWER SYSTEMS, INC.-[JP]	JP	05/01/2015	1
UNIVERSIDADE FEDERAL DE SANTA MARIA-[BR]	BR	13/02/2015	1
JOSÉ LUIZ NUNES DA SILVA-[BR]	BR	02/03/2015	1
LIMITLESS ENERGY LTDA-[BR]	BR	27/03/2015	1
BRILLIANT LIGHT POWER, INC.-[US]	US	29/05/2015	1
FIELD UPGRADING LIMITED-[CA]	CA	04/06/2015	1
MARCELO RODRIGO ROSA MORAIS-[BR]	BR	05/06/2015	1
JULIO DUAMEL OMAR FUERTES-[BR]	BR	08/06/2015	1
PAULO CESAR DE OLIVEIRA-[BR]	BR	18/06/2015	1
CHEMETICS INC-[CA]	CA	20/06/2015	1
NUVERA FUEL CELLS, LLC-[US]	US	25/06/2015	1
THE BOARD OF TRUSTEES OF THE LELAND STANFORD JUNIOR UNIVERSITY-[US]	US	17/07/2015	1
MITSUBISHI POWER EUROPE GMBH-[DE]	DE	31/07/2015	1
HIDROGAS LTDA-[BR]	BR	12/08/2015	1
SHELL INTERNATIONALE RESEARCH MAATSCHAPPIJ B.V.-[NL]	NL	26/10/2015	1
DENER GUSTAVO KRUZISKI-[BR]	BR	25/11/2015	1
FRANCISLEI SANTA ANNA SANTOS-[BR]	BR	09/12/2015	1
HIDROGAS LTDA-[BR]	BR	12/12/2015	1
JOI SCIENTIFIC, INC.-[US]	US	15/12/2015	1
INNOFERM TECNOLOGIA LTDA.-[BR]	BR	22/12/2015	1
ASAHI KASEI KABUSHIKI KAISHA-[JP]	JP	22/12/2015	1
MARCELO DE JESUS RIBEIRO DA SILVEIRA-[BR]	BR	29/12/2015	1
ALEXANDRE TERRA DE CALAZANS FERNANDES-[BR]	BR	30/12/2015	1
BRILLIANT LIGHT POWER, INC.-[US]	US	08/01/2016	1
LUMISHIELD TECHNOLOGIES, INCORPORATED-[US]	US	16/02/2016	1
ANDRÉ COLEN DE BRITO DABIEN HADDAD-[BR]	BR	07/03/2016	1
FUJI CHEMICAL INDUSTRIES CO., LTD.-[JP]; KWANSEI GAKUIN EDUCATIONAL FOUNDATION-[JP]	JP	25/03/2016	1
JOSE CARLOS DOS SANTOS SADERI-[BR]	BR	29/03/2016	1
TECHNISCHE UNIVERSITEIT DELFT-[NL]	NL	28/04/2016	1
ISAC BARBOSA JUNIOR-[BR]	BR	06/05/2016	1
1) IULIU IONESCU; E 2) ALEXANDRU TORDAI-[RO]	RO	06/05/2016	1
SPRAYING SYSTEMS CO.-[US]	US	13/06/2016	1
ENGIE-[FR]	FR	12/07/2016	1
ENGIE-[FR]	FR	12/07/2016	1

FUELSAVE GMBH-[DE]	DE	21/07/2016	1
FUELSAVE GMBH-[DE]	DE	21/07/2016	1
AKZO NOBEL CHEMICALS INTERNATIONAL B.V.-[NL]	NL	22/09/2016	1
ECOEDGE TECHNOLOGY, LLC.-[US]	US	29/09/2016	1
AVADAIN LLC-[US]	US	30/09/2016	1
LOGIC SWISS AG-[CH]	CH	11/11/2016	1
BRAZUKAS ENERGY SAVING TECHNOLOGIES PTE. LTD.-[SG]	SG	14/11/2016	1
AVOCET INFINITE PLC-[GB]	GB	15/12/2016	1
MYFC AB-[SE]	SE	20/12/2016	1
HAROLDO DE MELO GARCIA JUNIOR-[BR]	BR	28/12/2016	1
MITSUBISHI GAS CHEMICAL COMPANY, INC.-[JP]; TOHOKU TECHNO ARCH CO., LTD.-[JP]	JP	13/01/2017	1
H2 ENGINEERING D.O.O.-[SI]	SI	23/01/2017	1
LANZATECH NZ, INC.-[US]	US	01/02/2017	1
UNIVERSIDADE ESTADUAL DO CENTRO-OESTE-[BR]; UNIVERSIDADE FEDERAL DA FRONTEIRA SUL - UFFS-[BR]	BR	01/02/2017	1
SPRAYING SYSTEMS CO.-[US]	US	10/03/2017	1
KIVERDI, INC.-[US]	US	18/03/2017	1
SALUS ENERGY SOLUTIONS, L.P.-[US]	US	25/05/2017	1
FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE MINAS GERAIS - FAPEMIG-[BR]; UNIVERSIDADE FEDERAL DE UBERLÂNDIA-[BR]	BR	06/06/2017	1
ALMA MATER STUDIORUM - UNIVERSITÀ DI BOLOGNA-[IT]	IT	06/06/2017	1
PETRÔNIO FILGUEIRAS DE ATHAYDE FILHO-[BR]	BR	26/06/2017	1
UNIVERSIDADE DE SÃO PAULO - USP-[BR]; UNIVERSIDADE FEDERAL DA PARAÍBA - UFPB-[BR]	BR	30/06/2017	1
ZHONGYING CHANGJIANG INTERNATIONAL NEW ENERGY INVESTMENT CO., LTD.-[CN]	CN	07/08/2017	1
JORGE GARCÉS BARÓN-[CL]	CL	11/08/2017	1
ONE SCIENTIFIC, INC.-[US]	US	31/08/2017	1
DYNACERT INC.-[CA]	CA	28/09/2017	1
WILSON ROBERTO TIAGO RODRIGUES-[BR]	BR	29/09/2017	1
MAURIZIO ASARO-[BR]	BR	14/11/2017	1
GINER LIFE SCIENCES, INC.-[US]	US	15/11/2017	1
THE BLUEDOT ALLIANCE B.V.-[NL]	NL	22/11/2017	1
FRANCO LEONARDI-[BR]; IGOR ZORNITTA ZANELLA-[BR]	BR	30/11/2017	1
TEC ADVANCED ANSTALT-[LI]	LI	15/12/2017	1
CARBON ENGINEERING LTD.-[CA]	CA	21/12/2017	1
TECHNISCHE UNIVERSITEIT DELFT-[NL]	NL	22/12/2017	1
MARCO ANTONIO ROMANO-[BR]	BR	15/02/2018	1

DIEHL AEROSPACE GMBH-[DE]	DE	16/02/2018	1
ASAHI KASEI KABUSHIKI KAISHA-[JP]	JP	22/03/2018	1
BULANE-[FR]	FR	25/04/2018	1
ERIC ARNO VIGEN-[US]; KENNETH STEPHEN BAILEY-[US]; ROBERT A. PLAISTED-[US]	US	13/06/2018	1
BRUNO CASTANHO EMÍDIO-[BR]	BR	17/06/2018	1
HALDOR TOPSØE A/S-[DK]	DK	11/07/2018	1
HALDOR TOPSØE A/S-[DK]	DK	11/07/2018	1
HALDOR TOPSØE A/S-[DK]	DK	20/07/2018	1
HALDOR TOPSØE A/S-[DK]	DK	20/07/2018	1
CENTRO DE TECNOLOGIAS ESTRATÉGICAS DO NORDESTE - CETENE-[BR]; UNIVERSIDADE FEDERAL DE SANTA MARIA-[BR]	BR	30/07/2018	1
HSIN-YUNG LIN-[CN]	CN	31/08/2018	1
HSIN-YUNG LIN-[CN]	CN	31/08/2018	1
HYMETH APS-[DK]	DK	19/09/2018	1
HALDOR TOPSØE A/S-[DK]	DK	01/10/2018	1
JOSÉ ARMANDO DA SILVA LIMA-[BR]	BR	19/10/2018	1
BRILLIANT LIGHT POWER, INC.-[US]	US	05/12/2018	1
CHINT GROUP CORPORATION-[CN]	CN	24/12/2018	1
LUCAS DE ALMEIDA REZENDE-[BR]	BR	14/01/2019	1
OPUS-12 INCORPORATED-[US]	US	22/01/2019	1
LANZATECH, INC.-[US]	US	12/02/2019	1
FUELSAVE GMBH-[DE]	DE	18/03/2019	1
TECHNION RESEARCH AND DEVELOPMENT FOUNDATION LTD.-[IL]	IL	20/03/2019	1
HYMETH APS-[DK]	DK	21/03/2019	1
HYMETH APS-[DK]	DK	21/03/2019	1
LANZATECH, INC.-[US]	US	02/04/2019	1
GIOVANI SABINO-[BR]; JOEL IGNACIO-[BR]	BR	04/04/2019	1
ALEXANDER ZILBERMAN-[IL]; DENIS GINZBURG-[IL]; ELECTRIQ-GLOBAL ENERGY SOLUTIONS LTD.-[IL]; EREZ KARASENTI-[IL]; ROMAN FUTERMAN-[IL]	IL	17/04/2019	1
HYSILABS, SAS-[FR]	FR	30/04/2019	1
TORVEX ENERGY LIMITED-[GB]	GB	07/05/2019	1
CENTRO FEDERAL DE EDUCAÇÃO TECNOLÓGICA DE MINAS GERAIS-[BR]; FUNDAÇÃO UNIVERSIDADE FEDERAL DO ABC-[BR]; UNIVERSIDADE FEDERAL DE MINAS GERAIS-[BR]	BR	03/07/2019	1
ANGELO AGRO-[BE]	BE	08/07/2019	1
HALDOR TOPSØE A/S-[DK]	DK	09/07/2019	1
UNIVERSIDADE FEDERAL DE CAMPINA GRANDE - PB-[BR]	BR	11/07/2019	1
MARCOS CÉSAR PEREIRA DA SILVA INFORMÁTICA ME-[BR]	BR	17/07/2019	1
NUTRAGENOM, LLC-[US]	US	22/07/2019	1

MARCOS CÉSAR PEREIRA DA SILVA INFORMÁTICA ME-[BR]	BR	20/08/2019	1
HALDOR TOPSØE A/S-[DK]	DK	28/08/2019	1
RENE FRANCISCO BOSCHI GONÇALVES-[BR]	BR	16/09/2019	1
ENI S.P.A.-[IT]	IT	18/09/2019	1
HYMETH APS-[DK]	DK	23/09/2019	1
CGE ENERGY LIMITED-[GB]	GB	08/10/2019	1
ANDRÉ LUIS BARBOSA NICÁCIO-[BR]; JOÃO ROBERTO DE ASSIS-[BR]	BR	21/11/2019	1
OPUS 12 INCORPORATED-[US]	US	26/11/2019	1
H2 SOLUTION S.R.O.-[CZ]	CZ	02/12/2019	1
CERES INTELLECTUAL PROPERTY COMPANY LIMITED-[GB]	GB	03/12/2019	1
OPUS 12 INCORPORATED-[US]	US	18/12/2019	1
HAROLDO DE MELO GARCIA JUNIOR-[BR]	BR	03/01/2020	1
BRILLIANT LIGHT POWER, INC.-[US]	US	16/01/2020	1
INSTITUTO DE TECNOLOGIA E PESQUISA-[BR]; UNIVERSIDADE TIRADENTES-[BR]	BR	29/01/2020	1
ACHÍNIBAHJEECHIN INTELLECTUAL PROPERTY, LLC-[US]	US	14/02/2020	1
NORTHEASTERN UNIVERSITY-[US]	US	18/02/2020	1
HYMETH APS-[DK]	DK	20/02/2020	1
TRIBOTECC GMBH-[AT]	AT	21/02/2020	1
MASSACHUSETTS INSTITUTE OF TECHNOLOGY-[US]	US	13/03/2020	1
JOHNSON MATTHEY PUBLIC LIMITED COMPANY-[GB]	GB	01/04/2020	1
DYNELECTRO APS-[DK]	DK	03/04/2020	1
BASF SE-[DE]; THYSSENKRUP INDUSTRIAL SOLUTIONS AG-[DE]; THYSSENKRUPP AG-[DE]	DE	28/05/2020	1
UNIVERSIDADE FEDERAL DA PARAIBA-[BR]	BR	29/05/2020	1
NANOPTEK CORPORATION-[US]	US	05/08/2020	1
BRIMSTONE ENERGY INC.-[US]; CALIFORNIA INSTITUTE OF TECHNOLOGY-[US]	US	13/08/2020	1
THYSSENKRUPP UHDE CHLORINE ENGINEERS GMBH-[DE]	DE	19/08/2020	1
INSTITUTO FEDERAL DE EDUCAÇÃO, CIÊNCIA E TECNOLOGIA DO CEARÁ-[BR]	BR	28/08/2021	1

Appendix D – knowledge diffusion through networks database

Year	Event	Events
2019	Congresso Brasileiro de H2	1
2020	Promoted and held by Brazil-Germany Alliance	4
2021	Forum Internacional do Hidrogenio Verde	1
2021	Workshop Panorama atual e potenciais para o hidrogênio verde no Brasil	1
2021	Promoted and held by Brazil-Germany Alliance	12
2021	Congresso Brasileiro de H2	1
2021	38 EEBA	1
2022	Hidrogenio Submit	1
2022	Promoted and held by Brazil-Germany Alliance	33
2022	Congresso Brasileiro de Planejamento Energetico	1
2022	Congresso Brasil-Alemanha de Hidrogenio	1
2022	Comitê Gestor do Programa Nacional de Hidrogênio (Coges-PNH2)	1
2022	Forum de Energias Renovaveis	1
2022	Estratégia para indústria de baixo carbono	1

Appendix E – guidance of the search database

Year	**Event**	**Positive guidance of the search**	**Negative guidance of search**
2010	Energy hydrogen in Brazil - subsidies for competitiveness policies: 2010-2025.	1	0
2021	Hydrogen National Plan	0	-1
2022	Law bills	2	0

Appendix G – creation of legitimacy database

Year	Event	Positive advocacy coalition	Negative advocacy coalition
2002	Creation of ProH2/PROCAC support R&D and creation technical regulation for a hydrogen economy.	1	-1
2005	Roadmap for structuring the hydrogen economy in Brazil.	1	-1
2010	Energy hydrogen in Brazil - subsidies for competitiveness policies: 2010-2025.	1	0
2016		1	0
2017	ST&I strategic agenda in the Brazilian electricity sector.	1	0
2018	Science, technology, and innovation plan for Renewable and biofuels between 2018-2022.	2	0
2020	National Energy Plan 2050.	1	0
2021	Hydrogen National Plan	1	0
2022	Law bills	3	0