Developing a Green Hydrogen Economy in Brazil: Obstacles and Enablers

Max Thomsen

Dissertation written under the supervision of
José Antônio Puppim de Oliveira

Dissertation submitted in partial fulfilment of requirements for the MSc in International Management, at Universidade Católica Portuguesa and for the MSc in Management at Escola Brasileira de Administração Pública e de Empresas, at Fundação Getúlio Vargas, **11/09/2023**.

Abstract

This dissertation aims to identify the main obstacles and enabling strategies for the development of a green hydrogen (GH2) economy in Brazil. To this end, this case study encompasses an analysis of qualitative data from a series of expert interviews and relevant literature, through the lens of five theoretical propositions about barriers to the transition to GH2, grounded in the multi-level perspective on socio-technical systems. It was found that economic and institutional barriers are the most prevalent, as numerous factors inhibit financial investment decisions and an insufficient regulatory framework perpetuates uncertainty in the market. Additionally, required resources and infrastructure are not yet sufficiently available, and insufficient collaboration between diverse stakeholders makes coordination for the development of this incipient market challenging. Based on the discussion of identified barriers and enabling strategies, nine practical strategic approaches for the development of the Brazilian GH2 sector are proposed, primarily addressing approaches to increase economic viability and create a favorable regulatory environment. This case analysis is limited by the scarcity of applicable data, the non-comprehensive range of interviewed experts and the fact that developments in GH2 are rapid and the accuracy and relevance of the study's findings may therefore be subjected to changes. Among the first to use the specific theoretical framework in connection to GH2, this research was able to show that the multi-level perspective is an adequate framework to analyze transitions toward GH2, its obstacles and enabling strategies in specific national contexts.

Keywords: *decarbonization, green hydrogen, barriers to transition, sustainability transition, multi-level perspective*

Title: Developing a Green Hydrogen Economy in Brazil: Obstacles and Enablers

Author: Max Thomsen

Resumo

Esta dissertação tem como objetivo identificar os principais obstáculos e estratégias viabilizadoras para o desenvolvimento de uma economia de hidrogênio verde (GH2) no Brasil. O estudo de caso engloba uma análise de dados qualitativos obtidos por uma série de entrevistas com especialistas e da literatura relevante, através de cinco proposições teóricas sobre barreiras à transição para o GH2, fundamentadas na perspectiva multinível de sistemas sociotécnicos. Descobriu-se que as barreiras econômicas e institucionais são as mais predominantes, pois vários fatores inibem as decisões de investimento financeiro e uma estrutura regulatória insuficiente perpetua a incerteza no mercado. Além disso, os recursos e a infraestrutura necessários ainda não estão suficientemente disponíveis, e a colaboração insuficiente entre as diversas partes interessadas torna desafiadora a coordenação para o desenvolvimento desse mercado incipiente. Com base na discussão das barreiras identificadas e das estratégias facilitadoras, são propostas nove abordagens estratégicas para o desenvolvimento do setor GH2, tratando principalmente de abordagens para aumentar a viabilidade econômica e criar um ambiente regulatório favorável no Brasil. Este estudo de caso é limitado pela escassez de dados aplicáveis, pelo conjunto não exaustivo de especialistas entrevistados e pelo fato de que os desenvolvimentos no GH2 são rápidos e a precisão e a relevância das conclusões podem estar sujeitas a alterações. Entre as primeiras a usar a estrutura teórica específica em relação ao GH2, esta pesquisa conseguiu mostrar que a perspectiva multinível é uma estrutura adequada para analisar as transições para o GH2, seus obstáculos e estratégias viabilizadoras em contextos nacionais específicos.

Palavras chaves: *descarbonização, hidrogénio verde, barreiras à transição, transição para a sustentabilidade, perspectiva multinível*

Título: Desenvolvimento de uma economia de hidrogénio verde no Brasil: Obstáculos e Viabilizadores

Autor: Max Thomsen

Acknowledgements

I would like to express my gratitude to those who made the completion of this thesis and this master's program possible.

I thank my supervisor, José Puppim, for his patience, support and guidance. I thank the interviewed experts for their time and effort. Further, I thank my former team at AHK Rio for enabling me to develop my interest in the energy transition in Brazil, as this has already started to heavily shape my career and allowed me to start working with topics that genuinely interest me. I thank Anderson Ricci for his resourcefulness and support during the program. Both the staff at Católica Lisbon SBE and at FGV EBAPE made studying for these two years seamless.

I am immensely grateful for having had the opportunity to spend these last two years with wonderful personalities. Thank you, Zach, Max, Lea, Johannes and friends at the Projeto Morrinho in Laranjeiras.

Lastly, my family and my girlfriend are the people that have provided me with stability and unconditional support, which I cherish greatly.

Summary of Contents

List of Abbreviations

BNDES	Brazilian Development Bank
CAPEX	capital expenditures
CBAM	Carbon Border Adjustment Mechanism
CCUS	carbon capture, usage and storage
CfD	contracts for difference
CNI	Brazilian National Confederation of Industry
DRI	directly reduced iron
FID	financial investment decision
GH2	green and renewable hydrogen
GHG	greenhouse gas
GIZ	German Agency for International Cooperation
GW	gigawatt
H2	hydrogen
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCOE	levelized cost of electricity
LCOH2	levelized cost of hydrogen
MLP	multi-level perspective
MME	Brazilian Ministry of Mines and Energy
MoU	memorandum of understanding
MW	megawatt
ODA	official development assistance
PNH2	Brazilian National Hydrogen Program
PPP	public-private-partnership
R&D	research & development
RE	renewable energy
STS	socio-technical system
STT	socio-technical transition
ZPE	export processing zone

List of Figures

List of Tables

1. Introduction

Rapid human development experienced across the globe since the first industrialization is based on the energy we extract from fossil fuels, most importantly coal, oil and gas. From a sectoral perspective, power generation accounted for 42.2%, global industry emitted 26.3%, transportation accounted for 23% and the buildings sector came in at 8.5% of total CO2 emissions in 2022 (IEA, 2023). The global energy matrix feeds these sectors and it consisted in principal of fossil fuels, namely 25.2% coal, 29% oil, 22.8% natural gas, whilst old and modern renewable energy sources (REs), such as hydropower, wind, solar and modern biofuels together merely accounted for 11.28% (Ritchie et al., 2022).

There is a need to transition towards a low-carbon energy system and efforts to reduce our reliance on fossil fuels include ramping-up RE power generation capacity, decarbonizing industrial processes by transforming them and using “green” feedstocks, replacing combustion-based transportation with electric vehicles, and electrifying or centralizing heating in the building sector. These and many other proposed actions will require system-wide transitions and understanding how such transitions may be brought about through intelligent governance has been debated scientifically for at least three decades (e.g., Grin et al., 2010; Kemp, 1994; Loorbach et al., 2017). This transition implies the need to promote technologies that are not yet fully tested and have not reached economic viability. Green hydrogen (GH2) represents a technology with substantial potentials for the decarbonization of hard-to-abate and hard-to-electrify indsutries, which is why development strategies for the diffusion of this technology are part of the discussion about accelerating the energy transition (IEA, 2019).

This dissertation focuses on green hydrogen and its role in pursuits towards the decarbonization of a variety of industries, using a theoretical lens to analyze the transition, its obstacles and potential enabling strategies. More specifically, it focuses on the development of the GH2 sector in one specific geographical market: Brazil. As is the case for a number of other emerging economies, Brazil harbors many characteristics that could enable the South-American country to become an important player in the global hydrogen economy, strengthening domestic industry and improving socioeconomic realities across the country (Gurlit et al., 2021). Among the competitive edges for a Brazilian green hydrogen economy are the country’s abundant renewable energy sources with enormous untapped potentials, its integrated power grid, geographic advantages for exportation to future high-demand markets and a foreseeably substantial demand from domestic industries (Sawaya et al., 2022).

Given this context, this research endeavor seeks to answer the following research question:

> *What are the main obstacles to the development of a green hydrogen economy in Brazil and how could this development be enabled?*

The remainder of this paper is structured as follows. Chapter 2 provides the necessary theoretical background. To start, it introduces the field of sustainability transitions literature and explains the framework used in the subsequent case analysis: the multi-level perspective on socio-technical transitions. The chapter further provides technical background on hydrogen, discusses how GH2 is seen as a vector for global decarbonization and touches on the challenges for the realization of this scenario. Chapter 3 describes the methodology used for case analysis. Chapter 4 presents the results from the analysis of the Brazilian GH2 sector development, its obstacles and enabling strategies. Thereafter, chapter 5 discusses these findings and applies the chosen theoretical framework in their interpretation. Lastly, the dissertation ends on a conclusion summarizing the research and its results, highlighting limitations, implications and possible directions of future research.

2. Literature review & theoretical background

This chapter has four main components. In the first half it presents the necessary theoretical context by briefly discussing sustainability transitions research before narrowing in on the relevant theoretical framework used in this case study: the multi-level perspective on socio-technical transitions. In the second half, the chapter reviews hydrogen technology, and its prospective role as a vector for decarbonization. Section 2.3 further provides an overview of the frequently discussed barriers to a ramp-up of green hydrogen before the last section provides a brief introduction into the increasingly discussed competitive advantages of Brazil

2.1 Sustainability transitions research

This section provides background on sustainability transitions research, outlines different frameworks that are commonly used to analyze such transitions and explains important terminology necessary to navigate throughout the remainder of this article.

As was established in the introduction and in the first part of this chapter, climate and sustainability discourses are more and more urgently highlighting the need for fundamental changes in many of the sectors that support and represent how our societies function today. The large-scale challenge to bring about these changes represents a need for not just incremental improvements to, for instance, decouple economic productivity from CO2-emissions, but for system-wide transitions from fossil-fuel based, unsustainable practices to ones more in line with our planetary boundaries.

Large parts of natural and social sciences have been utilizing the term *transition* for decades and when doing so, they typically refer to "[…] a nonlinear shift from one dynamic equilibrium to another." (Loorbach et al., 2017) When discussing *sustainability transitions*, researchers therefore refer to the wide-ranging and large-scale systemic changes that societies strive for (Loorbach et al., 2017) in an effort to, for instance, decarbonize energy systems or redesign mobility.

Even though related scientific inquiries have been conducted for longer (e.g.: Geels, 2002; Kemp, 1994; Kemp et al., 1998), the field of sustainability transitions research has experienced institutionalization with the founding of the Sustainability Transitions Research Network (STRN) in 2009 (Markard et al., 2012), which unites many of the impactful scientists of this multidisciplinary field. As such, the field has gone through a strong disciplinary diversification and geographical expansion in the last 15 years (Köhler et al., 2019). Examples of such research are articles like Verbong & Geels's (2010) research about sustainability transitions in the electricity sector or Nurdiawati & Urban's (2022) inquiry into the decarbonization of the Swedish refinery industry. When reviewing the literature on sustainability transitions, it becomes clear that a large part of it addresses developments in the most "problematic" human systems, such as the energy and the transportation sector.

In order to understand frameworks for the analysis of sustainability transitions, the concept of *socio-technical systems* (STS) is essential. An STS consists of numerous actors (such as firms, universities, state actors), institutions (such as common practices, norms, regulations) and technological artifacts (Geels, 2004). When an STS undergoes fundamental reconfigurations in these three dimensions, sustainability transitions literature speaks of *socio-technical transitions* (STT).

At the beginning of many sustainability transitions stand novel technologies, which are brought about by processes of innovation. Thus, the four main theoretical frameworks, aiming to aid in understanding sustainability transitions through a systemic lens emphasize the role of such innovations. These are *Strategic Niche Management* (SNM), *Technological Innovation Systems* (TIS), *Transition Management* (TM) and the *Multi-Level Perspective* (MLP) (Köhler et al., 2019). The MLP understand a STS as consisting of three distinct levels: niche innovations, the socio-technical regime and the exogenous landscape level (Geels & Schot, 2007). As this framework will be employed throughout the remainder of this research article in order to analyze the STTs towards green hydrogen in Brazil, the next section will elaborate on this concept more extensively.

2.2 The multilevel perspective on socio-technical transitions

This section discusses the multi-level perspective (MLP) on socio-technical transitions. It explains the framework, its components, its applicability, provides examples and also touches on criticisms and limitations.

As established in the pervious section, the MLP is one way of looking at socio-technical transitions towards sustainability. The framework divides socio-technical systems in three interacting levels, which are no ontological representations of reality, but rather analytical constructs with the purpose of facilitating the comprehension of complex socio-technical developments (Geels, 2004). These levels are the *technological niches*, *socio-technical regimes* and the *socio-technical landscape* (Geels, 2002) (see *Figure 1*).

The socio-technical regime constitutes the part of an STS which is the established dominant configuration of actors, institutions and artefacts (Geels, 2004). The complexity, the depth and a number of path-dependencies and lock-in mechanisms present in this configuration stabilize the system and make it less susceptible to system-wide and more inclined to incremental change (Geels & Schot, 2007). An STS like the electricity system is an adequate example of such a configuration. It encompasses a range of interconnected elements and in most places relies on a centralized and fossil fuel based generation system. Here, some of the powerful key actors would be large utility companies, industry associations and relevant public entities.

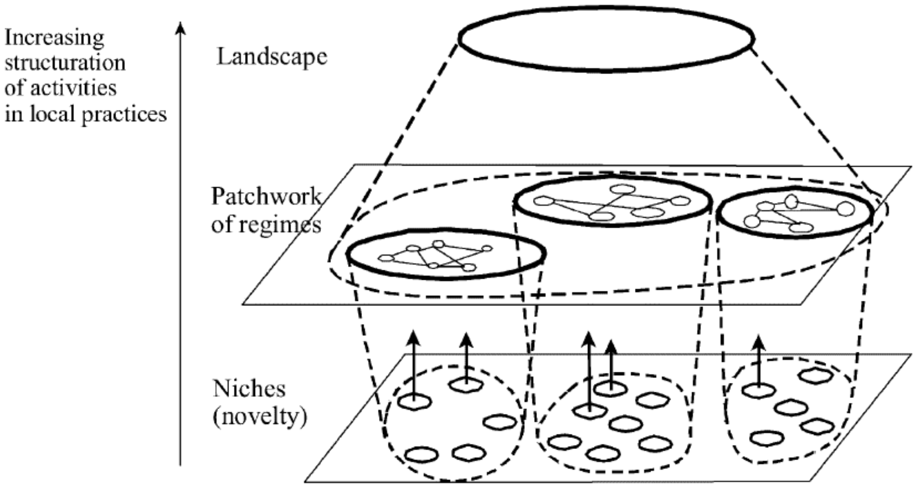


Figure 1: Multiple levels as a nested hierarchy as per Geels (2002)

Among these and other actors exist institutions, which could be policies like fossil-fuel subsidies to protect national industries, the utilities' strong political influence exerted through lobbying and also commonly held beliefs as, for instance, a societies opposition to nuclear power. Relevant artifacts could be transmission lines, electric heating technologies, among others.

Technological niches are isolated spaces where niche actors, such as start-ups or R&D facilities of companies develop radical innovations that differ from the existing socio-technical regime (Geels, 2011). Essential because of their incipient role in major transitions, such niches face significant challenges, as lock-in mechanisms and path dependencies in currently existing regimes represent tall entry barriers. Taking the example of the energy transition towards clean, renewable energy sources, wind energy is in some geographies and was in others a niche technology. In Brazil, for instance, wind energy accounted for only 0.15% of the electricity matrix in 2007 and this share had increased to 10.79% by 2021 (Panos et al., 2022). The establishment of this technology as an important source of electricity in Brazil represents its emancipation from its niche position. In this example, niche actors could be research labs (corporate or academic), community-based renewable energy projects and wind turbine manufacturers, to name a few.

The landscape level represents the exogenous context that exerts influence on the socio-technical system (Geels, 2004). Being the most macro of all three levels, it captures very slow-changing developments, such as changing demographics, economic trends, geopolitical dynamics, ideology and climate change. These more cumbersome changes can be accelerated or disrupted by shocks, such as the energy crisis brought about by the Russian invasion of Ukraine or recessions and inflationary tendencies linked to the Covid-19 pandemic and associated government spending.

The three levels do not exist in isolation from one another. Key characteristics of the MLP framework are the interactions between the levels, which inhibit and enable innovations and which, if steered correctly, can facilitate transitions towards more desirable systemic equilibria.

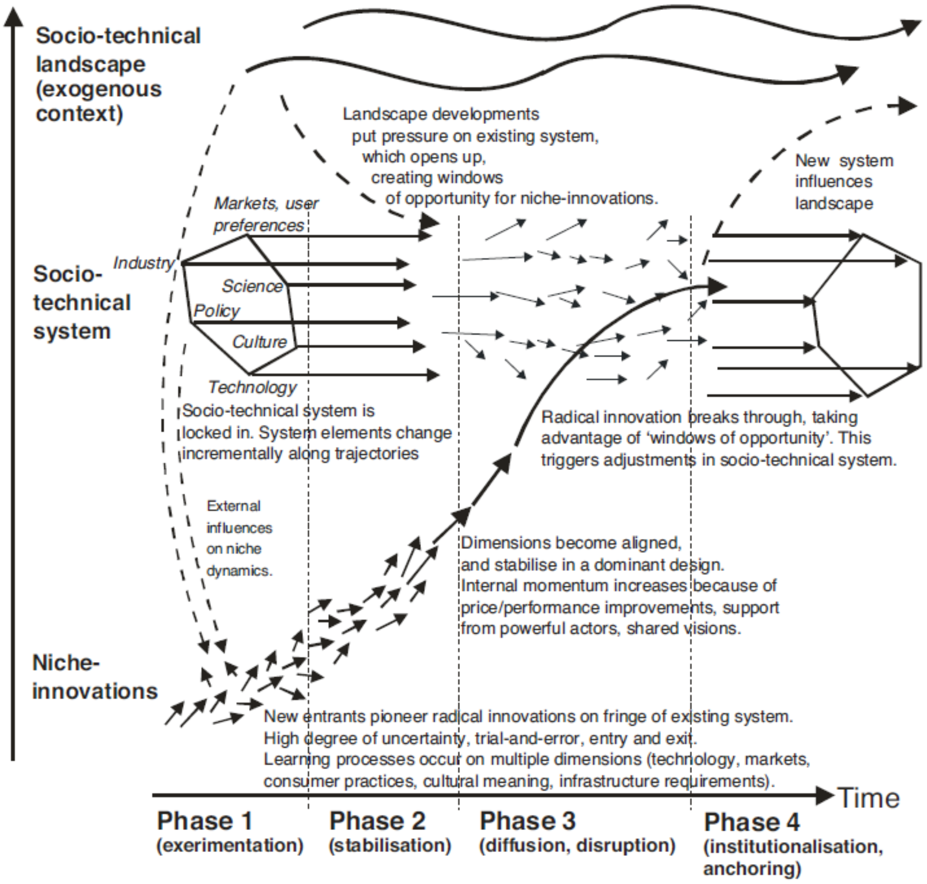


Figure 2: The multi-level perspective on socio-technical transitions as per Geels (2019)

According to the classic idea of the MLP, systemic change occurs during specific windows of opportunity (Geels, 2004). Such windows of opportunity open when a combination of bottom-up pressures from increasingly mature niche innovations and top-down pressures from the exogenous landscape manage to destabilize the current socio-technical regime (Geels & Schot, 2007). As illustrated by *Figure 2*, this conceptually occurs in a four-phase process. It consists of early testing, the emergence of a superior design, the penetration of the regime enabled by the innovations competitiveness and windows of opportunity and the establishment of new configurations in the regime (Geels, 2019).

To illustrate, one can consider the energy transition towards modern renewable technologies, such as solar photovoltaic, wind power or biogas. The exogenous landscape level factors that enabled the advent of these technologies vary between countries.

In Brazil, a state-led effort to boost wind power came about because of the country's heavy dependency on hydroelectric energy, associated concerns about the security of supply during dry seasons and the associated need for diversification of power sources (Muhammed & Tekbiyik-Ersoy, 2020). From 2002 onwards, a series of increasingly effective government programs aimed to protect modern renewable energies from market selection pressures, which ultimately resulted in their competitiveness and a substantial growth in market share of these technologies (Muhammed & Tekbiyik-Ersoy, 2020). Given current geo- and energy-political developments brought about by the Russian invasion of Ukraine, countries that previously showed a strong dependency on Russian fossil fuels have accelerated their efforts to ramp-up renewable energy in order to reduce bilateral energy dependencies. Global efforts to reduce carbon emissions are very much focused on energy systems and therefore, an increasing realization of man-made climate change represents another major exogenous factor that should not go unmentioned.

These examples demonstrate that a myriad of exogenous factors may exert top-down pressures on socio-technical regimes. In many cases, these pressures also have effects on increased innovative activity in technological niches which subsequently may or may not lead to the destabilization of the established regime (Geels, 2004).

Transition pathways

Established in Geels & Schot's seminal research article from the year 2007, there are different pathways in which transitions may unfold depending on the given configuration of landscape pressures and niche innovations, and depending on the corresponding responses of regime actors. Due to the dynamic adaptability of established socio-technical regimes, a scenario where landscape pressures are absent is not going lead to substantial systemic transitions, but to a *reproduction process* in the regime (Geels & Schot, 2007). Below follow the explanations of possible transition pathways.

In the first configuration discussed by the authors, modest pressure from the landscape level occurs at a moment where niche innovations have not reached market maturity (characterized by the absence of dominant designs, participation of potent actors and a certain degree of early market participation). In response to this constellation of factors, regime actors adjust the development and innovation trajectories of the regime to better absorb the landscape pressures. This pathway is referred to as *transformation path* (Geels & Schot, 2007).

Assuming a scenario where landscape pressures are of stronger magnitudes, occur suddenly, and have wide ranging implications on the established socio-technical regime, a disintegration of it will occur. Assuming further that in the moment of rupture various innovations emerge of which none has proven to be superior, these innovations will compete until the successful innovation leads to the configuration of a novel regime. Geels & Schot (2007) call this the *de-alignment and re-alignment path*.

Thirdly, the authors speak of *technological substitution* when strong landscape pressures meet mature niche innovations. In this scenario, emerging innovations will replace existing regime-technologies during windows of opportunity (Geels, 2004).

The last pathway that is particularly relevant for socio-technical systems is characterized by the interaction of several different but linked technologies. In the *reconfiguration pathway*, innovative technologies are adapted in some parts of the system, which thereafter results in further adjustments and increasingly significant change of the regime (Geels & Schot, 2007).

Importantly, this concept of transition pathways does not characterize them as being mutually exclusive. If landscape pressures are disruptive, a *sequence of transition pathways* may be the actual turn of events, depending on how dominant regime actors react to the disruptions (Geels & Schot, 2007). *Table 1* provides a summary of the different pathways and the configurations that lead to them.

Reproduction process	Transformation path	De-alignment & re-alignment path	Technological substitution	Reconfiguration pathway	Sequence of transition pathways
No landscape pressure	Moderate landscape pressure	Sudden, high magnitude landscape pressure with wide-ranging impacts	Any type of strong landscape pressure	Not necessarily characterized by landscape pressure	Disruptive change in the landscape (slowly building up pressure)
The regime dynamically adapts, implements incremental changes and there is no window of opportunity	Regime actors adjust technological and innovation trajectories in the regime to the landscape pressures	Immature innovations compete in the regime until one becomes dominant and leads to a new regime	Mature innovation uses the window of opportunity to replace established technology	Initial adoption of a mature innovation leads to further adjustments and increasingly significant change	Depending on regime actors' response, a sequence of transition pathways may occur

Table 1: Summary of the transition pathways as per Geels & Schot (2007)

There are also dynamics at play that have a stabilizing effect on socio-technical regimes. These dynamics are typically referred to as lock-in mechanisms (Geels, 2004). Economies of scale lead to per unit cost reductions, which puts large incumbent actors at a competitive advantage against emerging, new entrants, which is equally true for large sunk investments into capabilities and physical capital. Further, established industries with vested interests typically exert significant influence on key actors through activities such as lobbying and they have so-called 'social capital'. An illustration of social capital, the German coal industry has been a major employer in the east and the west of the country for decades. Working in coal mines has been a source of income and of cultural identification for generations, representing firm motivations for a society's resistance to rapidly dismantle this industry. Other social lock-in mechanisms can be the fact that users of technology have gotten used to how and when to use them and are resistant to changing those habits.

In general, multi-dimensional struggles are observable between the dominant regimes and aspiring niche innovations (Geels et al., 2017). In the economic sphere, there is an increasing stand-off between traditional, often dirty technologies and newer, cleaner ones. This competition frequently occurs on an uneven playing field, as incumbent actors and artefacts benefit from preferential treatment through institutions such as subsidies and more significant political influence. Further, debates in the public sphere are often shaped by more fundamental, cultural discourses about what the role of the market is, and what the role of the state ought to be (Geels, 2019). Individuals, particularly in developed countries, start to experience sustainability transitions more and more directly, as for instance through the construction of wind-parks in the vicinity of residential areas, new regulation about heating technologies for private households and access restrictions for old, heavily polluting cars in many city-centers.

To summarize, one could list the following barriers encountered by (green) innovations when encountering the dominant regime (Geels, 2004, 2019; Geels & Schot, 2007):

1) **Economic barriers**: Established technologies often benefit from economies of scale, large sunk costs of capital and established supply chains. Novel, green innovations often have difficulty matching these on the open market. The upfront cost of green innovations might be high, creating a barrier for both producers and consumers, and emphasizing the important role of large, incumbent actors in sustainability transitions.
2) **Institutional barriers**: Established technologies and practices often have established systemic support, such as regulatory frameworks, incentivizing policies, provided infrastructure, and industry standards. Such supporting schemes make systems resistant to change, inhibiting innovations in gaining traction. Existing regulations may favor incumbent technologies and disadvantage green innovations.
3) **Resource constraints**: Developing and scaling up new technologies can require significant financial, human, and material resources. When these resources are limited or not readily attainable, it can present an obstacle to the advancement of innovations.
4) **Insufficient supporting infrastructure**: Green innovations often require non-existent and innovative infrastructure that has to be provided by third-party actors and is associated with high costs and long time-horizons.
5) **Coordination challenges**: Coordinating different stakeholders, such as government bodies, industries, research organizations, and consumers, is often crucial for driving significant innovations on a large scale. Challenges in effectively managing these collaborative endeavors can result in delays to the progress and implementation of novel technologies.

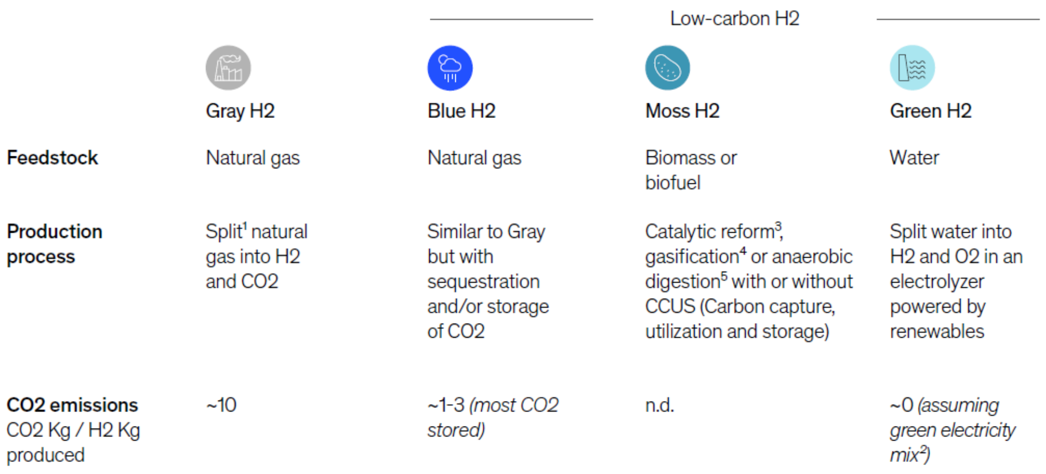
An innovation is unlikely to face none and more likely face some or several of these barriers when trying to enter mainstream regimes. For this research, the barriers described in the literature shall serve to analyze the case of GH2 in Brazil.

Following the previous description of sustainability transitions discourses and the multi-level-perspective on STTs, the ensuing section elaborates on green hydrogen and its prospective role in the sustainable energy transition.

2.3 Hydrogen: present & future

Given the urgent need for global decarbonization outlined in the introduction, the second half of chapter 2 presents the case for green hydrogen as a vector for decarbonization. It explains the technology, its relevance for decarbonization in multiple economic sectors and also discusses the most relevant bottlenecks for a large-scale adoption.

Hydrogen (chemically: H_2) is a highly flammable gas and also the lightest and most abundant element in the universe. Next to its many economic uses, which will be described later in this section, hydrogen is more commonly encountered in chemical compounds with other elements, forming water (H_2O), methane (CH_4) or ammonia (NH_3), among others. As it is rarely found in nature in its pure, gaseous form, hydrogen is most commonly produced using one of a series of possible processes. Depending on what process is used to separate hydrogen from other elements or molecules it is often referred to using a color code. It is worth noting that this color spectrum is not used consistently throughout scientific, economic and political discourses and that is often adapted to the context of discussion. Given this paper's focus on the case of Brazil, it uses the color taxonomy described by Gurlit et al. (2021) in an article published by McKinsey & Company, illustrated in *Figure 3*.



		Low-carbon H2		
	Gray H2	**Blue H2**	**Moss H2**	**Green H2**
Feedstock	Natural gas	Natural gas	Biomass or biofuel	Water
Production process	Split[1] natural gas into H2 and CO2	Similar to Gray but with sequestration and/or storage of CO2	Catalytic reform[3], gasification[4] or anaerobic digestion[5] with or without CCUS (Carbon capture, utilization and storage)	Split water into H2 and O2 in an electrolyzer powered by renewables
CO2 emissions CO2 Kg / H2 Kg produced	~10	~1-3 *(most CO2 stored)*	n.d.	~0 *(assuming green electricity mix[2])*

Figure 3: Hydrogen color taxonomy as per Gurlit et al. (2021)

According to the IEA (2022), *gray hydrogen* made up 62% of the global hydrogen production mix, hydrogen generated through coal gasification accounted for 19% and hydrogen as a by-product from refinery processes stood at 18% in 2021. These technological routes hence made up a staggering 99% of 94 million tons of hydrogen generation, resulting in emissions of 900

Mt of CO_2 (IEA, 2022b). Fort the purpose of this article, the term *gray* hydrogen will refer to any of these heavily polluting methods of production.

Less than 1% of globally produced hydrogen was associated with low emissions, mostly because the method of *carbon capture, usage and storage* (CCUS) was added to the process to fossil-fuel based sourcing. When the emissions of hydrogen are later abated with CCUS, we refer to it as *blue hydrogen*.

Green hydrogen is generated through the process of electrolysis. Here, electrolyzer technology is used to split water (H_2O) into hydrogen (H_2) and oxygen (O_2). The energy carrier induced in this process is electricity and if it stems from exclusively renewable sources, the product is referred to as green hydrogen. Water electrolysis only made up 0.1% of global hydrogen generation in 2021, but it had grown by almost 20% in comparison to 2020 and the installed capacity of electrolyzers had grown by 70% (IEA, 2022b). Hydrogen produced from biomass or biofuel, one of the least technologically developed methods today, can be referred to as *moss H_2*.

As of 2021, hydrogen was primarily consumed in refining (40 Mt, 43%) and in different industrial applications (54 Mt, 57%) such as the production of ammonia, methanol or directly reduced iron (DRI) for steel manufacturing (IEA, 2022b). Newer uses of hydrogen, such as in transport, power generation and buildings only made up 0.4% of global demand (IEA, 2022b).

In refineries, H_2 is used to reduce heavy oils to more usable, leaner petroleum products. The main consumer of such products is the transportation sector. The hydrogen used in refineries is primarily sourced in on-site generation processes that use fossil-fuel based hydrogen, with the remainder being supplied externally to attain a necessary degree of operational and financial flexibility (IEA, 2022b). Given the inherent focus on oil, blue hydrogen, i.e. a coupling of these productive processes with subsequent CCUS, appears as the most feasible technological route towards the use of low-carbon hydrogen in refineries globally, in the short- and medium-term (IEA, 2022b).

In the industry, the largest share of hydrogen (63%) is used to produce ammonia, a base resource for the production of nitrogen fertilizers and feedstock for a number of specialized industrial uses (IEA, 2022b). Methanol, the second largest recipient of hydrogen among industry consumers (28%), is a feedstock for the chemical industry and an alternative fuel in a number of applications (IEA, 2022b). Just like ammonia, methanol is associated with substantial CO_2-

emissions and thus, using electrolysis and CCUS to decarbonize a principal feedstock could help to reduce the sector's carbon-footprint.

In steel manufacturing (9%) hydrogen is increasingly used to produce directly reduced iron (DRI), a process replacing coal-based procedures with a hydrogen-based one (IEA, 2022b). As in previous application examples, using CCUS in on-site hydrogen production would help to reduce emissions from steel-making. Depending on local conditions, GH2 could prospectively be induced in the process as well.

Another potential use sector still in the infant stage yet worth mentioning is the transport sector. Even though it only accounted for 0.03% of global hydrogen demand in 2021 (IEA, 2022b), hydrogen, particularly for road, but also for rail, sea and air transport, is subject of public debate about alternatives to electrification. Technically, hydrogen would ideally be used in fuel-cell technology (cars, buses, trucks, rail) or in the form of derivative fuels, such as sustainable-aviation fuels (SAF) or ammonia and methanol (shipping).

Green hydrogen as a vector for decarbonization

The idea of a "hydrogen economy" as a scenario where human energy systems transition to running on hydrogen instead of fossil fuels was first comprehensively described by Bockris (1972) over 50 years ago. Ever since questions related to resource depletion and increasingly problematic pollution levels have been of public concern, different possible technological routes such as hydrogen as an energy carrier are being evaluated technologically, economically and politically (e.g., Barreto et al., 2003; Crabtree et al., 2004; Dunn, 2002). Today, many of these analyses have led to a situation where the idea of a hydrogen-based economy can be defined as the application of hydrogen as an energy transporter for various industries in conjunction with electricity (Yap & McLellan, 2023), particularly those that are not or only inefficiently electrifiable, such as heavy industry, long-haul transportation and seasonal storage.

Hydrogen has the unique ability to replace fossil fuels in many applications avoiding CO2-emissions, making it an important energy source for achieving a zero-carbon future. The global competition for clean hydrogen brings about new geopolitical realities and interdependence, but it promises new opportunities in the fight against carbon emissions.

Numerous estimates and scenarios have been outlined and are constantly being adapted to current developments in energy markets and geopolitics. By 2050, clean hydrogen (primarily green & blue) could show itself responsible for the abatement of up to seven gigatons CO2, which may be around 20% of globally avoided emissions by that time (Heid et al., 2022).

Additionally, there is an ever growing project pipeline with initiatives within the green hydrogen value chain, totaling today more than 1040 announced projects, accounting for a 320 billion US$ in announced investments, of which 29 billion US$ have already passed the financial investment decision (Hydrogen Council & McKinsey & Company, 2023). These projections and investments go along with a projected annual hydrogen demand of approximately 660 million metric tons by 2050 (Heid et al., 2022), equivalent to a 7-sevenfold increase from today's demand. Many estimates predict green hydrogen becoming more affordable than both blue and gray hydrogen, because of increasing carbon prices and decreasing costs for electrolyzers and renewable energies, the two principal cost drivers (e.g., Heid et al., 2022; Tarvydas, 2022).

Testament to the global acceptance of H2 as an important energy carrier of the future are the approximately 47 national, and numerous sub-national hydrogen strategies (HyResource, 2023) that have been published since the discussion around this technology started to gain traction. These strategies vary in ambition and there is little global consensus about the most or more desirable technological routes. Further, the way countries begin to position themselves in the geopolitics of hydrogen starts to show increasingly. Eicke & De Blasio (2022) discussed in a recent analysis how newly-formed hydrogen value chains lead to different countries taking on different roles, depending on their ability to produce, export or import and consume green hydrogen and its derivatives.

Two recent initiatives that should not go unmentioned, because of their significance for global hydrogen developments are the *Inflation Reduction Act* (IRA) in the United States, signed by President Biden in August 2022 and a global call for tenders of green hydrogen and Power-to-X (PtX) technologies, put out by the German Federal Government. Part of the IRA is a tax credit of 3 US$ per kilogram of hydrogen produced from renewable and nuclear energy (i.e., "clean" energy) (The White House, 2023) and as a result, the USA have seen a spike in announced private investments into the hydrogen value-chain. The German call for tenders goes by the name of *H2Global* and it is relevant because it is the first initiative of triggering supply internationally, through a so-called *contracts for difference* (CfD) mechanism, where public funds are used to provide long-term offtaking opportunities for producers of these technologies in promising markets across the world (H2Gobal Stiftung, 2022).

Challenges for the development of a green hydrogen economy

Given the promise of GH2 for decarbonization, the bottlenecks for its large-scale adoption are subject of scientific, political and business debate and efforts to overcome them.

Firstly, the as-is situation lags behind where global hydrogen developments should be, if they are to be in-line with the self-set decarbonization targets (Hydrogen Council & McKinsey & Company, 2023; IEA, 2022b; IRENA, 2022; Tarvydas, 2022). According to an analysis by McKinsey & Company, a fact that inhibits clean hydrogen growth is a total funding gap of 460 billion US$, which stretches almost evenly across the value chain of production, distribution and storage, and end-use applications (Heid et al., 2022)

Depending on the particular political and geographic context, the bottlenecks for large-scale production and use of GH2 vary. While there are numerous challenges – often of technological nature – these three are among the most discussed and are closely related: high production costs, insufficient regulations and standards, lacking infrastructure (IEA, 2019; IRENA, 2021; Noussan et al., 2021).

Green hydrogen, produced through electrolysis powered by renewable energy, is today more expensive than fossil fuel based technological routes, such as grey or blue hydrogen. As of 2021, gray hydrogen cost on average 1.5-2.5 US$/kg H2, blue hydrogen 1.5-3.0 US$/kg H2 and green hydrogen 4.0-9.0 US$/kg H2 (IEA, 2022b). Because induced electric energy makes up a large share of these costs, they have recently been quite volatile due to the turmoil induced in global natural gas and energy markets that resulted from the Russian invasion of Ukraine in February 2022. At the time of writing this article, prices had started to return to pre-invasion levels.

Looking more precisely at the cost structure of GH2, its drivers are in principal cost of the electricity induced in the electrolysis, capital expenditures (CAPEX) when building a plant, operation and maintenance costs, cost of capital and water costs (IEA, 2022b).

Electricity makes up about 50-70% of green hydrogen’s cost. Defining for the cost of electricity are the costs associated with building, for instance, wind or solar parks (CAPEX), the availability of RE sources (varying throughout the year and between geographies), the regulatory framework and the presence or absence of incentives for REs or carbon pricing mechanisms, grid integration and infrastructure, market competition and demand, and cost of capital to finance capital investments (IEA, 2022c). Reviewing these cost drivers it becomes clear, that the price of renewable power varies greatly between countries, depending on their performance on the different cost drivers. To a large extent, this is the reason why some markets are generally considered more promising for the production of green H2 than others.

CAPEX for green hydrogen production facilities consist, to a large extent of electrolyzer costs and make up about 20-30% of total green hydrogen cost. Technological advancements and economies of scale are ultimately what is going to influence electrolyzer costs. Alkaline electrolysis and PEM electrolysis are the two technological routes that accounted for about 95% of installed electrolysis capacity in 2021 (IEA, 2022b) and China and Europe jointly contributed about 80% of electrolyzer manufacturing (IEA, 2022a). Given this concentrated manufacturing capacity, other markets may see significant cost premiums for electrolyzer imports because of long transportation routes and technology import taxes. Alkaline electrolyzers are today the most financially viable technological solution, but PEM electrolyzers have a smaller carbon-footprint and a higher output efficiency (IRENA, 2021).

Next to these two main cost drivers, operation and maintenance (~5-10%) can be country-specific and cost of capital (~5-10%) depends largely on the current economic situation. Water cost is, in most cases, only of marginal importance. Increases in scale and water demand of green hydrogen production will, however, likely see to an increase in discussions about which are the best ways of sourcing water so that the hydrogen industry does not begin to compete with other, more basic consumers of water.

A second key bottleneck for the ramp-up of GH2 are insufficient regulatory frameworks and standards. Harmonized global standards for what precisely constitutes green hydrogen, e.g. what is the exact criteria in terms of carbo intensity, would enable the quicker development of global GH2 trade, but their absence creates uncertainties and market inefficiencies. Connected to this are doubts about the modalities of hydrogen certification, and considerations about what would qualify a certifying entity. The certification landscape today is scattered, as individual markets are unlikely to introduce standards that would be unfavorable for production and consumption within the economic area. The IRENA (2023) identified 13 certifications globally, which are far from consensual about the technical criteria for green, clean or renewable hydrogen. Additionally, for green hydrogen to be produced and consumed on a large scale, regulatory frameworks governing this market will have to be established. Such frameworks may regulate pricing, contractual questions, and market concentration and access, among others. The definition of such regulation will be a significant challenge, involving many different stakeholders and potentially conflicting interests.

Observing its value chain, the third major barrier to overcome is the transportation and storage of green hydrogen and associated needs for infrastructure development. These logistical questions are particularly challenging, because hydrogen has much lower energy density than energy carriers like natural gas, which makes it inefficient to transport it in its gaseous state and, hence, creates a need for storage and transport technology that either creates high pressure or cools H2 down to very low temperatures (IEA, 2019). The most feasible means of transportation are pipeline networks or maritime transport (IEA, 2022b). Existing gas pipeline infrastructure would have to be substantially retrofitted for it to be able to transport high percentages of hydrogen, and for maritime transport transforming H2 into derivatives such as ammonia or directly exporting green hydrogen based products are technologically more feasible approaches. The necessary type of transporting infrastructure is, in any scenario, associated with substantial investments and regulatory guidance to guarantee minimal environmental impacts, safety and efficiency. Again, such regulations will have to be harmonized across sub-national and national borders, which introduces an additional degree of complexity. Next to the physical infrastructure, skilled personnel for the development and the operation of production, transportation and application technology represents another significant gap (IRENA, 2020).

2.4 Brazil’s potential in hydrogen

In order to provide some background on the role of GH2 in Brazil, this section outlines arguments for why Brazil is frequently discussed as being among the most promising markets for green hydrogen.

Given the challenges for a ramp-up of green hydrogen mentioned above, Brazil has some strong competitive advantages over other markets to develop this technology. A study by McKinsey & Company drew a scenario were the domestic Brazilian market for green hydrogen could potentially reach a volume of 10-12 billion US$, with exports possibly reaching values of 4-6 billion US$ in 2040 (Gurlit et al., 2021). According to the same projections, the LCOH2 (green) could fall to about 1.50 US$/kg in 2030, making it competitive with other production methods and other promising geographies (Gurlit et al., 2021).

One main reason for such positive scenarios is the fact that Brazil has an abundance of renewable electric energy sources and generated 83% of electricity from renewable sources in 2021 (EPE, 2022). Additionally, wind and solar energy are the fastest growing energy sources in Brazil, with the levelized cost of electricity (LCOE) of the former projected to drop by up to 27% and of the latter by up to 46% by 2040 (Sawaya et al., 2022), as untapped potentials such as off-shore wind will be leveraged increasingly. As explained in the previous section, electricity prices are the biggest cost driver for green hydrogen production, showing the significance of these projections. A further advantage for Brazil to potentially assume a role as a major exporter of green hydrogen and derivatives is that the country's Northeast has both enormous potentials for RE generation and a strategic geographic positioning for exports, particularly to Europe (Gurlit et al., 2021), which has already announced large future important demands. Brazil has a well-integrated power grid, and is home to numerous opportunities for driving domestic demand in heavy industries, of which some could even begin using green hydrogen as a feedstock within the next few years (CNI, 2022).

H2, especially when based on renewable sources, is unavoidable when discussing the future of our energy systems today. For Brazil, it not only represents a promising pathway for decarbonization and export, but also for new economic prosperity and growth of domestic industries (CNI, 2022).

Given that this research set out to analyze the transition toward green hydrogen in Brazil, the following chapter will elaborate on the methodology used to analyze the development of the green hydrogen sector in Brazil under consideration of the theoretical groundwork presented in section 2.2, in order to identify the main obstacles and enabling strategies.

3. Methodology

This chapter explains and argues for the chosen research design. It describes the single-case study design according to Yin (2017), outlines the approach's limitations and details the different data collection methods used.

3.1 The single-case study

This research is a single-case study as described by Yin (2017) in his sixth and most recent book about case study research. The author posits that in order for the case study approach to be selected over other possible methods, the research topic has to fulfill three important requirements.

Firstly, an explanatory research approach aiming to answer an explanatory research question represents a condition where a case study can be the right choice of method. The research question for this research project is:

> *What are the main obstacles to the development of a green hydrogen economy in Brazil and how could this development be enabled?*

The research approach therefore fulfills the first criterion.

Secondly, the research should be focused on contemporary events, rather than strictly historical ones. Globally speaking, the ramp-up of green hydrogen is still in an infant state. Even though the number of national hydrogen strategies has been growing since Japan published the first one in 2017, frequently discussed scenarios for the green hydrogen roll-out typically use time horizons that go until 2050 - the mark at which many parts of the world aim to have reached carbon neutrality. Especially when considering the negligible share of green hydrogen and its derivatives in hydrogen generation and application globally and in Brazil today, there is no doubt about the contemporality of the topic.

Thirdly, the events of interest ought to be outside the researcher's sphere of influence. Analyzing systemic transitions and the actors and processes they encompass is a complex, multi-variable undertaking. Trying to correctly capture the dynamics at work in the development of a GH2 sector in Brazil is far from a laboratory condition and I as a researcher have no direct way of influencing these events. This research endeavor therefore fulfills the third of Yin's requirements.

Including these and other characteristics, Yin (2017) lists the following features as defining a case study:

- Contemporality of the phenomenon under analysis;
- In a real-world context → blurry boundaries between phenomenon and its environment;
- A complex situation where there are more relevant variables than data points;
- Necessitates the development of theoretical propositions;
- Uses a variety of data sources.

Given this criteria, one can delineate this case study approach from other types. It follows a methodical procedure and has an explanatory purpose, which is why it should be differentiated from, for instance, a "teaching case" with the purpose of being used in pedagogical settings. This case study aims to study a specific sustainability transition, based on propositions grounded in a theoretical framework. It uses the multi-level-perspective on socio-technical transitions including the transition pathways elaborated by Geels & Schot (2007). Different from randomized experiments, it does not aim for generalized inferences to populations or the world as such, that is, it will not make statistical generalizations. Sustainability transitions theory and literature about the H2 ramp-up are used to arrive at theoretical propositions that shape the study's design and ultimately shall help to arrive at argumentative claims about how the development of the Brazilian GH2 economy may be best enabled.

The research question stated above was defined through an extensive study of scientific literature, sector studies, reports, forecasts and relevant news articles. Studies on the socio-technical transitions involved in the roll-out of different "green" technologies exist in large numbers, especially in the realms of transportation (e.g., electric vehicles) and energy (e.g., wind or solar PV). Case-specific analyses on how the transition towards green or renewable hydrogen unfolds in different markets are, however, to this day few in number. Some examples partially taking a socio-technical perspective on such transitions linked to hydrogen include those of Gordon et al. (2023), Griffiths et al. (2021), McDowall (2014), but given the particularities of either case and the pace of developments in green hydrogen, this case study will add to the literature both through its use and testing of a relevant framework for systemic transitions towards sustainability and the analyses of processes that are highly relevant for the decarbonization and the realization of economic potentials in Brazil.

This case study represents a single-case design, because the analysis of green hydrogen sector development in Brazil represents a critical case (Yin, 2017) for analyzing a sustainability transition in a market with unique conditions for the large-scale development and adoption of this technology (Gurlit et al., 2021; Sawaya et al., 2022). Therefore, this single-case study can make a meaningful contribution to knowledge on systemic transitions, in particular towards decarbonized energy systems by confirming, challenging or extending the MLP-explanations for how such transitions unfold and what inhibits them (Geels, 2004; Geels et al., 2017; Geels & Kemp, 2007). Given the prevalence of such discourses on a global level, comprehensively analyzing the specific case of Brazil using the prominent MLP-framework justifies this approach.

The MLP is suitable for analyzing the development of Brazil's green hydrogen sector, as it offers a comprehensive framework that can assess the interplay of incumbent and emerging actors, institutions and artefacts. By considering niche innovations, different barriers, and long-term transition dynamics, MLP provides a structured lens to identify obstacles and propose enabling strategies for the growth of the green hydrogen sector in Brazil. Its multi-level analysis is particularly valuable for understanding the sector's progress at different levels of the socio-technical system, allowing for a holistic understanding of the transition process.

Considering Yin’s differentiation of *embedded* and *holistic* single-case study designs, the latter is more appropriate given the holistic nature of the employed MLP-framework. While this bears the risk of generating too abstract of a focus, not focusing on specific industries is advisable given the infant stage of green hydrogen in Brazil, the limited availability of applicable data and the importance of jointly regarding all (potentially) relevant actors and sectors in the Brazilian green hydrogen ecosystem in order to understand the full range of dynamics at play.

Yin (2017) further points to the importance of using a case study protocol. This is a document that consolidates the important components of a case study to be reported on, such as the context, the main objectives, data collection procedures etc., and it serves to enhance the study’s reliability and to keep the researcher’s focus on target. For the purpose of this master’s thesis, the dissertation itself serves as protocol and report of the case study. Most of the important components mentioned by Yin (2017) are therefore included, as structure and terminology are more adapted to the specific academic context and guidelines provided by the supervising universities.

3.2 Data collection

The unit of analysis for this study is the socio-technical system for green hydrogen in Brazil, not to be confused with the units of data collection (Yin, 2017), which are documents (secondary data) and interview transcripts (primary data).

Essentially, the data collection procedure consisted of five steps:

1. Accumulation and study of relevant documents as secondary data sources;
2. Identification and contacting of suitable interviewees;
3. Development of a questionnaire for semi-structured interviews;
4. Conducting the interviews (including video recording);
5. Transcription and translation of the recordings.

In the first step, sectoral studies and academic research articles were accumulated in order to collect relevant secondary data. The result represented a starting point for the identification of appropriate interviewees for the collection of primary data. These interviewees were contacted mostly via e-mail, including the research letter emitted by my university. The expected difficulties in receiving positive, if any, responses and in the timely scheduling of interviews led to a certain limitation in the number and range of interviewed experts. The number and diversity of documents (i.e. secondary data) that could be identified in the first step did, however, alleviate the impact of the limited number and range of interviewees. Once the interviews had been scheduled, a questionnaire for a semi-structured interview (Yin, 2017) using a limited number of guiding questions was developed. While the questionnaire was iteratively adapted from one interview to the next, the core structure and contents did not change much and a model of the questionnaire is revisable in *Annex A*.

Interviews were conducted with six experts that address green hydrogen in Brazil from different perspectives, namely: one specialized consultant, one individual from academia and research, one from sectoral representation, one representing an electricity market operator and two from the private sector (generation and application of green hydrogen). (See *Table 2* for a summary.) Five out of six interviews were conducted in Portuguese given interviewees' preferences.[2] All interviews were conducted through Microsoft Teams and recorded, based on the interviewees' permission. As a last step to prepare the collected data for analysis, the interviews' recordings

---

[2] The ability to understand and speak Portuguese was relevant throughout the execution of this case study research. Next to the interviews, a substantial part of the secondary data assessed was in Portuguese. Because the researcher speaks both languages, this was no limitation but should be mentioned for the sake of completeness.

were transcribed and in five out of six cases translated into English, using the translation tool DeepL[3].

As the interviewed experts were anonymized after each conversation, the remainder of the article will refer to them with numbers. *Table 2* attaches a number to each interviewee and further provides information on the type of actor. *Table 3* summarizes the relevant documents that provided secondary data for the analysis of the Brazilian case.

Interviewee number	Type of actor	Month of interview	Format & length	Language	Consented to recording & anonymized transcription
1	Specialized Consultant	April 2023	Video call (41 min.)	English	Yes
2	Private sector (project manager)	April 2023	Video call (27 min.)	Portuguese	Yes
3	Academia & Research (professor)	April 2023	Video call (35 min.)	Portuguese	Yes
4	Market Operator (manager)	May 2023	Video call (29 min.)	Portuguese	Yes
5	Sectoral representation (senior analyst)	May 2023	Video call (46 min.)	Portuguese	Yes
6	Private sector (project manager)	May 2023	Video call (65 min.)	Portuguese	Yes

Table 2: Interviewed experts

Type	Sources
Documents	Sectoral Reports (BNDES, 2022), (CNI, 2022), (IPEA, 2022), (GIZ & MME, 2021) Research Articles (Chantre et al., 2022), (Fernandes et al., 2023), (Gurlit et al., 2021), (Sawaya et al., 2022) Governmental publications surrounding PNH2 (EPE & MME, 2021), (MME, 2021), (MME, 2022)

Table 3:Main sources for secondary data collection

---

[3] The DeepL translation tool uses artificial intelligence and deep learning techniques to provide high-quality translation services.

3.3 Analytic strategy

In order to analyze the collected data, this research relies on theoretical propositions. The propositions represent the barriers identified in both GH2 and MLP literature. They have the purpose of guiding the research to focus on the obstacles and enabling strategies to the development of a green hydrogen economy in Brazil, linking theory and real-life phenomena. The propositions were formulated based on extensive literature review and help in keeping the endeavor on-track towards answering the research question.

The research propositions are:

P1	**Economic barriers** *A number of factors perpetuate cost disadvantages of GH2 against competing energy carriers in Brazil.*
P2	**Institutional barriers** *Existing regulations and practices concerning GH2 provide unfavorable economic conditions for the development of this sector in Brazil.*
P3	**Resource constraints** *The resources necessary for the development of the GH2 sector in Brazil are not sufficiently available, representing an obstacle to its development.*
P4	**Insufficient supporting infrastructure** *The infrastructure required for the ramp-up of GH2 in Brazil is insufficient and represents a barrier to the development of this sector.*
P5	**Coordination challenges** *Effectively coordinating the different important stakeholders for the development of the GH2 sector in Brazil represents a relevant barrier.*

Table 4: Research propositions used for qualitative primary and secondary data analysis (author's elaboration)

In order to compare the theoretical propositions to the collected data, the analytic technique (Yin, 2017) is pattern matching for process and outcomes. This means that the processes and outcomes suggested by the propositions will be compared with actual, contemporary events. This will allow for a testing of the multi-level-perspective and its transition pathways (Geels & Schot, 2007), using the critical case of green hydrogen in Brazil. In practice, this means that both the interview transcripts and identified documents are analyzed using the color code presented in *Table 4*.

3.4 Validity & limitations

This section argues for the research design described above. It explains how the study performs against the criteria of *construct validity*, *internal validity*, *external validity* and *reliability* (Gibbert et al., 2008), also pointing to limitations.

Assessing *construct validity* is to test how well a given research design actually investigates or measures what it seeks to investigate. Seeking to answer the research question, I argue that construct validity is satisfied because the research provides a logical chain of evidence stemming from multiple, diverse sources. A warranted critique of this research design would be to point out that the range of interviewees does not allow for insights into the perspective of the full diversity of relevant players in the green hydrogen ecosystem. This, in fact, weakens construct validity.

Secondly, i*nternal validity* concerns the inference of causality between one event and another. This is especially relevant in a research endeavor like this one, because of the systemic complexity that this holistic single-case study faces when assessing the socio-technical system of GH2 in Brazil. While the causalities outlined in this research are not immune to criticism, this article does not claim unequivocal completeness and the previously explained analytic strategy does strengthen the findings' plausibility.

Thirdly, a study has e*xternal validity* when its findings can be generalized beyond the unit of analysis of it. Given that the theoretical propositions were derived from seminal theory explaining the phenomenological nature of systemic transitions, a satisfactory degree of external validity is given. However, it should be noted that individual geographic and national contexts yield unique characteristics that should lead anyone reading this article to be cautious about extrapolating from developments in Brazil to developments elsewhere.

Lastly, this entire chapter and the inclusion of annexes detailing the methodology serve to strengthen the *reliability* of this case study. It does so through a detailed description of the approaches towards data collection and analysis and by maintaining a chain of evidence. Even though unlikely, this would theoretically allow for an exact replication of the research at a later point in time, which, given rapid developments in and around GH2, might confirm or offer novel findings.

The following chapter presents the results obtained in the data collection procedure described above.

4. Results

This research focuses on the development of a green hydrogen economy in Brazil and its obstacles and enablers. It set out to answer the following research question:

> *What are the main obstacles to the development of a green hydrogen economy in Brazil and how could this development be enabled?*

In the following sections, this chapter presents in a non-interpretative manner the results from data collection through interviews (primary sources) and the analysis of documents (secondary data).

The first section presents the results regarding the status quo of hydrogen in Brazil, outlining gathered information about production, consumption, policy, regulatory matters and different actors' initiatives. This section presents both, the data collected about the present and the future state of H2 in Brazil and serves to set the stage for the results directly addressing the research question.

The ensuing five sections each present the identified obstacles to the development of a hydrogen economy in Brazil, structured in the five types of barriers that were previously derived from the literature about the multi-level perspective on socio-technical transitions: economic barriers, institutional barriers, resource constraints, lack of supporting infrastructure, coordination challenges. Each of these sections also provides identified enabling strategies to overcome the respective challenge. It should be noted that many identified obstacles and enablers could just as well be allocated to two or even three different categories, which is associated with the many interdependencies in socio-technical energy systems.

Table 5 at the end of the chapter contains a summary of the identified obstacles and enabling strategies.

4.1 Hydrogen in Brazil: present and future

Actors & Artefacts

While green hydrogen is being discussed as a technology of opportunity in the future, Brazil is already home to industrial hydrogen production and consumption. According to the most recent obtainable data, the state-owned oil and gas company Petrobras was the main producer of H2 in the country (95%) in 2018, a self-producer and primarily produced gray hydrogen through steam methane reforming (SMR) (GIZ & MME, 2021). As of 2019, Petrobras consumed this hydrogen almost exclusively in refinery processes, as it had divested heavily from nitrogen fertilizer production (using the H2 derivative ammonia) in previous years (GIZ & MME, 2021). Hydrogen production facilities are, to a large extent, located in proximity to the gas pipeline network in Brazil's coastal regions. These pipeline networks (about 10.000 km as of 2021) typically transport natural gas from offshore exploration in the industrial centers along the coast (GIZ & MME, 2021). In spite of being one of the biggest fertilizer consumers in the world, Brazil’s fertilizer production has almost completely moved overseas and with it an ammonia consuming industry (CNI, 2022). Other producers of hydrogen are industrial gas companies, which supply small volumes to industries, such as steel, food, flat glass and power generation. Given the small quantities, hydrogen is distributed in compressed form via road transport (GIZ & MME, 2021).

When asked about how developments surrounding green hydrogen have initially unfolded in Brazil, interviewees 1, 2, 5 and 6 emphasized that, different from how it occurred in many other countries, in Brazil the private sector became active before the federal and state governments started to show interest in the developments surrounding green hydrogen and Brazil’s potentials for generation and export. Interviewee 2 stated that private sector interest in the technology had its roots in an international discussion that was largely driven by European countries, who began outlining their strategies and announcing substantial future import demand for GH2 and derivatives.

Interviewees 1, 2, 3, 4 and 5 highlighted the notable activity of state governments that have started to identify green hydrogen as a strategic priority, often through the initiatives in industrial ports or the identification of usable areas. Interviewee 1 emphasized a contrast, saying that the federal government took longer to show initiative towards assuming its attitude in relation to H2-technologies and interviewee 5 stated that related working processes at the federal level were untransparent, leaving many other actors with uncertainty about what to expect from the future of this market.

Interviewees 1 and 3 further highlighted the protagonism of the German Federal Government and associated agencies, which are active in Brazil through development cooperation projects (e.g., *H2Brasil)* that aim to propel the market for green hydrogen.

All six interviewees emphasized the importance and proactivity of industrial hub initiatives in the North- and Southeast that identified green hydrogen and its derivatives as strategically promising and that have, beginning strongly in 2021, started to attract multinational and

Brazilian companies, interested in leveraging these strategic advantages. The most frequently mentioned hub initiatives were those at the Port of Pecém (Ceará), at the Port of Açu (Rio de Janeiro) and at the Port of Suape (Pernambuco), which were discussed by all interviewed experts and in many of the analyzed documents (BNDES, 2022; CNI, 2022; GIZ & MME, 2021; IPEA, 2022). Regarding the Port of Pecém, interviewees 5 and 6 highlighted the importance of its export processing zone (ZPE), which encompasses administrative, tax and currency exchange incentives for exporting companies.

Figure 4: Announced H2-related projects in Brazil as derived from EPE (2023)

In this context, five out of six interviewees discussed the numerous memorandums of understanding (MoUs) that were signed between industrial ports – often to a large extent owned by state authorities – and energy or industrial companies, such as the Portuguese EDP at the Port of Pecém, that has inaugurated a small-scale pilot plant which has already generated the first molecule of green hydrogen in December of 2022. Another project example mentioned frequently was that of the Brazilian fertilizer company Unigel in the state of Bahia, aiming to produce green ammonia for fertilizer production on an industrial scale, which is supposed to start operations by the end of this year (2023). These also represent the two principal business models that interviewee 1 outlined as being either (1) the production in and around industrial port areas with favorable conditions for the use of REs or (1) the production in industrial clusters with a direct link to offtakers.

When last reviewing existing project announcements, these totaled financial volumes of more than 30 billion US$ (Forbes, 2023). *Figure 4* was drawn from a tool provided by the Brazilian Energy Research Office (EPE) and allows for insights into the localizations and volumes of announced H2-related projects in Brazil (EPE, 2023). As frequently discussed by the interviewees, these tend to concentrate in areas with high potential for RE generation, mostly in the North- and Southeast.

Interviewee 3 stated that it is likely going to be “actors that have the financial robustness to make major capital investments” that will be at the forefront of the development of production in this sector. Describing the gap between MoUs and concrete FIDs, interviewee 4 expressed that “a market is born by demand” and in line with this statement interviewee 1 elaborated that in the short-and mid-term green hydrogen generation will most likely occur in industrial clusters that directly connect supply and demand, as in the case of Unigel in Bahia.

When asked about what they believe will be the most important consuming industries of green hydrogen and its derivatives in the future, all but one interviewee listed a number of sectors. Five interviewees described both the (petrochemical) fertilizer industry and the refinery sector as the most important industries in Brazil to prospectively consume green hydrogen and its derivatives. The Brazilian steel industry found the third most mentions (four) and other sectors that were touched on by less experts were the transport, buildings and the chemical industry. Given its vocation, the Brazilian National Confederation of Industry (CNI) focused its 2022 study on the potentials of different industrial sectors for the insertion of sustainable hydrogen and identified significant opportunities for the development of a domestic consuming market (CNI, 2022).

Across this and other studies (e.g., BNDES, 2022; Chantre et al., 2022; GIZ & MME, 2021) the most highlighted sectors remain the same, whilst the time dimensions are increasingly highlighted, explained by technological readiness and required investments. To this extend, the CNI (2022) identified the ammonia (/green fertilizers) and steel industry as the most apt short-term drivers of domestic GH2 demand, with the production of methanol for the chemical and petrochemical industry described as a medium-term offtaker. This is in line with statements of interviewees 1 and 3, who explained that that industries already using hydrogen as a feedstock are the likeliest to start demanding GH2 in the short- and mid-term, because their adaption does not require the same CAPEX as that of more “technologically distant” industries, and they have the opportunity to increasingly blend green or low-carbon hydrogen into their productive processes. Interviewee 1 further stated, that among the biggest motivations for such industries is to maintain international competitiveness in the light of increasingly rigid emissions requirements in other markets, such as the announced *Carbon Border Adjustment Mechanism* (CBAM) in the EU. Such greening of industrial outputs found a notable number of mentions across the interviews and analyzed documents.

Institutions

Legislative and regulatory activity regarding hydrogen in Brazil has regained attention, but Brazilian policy makers have eyed this energy carrier for quite some time. In 2005, the Brazilian Ministry of Energy and Mining (MME) published its *Roadmap for Structuring the Hydrogen Economy in Brazil*, which identified Brazil's potential competitive advantages, different feasible technological routes and the possibility of a market consisting of distributed generation. In 2017, the Brazilian Hydrogen Association (ABH2) was founded in order to integrate public and private actors and resources, and to enable a coordinated development of the sector. Ultimately, these and other initiatives culminated in the publication of the *National Hydrogen Program* (PNH2), which proposes governance guidelines for the development of the hydrogen sectors (MME, 2021). In 2022, the PNH2 was followed up with its *Triannual Working Plan 2023-2025*, with the objective of guiding the actions of the federal government in the development of the hydrogen sector in the next years and organized along six axis: improve the scientific and technological bases; training of qualified professionals; energy planning; legal and regulatory framework; and opening, growth of the market and competitiveness and international cooperation (MME, 2022). The axis themselves include further guidelines and are executed in five thematic chambers (all axis but "international cooperation") which encompass concrete actions and time horizons, and which aim for the inclusion of other actors from the H2 ecosystem. The plan further mentions numerous existing policies and regulations as complementary, which was also repetitively commented on by the interviewees.

The program's steering committee is headed by the Ministry of Mines and Energy (MME) and contains members from 14 different governmental entities[4] (MME, 2022). The plan was open for public consultation between the end of 2022 and the beginning of 2023, allowing for suggestions to adapt the plan.

In March 2023, a bill ("Lei do Hidrogênio") was presented in the Senate that includes hydrogen as an energy source in the Brazilian matrix and establishes goals for insertion in national gas

---

[4] *Ministry of Mines & Energy, Civil House of the Presidency of the Republic; Ministry of Finance; Ministry of Development, Industry, Trade and Services; Ministry of the Environment and Climate Change; Ministry of Foreign Affairs; Ministry of Science, Technology and Innovation; Ministry of Integration and Regional Development; Ministry of Education; Ministry of Agriculture and Livestock; Ministry of Ports and Airports; National Electric Energy Agency; National Agency of Petroleum, Natural Gas and Biofuels; Energy Research Company*

pipelines. The most recent development in Brazilian politics upon authorship of this article was the founding of a special senate commission on green hydrogen in March 2023 (Castro, 2023).

The following five sections present the obstacles to the roll-out of GH2 in Brazil that were identified by the analysis of collected primary and secondary data.

4.2 Economic barriers

Research proposition P1 regards the economic barriers to the development of the GH2 sector in Brazil and states: *A number of factors perpetuate cost disadvantages of GH2 against competing energy carriers in Brazil.* This section describes the identified factors before outlining the enabling strategies gathered during data analysis.

According to interviewee 4, reaching a viable cost is the most important challenge to the development of a green hydrogen market in Brazil. All interviewees and analyzed documents directly or indirectly discussed the difficulties in bringing down production costs in Brazil and linked them to a variety of causes.

Economic environment

Interviewee 3 named the current macroeconomic situation in Brazil as one of the reasons for why only few companies are actually taking FIDs. According to the expert, high interest rates make companies act in a more frugal way, with high opportunity cost making the required capital investments and the associated cost of capital unattractive. Interviewee 4 further stated that unfavorable currency exchange rates also play an inhibiting role for the competitiveness of Brazilian green H2.

Another aspect representing a barrier for investment in GH2 in Brazil is a phenomenon referred to as the “Brazil Cost” (GIZ & MME, 2021), which stands for the country’s complex tax system with a dense bureaucracy, logistical bottlenecks and legal uncertainty that does not encourage investment in the country. In line with this and the other previously mentioned factors, interviewees 1 and 3 speak of a real risk that the FIDs on many of the existing MoUs are not followed through on, but instead made in other markets.

Risk and uncertainty in offtaking

Further, interviewees 1, 2, 5 and 6 explicitly mentioned the absence of guaranteed offtaking, i.e. lacking security demand, as being one of the key factors inhibiting investments in production capacity and hence market development. Interviewee 2 spoke of “a big lack of confidence" in required long-term offtaking of the produced products as one reason why most projects have not passed the FID yet. These uncertainties regarding long-term demand (in volume and prices) perpetuate risks for investors and inhibit the funding of large projects (CNI, 2022; Gurlit et al., 2021). As CAPEX represent one of the main cost drivers for GH2, data clearly showed that given current certainties and risk levels investments are unlikely to occur if the conditions do not change.

Electricity, electrolysis and water

Further weighing in on the cost of imported technologies for electrolysis, interviewee 6 stated that high import taxes in Brazil add to the price of such technology and, hence, the price of green hydrogen production. Interviewees 1 and 6 further highlighted that importing these key technologies generates vulnerability to international price developments and geopolitical dynamics. Adding to the description of the two main drivers for the levelized cost of hydrogen, electrolyzers and electric energy, interviewee 4 explained that Brazilian electricity prices are competitive, but also not particularly cheap in global comparison.

Assuming an industrial scale production, interviewee 6 further highlighted the importance of an intelligent regulation of access to water for the hydrogen-industry, in order to ensure that water does not turn into a resource where industry competes with the population, which would in turn drive up the otherwise relatively low cost of a resource that is needed as feedstock and for the cooling of electrolyzers. Accessing and potentially treating water (e.g., through desalination) in likely producing arid regions like the Northeast may drive up cost, according to the CNI (2022).

Limited (national) access to financing schemes

In order to resolve the supply-demand dilemma in the nascent market of GH2, there are public financing schemes and public-private partnerships offered by wealthier countries, such as the H2Global instrument outlined in chapter 2.

Contrasting Brazil with other countries that are showing proactivity in green hydrogen, interviewees 1 and 2 pointed to the countries limited financial means to provide public financing mechanisms, such as public-private partnerships (PPPs) or contracts for difference, as a competitive disadvantage, as high national debt makes large government spending less likely (GIZ & MME, 2021).

Enabling strategies

When asked about the current lack of actual financial investment decisions, interviewee 3 said: “One thing is the strategic political decision; another thing is the financial decision.” The expert emphasized the view that financial decision-makers would be the key enablers for the development of the green hydrogen sector, as they would have to take FIDs as soon as it became financially viable.

Distributed generation in industrial clusters

Interviewee 2 described the linking of distributed generation in industrial clusters to energy-intensive consuming industries as the most cost-competitive model in the short- and mid-term, as it this manages avoiding distribution costs which could double the price of GH2. The creation of such clusters typically occurs through joined ventures between producers and consumers and may be subsidized by the state. According to the expert, it has become observable, that mainly producers that have a guaranteed offtaker, as is the case for Unigel which will use the generated green ammonia for the production of nitrogen fertilizers, actually do take a financial investment decision.

Expanding REs

Interviewee 5 stated that, given the cost structure of green hydrogen, a main focus would have to be the expansion of existing renewable energy capacity, next to leveraging untapped RE potentials, such as in off-shore wind. The expert recommended developing national industries, for instance for the production of RE technology, in order to bring down costs, avoiding high import tariffs and reducing dependencies.

Petrobras

Interviewee 3 stated that the involvement of influential actors, such as that of state-owned oil and gas giant Petrobras, could be a real accelerator as it would express ambitions of the federal government and activate substantial investment capacities. Pointing to the future, interviewee 3 underlined that important Brazilian players such as Petrobras, may not have started investing in green hydrogen technology yet, but may ultimately play an important role.

Bring key manufacturing industries to Brazil

Interviewee 5 suggested as a strategic priority to bring value generating industries, such as the manufacturing of electrolyzers and steam reformers, to Brazil, so that the country can build up technological know-how within its borders and create green products that will be highly competitive on the international market in the future. This then could contribute to a cost reduction of Brazilian GH2, as high import tariffs on technologies would be avoided. A first development in this sphere, the German Neuman & Esser group has already begun the construction of the first plant to produce electrolyzers and steam reformers in Brazil, in the state of Minas Gerais (Agência Minas, 2023).

Enable domestic producers to engage in/ bid for long-term offtaking contracts

Interviewees 1, 2 and 6 emphasized that long-term offtaking contracts would be a key for roll-out of green hydrogen in Brazil. The experts therefore expressed the view that enabling domestic producers to engage in and bid for long-term offtaking contracts would go a long way in catalyzing the market in the country.

Blue H2

A couple of sources advocated for technological openness, stating that blue hydrogen (made from natural gas) may serve as a transition product to green hydrogen. If there is abundant natural gas exploration from pre-salt, market growth based on the new gas law, and expanding infrastructure, gas prices could fall significantly over the medium and long terms (BNDES, 2022; Gurlit et al., 2021). According to the authors, this would help reap the economic development benefits, such as increased tax income and generation of jobs, using the existing natural gas infrastructure.

Recovery of national ammonia industry

As described in this chapter’s first section, the H2-derivative ammonia and an attached fertilizer producing industry has almost completely disappeared from Brazil. Ther recovery of a competitive national ammonia industry, using natural gas as a technological bridge could help stabilize the demand in the medium- and long-term, because of the high domestic fertilizer demand and other applications of ammonia in heavy-haul transport or potentially reconversion to hydrogen (BNDES, 2022).

4.3 Institutional barriers

Research proposition P2 considers the institutional barriers for the development of the GH2 sector in Brazil and states: *Related regulations and practices insufficiently favor the development of the GH2 sector in Brazil.* The applicable identified results and the enabling strategies gathered from data analysis are presented hereafter.

Interviewees 5 and 6 defined current regulatory frameworks and public policies as the most important barrier to the development of the green hydrogen market in Brazil. Interviewees 1 and 5 both argued that the previous federal administration did not prioritize hydrogen and said that an ambitious national strategy would be important to attract foreign investors whilst in competition with other promising geographies. In line with earlier mentioned descriptions of the private sectors proactivity in comparison to the federal level, interviewee 5 elaborated that he knew of

> “[…] a lot of companies that are wanting to move forward and what we've been realizing here is that to move forward faster and more safely, regulation at the federal level is going to be extremely important.”

Regulatory balancing

Interviewee 2 described a discursive conflict in the debate surrounding hydrogen and identified challenges of finding a right balance between a regulatory framework that provides markets with sufficient clarity and certainty without inhibiting the many possible routes of market and technology development, and that simultaneously promotes production routes aligned with the requirements of importing countries and markets (offtakers).

Insufficiencies in PNH2

A recurring theme, five out of six interviewees discussed insufficiencies in Brazil’s National Hydrogen Program and an insufficient regulatory framework.

When speaking about investments, interviewees 1, 2, 3 and 5 expressed the view that the PNH2 is not explicit enough in its ambitions and objectives. According to these experts, this leaves investors in a state of uncertainty and the absence of positioning on the federal level inhibits companies from taking FIDs. “Its marketing, it’s a concrete sign that is lacking.”, explained interviewee 1 and added that ambiguous political signals about a national vision and desired technological routes have left players in the market without clarity.

According to the CNI (2022), the program proposes no effective actions to attract investment into the demand side, perpetuating the offtaking dilemma. That is because the program does not clarify and evaluate the domestic demand market is, and no priority sectors are defined in it (CNI, 2022).

Touching on the newest iteration of the PNH2, its Triannual Working Plan, interviewees 3 and 5 stated that the intended speed for developments is too slow, prolonging regulatory ambiguity and failing to capture the accelerating nature of international developments in GH2. Interviewees 5 and 6 further cited insufficiencies in the involvement of other relevant stakeholders in policy and regulation development, which may lead to such misalignments with market requirements.

Omission from incentivizing regulation

Considering the wider regulatory environment within which GH2 is to compete with other energy carriers, interviewee 2 stated that the exclusion from potentially stimulating regulatory incentive schemes like REIDI[5] or the *Lei do Bem*[6], which, if turned applicable, could support infrastructure development and R&D programs along the value chain of GH2.

It was further identified that tax incentives, such as those that were used to develop wind and solar energy markets in Brazil (e.g., PROINFA), have not been introduced, leaving GH2 in a situation where the energy vector cannot compete under unprotected market conditions (CNI, 2022). Further, regulation that could indirectly increase the competitiveness of GH2, such as mandatory carbon pricing schemes or other decarbonization regimes have not been introduced (Chantre et al., 2022; CNI, 2022; Gurlit et al., 2021).

Uncertainty about technical standards

Commenting on technical standards and frameworks, interviewee 6 stated that the first Brazilian Certification for Renewable Hydrogen, that was launched by the Chamber for the Commercialization of Electric Energy (CCEE), was in its first iteration still very loose on the full range of scopes of GHG emissions, and interviewee 2 made a somewhat complementary comment stating that there is a lack of alignment in international certification standards, which, according to the expert, would be important to develop trade routes for green hydrogen. According to Sawaya et al. (2022), technical standards for H2 transport and storage are also yet to be defined.

---

[5] "Acronym for the Special Incentive Regime for the Development of Infrastructure, under which the following purchases are exempt from specific taxation: the sale or import of machinery, apparatus and equipment, the leasing of machinery, the sale of construction materials and the provision of services by legal entities." (Veiga, 2022)

[6] "The law establishes benefits focused on the reduction of IRPJ (Corporate Income Tax) and CSLL (Social Contribution on Net Income) linked to research and development of technologic innovation." (Deloitte, 2023)

Enabling strategies

In their description of the obstacles for GH2 market development in Brazil, the experts also suggested ways to improve conditions surrounding the regulatory framework and public policy.

In terms of more general approaches, it were suggested the inclusion of both the supply and the demand volumes of H2 in long-term energy planning through studies by EPE (CNI, 2022), the continuation of existing and the initiation of new international cooperation initiatives in energy (GIZ & MME, 2021), a plan for decarbonization in power and transport on the national level (Chantre et al., 2022) and studies for the evaluation of economic development and job creation potential through GH2 (GIZ & MME, 2021).

Industrial Policy

As previously described, interviewee 2 focused on the need for tight regulation of domestic industry, introducing emission reduction targets for specific sectors like the fertilizers industry. In line with this, interviewees 1 and 5 expressed that market developments could be accelerated through concrete emission reduction goals for specific industries, tied to financial incentives to reach them. Interviewee 5 also named the fertilizer industry as an example of an industry that would benefit from such regulation, and the elaboration of a national policy for the production of decarbonized fertilizers from GH2, was further described as a way to reduce vulnerability in fertilizer supply (CNI, 2022).

As stated by the CNI (2022), an industrial policy for competitive structuring of H2 supply-chain in the country should further include a selection of potentially competitive sectors and funding may be provided by the BNDES.

Expert 2 further emphasized that such regulation for the internal market should take into account the price benefits that can arise from geographically dispersed generation, with different hubs that would produce H2 for local consumption, saving the significant price premium from transport and logistics and avoiding associated technological challenges.

Improvements for PNH2

Five out of six experts suggested improvements to the National Hydrogen Program. Experts 1 and 5 stated that the PNH2 would improve if it started to include concrete, measurable objectives, for which both cited as an example an indicator for installed electrolyzer capacity.

In order to elaborate feasible, realistic targets, the CNI (2022) called for the involvement of both diverse governmental and non-governmental actors.

Experts 1, 3 and 5 argued that speeding up the timelines of the Triannual Working Plan would help to enable quicker developments in the GH2 market, whilst keeping up with global developments.

Interviewees 1 and 5 further stated that the national program should define priority sectors, particularly for the consumption of GH2. This expert stated that Brazil could be made more attractive to private investments, if the federal government was to send clear signals, that it supports infrastructure development (e.g., REIDI), seeks to involve all relevant agents and aims to leverage international cooperation for the development of this new market.

Incentivizing policies & regulations

Expert 2 expressed that a catalyst could be to include potential producers of green H2 (often power companies) into established incentive schemes, such as REIDI and the Lei do Bem. Interviewee 5 outlined that legislative initiatives, such as the Lei do Hidrogênio (described in the first section), could be a step-by-step way to create foreseeability of demand, providing producers with the necessary certainties to build up capacity.

Interviewee 6 explained that an enabling strategy from the regulator's side would be to allow for the creation of new export processing zones (ZPEs), such as the one in the Port of Pecém that was previously described. The expert argued that regulation should also focus on creating environments that lead to cost reductions in the import of key technologies, lowering producers' CAPEX.

Chantre et al. (2022) states that a new federal law that temporarily includes tax exemptions and incentives for the development of H2 infrastructure is needed, and interviewee 2 suggested the creation of incentive schemes through which large companies benefit from tax incentives for pilot or demonstration projects and smaller companies with less means can benefit from help for more fundamental research. However, opinions are divided, as experts 4 and 5 were clear in saying that direct tax breaks or similar incentives would not be an effective way of strengthening GH2 producers.

A frequently mentioned way of strengthening the competitiveness of GH2 in Brazil, is the introduction of mandatory carbon pricing mechanisms in order to increase the burden on less desirable and more polluting fossil alternatives (CNI, 2022; Gurlit et al., 2021; IPEA, 2022).

More concretely, Chantre et al. (2022) suggest a carbon tax, expanded by credits associated with producing GH2.

Support to access international financing

Additionally, interviewees 1 and 5 stated that national regulation could play an enabling role for companies seeking access to international financing schemes, provided by development banks or states (such as H2Global), which could provide a first injection of confidence for producers to build up capacity.

4.4 Resource constraints

Research proposition P3 addressed the resource constraints that often represent barriers to the roll-out of innovations and states: *There are financial, human and material resources necessary for the development of the GH2 sector in Brazil that are not sufficiently available, representing an obstacle to its development*. The identified resource constraints and applicable enabling strategies are outlined in this section.

Labor force & training

According to Interviewee 6, Chantre et al. (2022) and GIZ & MME (2021) gap in qualified labor force capable of working in and around the entire value chain of GH2 is observable and this state is perpetuated by a significant lack of professional training opportunities for the green hydrogen sector.

Investments in innovation

Additionally, interviewees 4 and 2 reported a lack of financial capital directed towards research and development on low carbon technologies as a further inhibiting factor for the development of solutions along the value chain. In their research, Chantre et al. (2022) identified lacking strategic initiatives targeted at providing reliable support for investments in innovations in relevant strategic sectors, different from prospectively competing markets.

Renewable energy

Even though Brazil separates itself from other countries through its abundance of renewable energy sources, this main input for electrolysis was also discussed as a potential challenge, as industrial scale production of GH2 may put this energy carrier in competition with multiple other demanders of renewable energy, which may potentially be more efficient or profitable (CNI, 2022)

Enabling Strategies

Experts 2 and 6 characterized increasing investments in R&D and innovation as key enablers for GH2 to become competitive.

Institutional support for R&D & Training (private & public)

Identified enabling strategies for the development of a labor force qualified to work in the GH2 value chain and furthering R&D initiatives were often intertwined in the data. GIZ & MME (2021) stated that universities & R&D centers warrant strategic priority as they enable the development of the sector through the communication about the subject, training of skilled professionals and development of new technologies. Touching on the same argument, Chantre et al. (2022) emphasized the importance of directing financial resources towards GH2 innovation and suggested a funding call for academic-private partnerships. A joint venture among the Pecém Complex, the Federation of Industries of the State of Ceará (FIEC) and the Federal University of Ceará (UFC), the Green Hydrogen Hub represents such a cross-sector partnership seeking to promote investment and innovation in the area of green hydrogen.

Addressing public sector activities, the CNI, (2022) called for the elaboration of national program for research and development in GH2, via the development of strategic projects with voluntary participation of companies that have R&D funds managed by ANEEL and ANP. Further proposed was the provision of incentives for federal technical schools, National Service for Industrial Training (SENAI) and for research funding and HR training institutions (Chantre et al., 2022; CNI, 2022).

Developing and expanding REs

When discussing renewable energies, interviewee 5 and a number of secondary sources (e.g., GIZ & MME, 2021; Gurlit et al., 2021) focused on the expansion of installed RE capacity, where particularly but not exclusively off-shore wind offers a large volume of untapped potential. Interviewee 5 further advocated for an increased development of the national RE industry, also for the manufacturing of RE equipment as a way to bring down costs by avoiding high import tariffs and reducing vulnerability to international price developments.

4.5 Lack of supporting infrastructure

Research proposition P4 concerns the necessary supporting infrastructure for the large-scale adoption of GH2 and states: *The infrastructure required for the ramp-up of GH2 in Brazil* *is insufficient and represents a significant barrier to the development of this sector.* The applicable results and enabling strategies are presented hereafter.

First of all, while the literature tends to outline lacking infrastructure and associated bottlenecks in logistics as one of the main challenges to GH2 development, it did not appear to be the interviewed experts' principal concern.

Geographic proportions

However, interviewees 2 and 6 did mention transport and storage of large amounts of green hydrogen as a potential bottleneck for a functioning green hydrogen economy in Brazil, given the country's continental size, technological and infrastructural bottlenecks.

Low technological maturity

The low technological maturity in transport and storage of H2 and the necessity of large investments in associated infrastructure were associated as high cost barriers in the literature (BNDES, 2022; GIZ & MME, 2021; IPEA, 2022). The CNI (2022) further pointed to bottlenecks in the power transmission system in the North and Northeast, where the renewable energy potential is the largest.

Insufficient pipeline network

The BNDES (2022) explained that both considerable means of transportations, gas pipelines and maritime transport, are currently not feasible. As hydrogen has a lower energy density (1/3) than gas, a 3-fold expansion of the existing infrastructure would be necessary to satisfy current needs, and as of now no that are technologically equipped to transport hydrogen on an industrial scale (BNDES, 2022).

Enabling strategies

In order to meet future domestic demand, GIZ & MME (2021) suggested that production could be semi-centralized near the large economic centers and industrial parks that consume green hydrogen in the country, a suggestion similar to those outlined in the previous sections.

The BNDES (2022) further expressed the strategic option of diversifying storage forms for H2 (e.g., export terminals, refueling stations & geological storage) and explained that local distribution from hubs to final consumers is already technologically feasible through low-pressure pipelines and via trucks.

4.6 Coordination Challenges

Research proposition P5 concerns the challenge of stakeholder coordination in the large scale adoption of an innovation and states: *Coordinating different stakeholders, such as government bodies, industries, research organizations, and sectorial associations, is crucial for the development of the GH2 sector in Brazil, and challenges in effectively managing this collaboration result in delays.* The relevant identified results are presented in this section.

Untransparent and exclusive policy development

In general terms, interviewees 5 and 6 expressed the view that diverse stakeholders are insufficiently included in developments on the federal level and interviewee 6 spoke of an untransparent policy development process regarding PNH2. Interviewee 5 spoke particularly about the public consultation on the Triannual Working Plan of PNH2, which aimed at the involvement of relevant actors. The expert expressed the view that the subsequent development of the plan was untransparent to those actors that had participated in the public consultation.

Competition for water resources in dry regions

Next to proactive market development activities, the data points to possible future conflicts once GH2 generation reaches industrial scale, particularly in the dry regions in the country's Northeast. Large amounts of water will be needed both as a feedstock for electrolysis and to cool electrolyzers, which may lead to distribution struggles or at least to local stakeholders' skepticism and resistance, according to interviewee 6 and Chantre et al., (2022).

Enabling strategies

Interviewee 3 suggested as an approach to addressing the six axis of the PNH2 the formation of sub-working groups involving a range of relevant actors, in order to allow for more stakeholder participation in the policy development process.

Interviewee 6 further described the great need for intersectoral partnerships to develop this new market in an optimal way. The same expert underlined the importance of including socioeconomic aspects and the local impact of hydrogen projects in their certification in Brazil. The professional further highlighted the importance of a thoughtful regulation of access to water for the emerging green hydrogen industry, especially in the semi-arid Northeast of Brazil.

MLP: Barriers to transition	**Obstacles to GH2 in Brazil**	**Enabling Strategies**
Economic barriers	• Macroeconomic environment • Risk and uncertainty of demand • Challenges along main cost drivers • Limited access (nationally) to financing schemes	• Distributed generation in industrial clusters • Involvement of Petrobras • Bring in manufacturing industries • Seek to engage in/ bid for long-term offtaking contracts • Blue H2 as bridge technology • Recovery of national ammonia & fertilizer production
Institutional barriers	• Regulatory balancing • Insufficiencies in PNH2 • Omission from incentivizing regulation • Uncertainty about technical standards	• Comprehensive industrial policy • Improvements for PNH2 • Inclusion in and creation of incentivizing policies & regulation • Support to access international financing
Resource constraints	• Labor force & training • Capital allocated for R&D • Competition for renewable energy	• Institutional support for R&D & Training (private & public) • Nationalizing and expanding REs
Insufficient supporting infrastructure	• Continental size of the country • Low technological maturity in transport and storage of H2 • Bottlenecks in power transmission in the Northeast • Insufficient pipeline network	• Focus on distributed generation and application in semi-centralized industrial clusters • Considering a diverse mix for storage and distribution
Coordination challenges	• Untransparent and exclusive policy development • Competition for water resources in dry regions	• Sub-working groups from all relevant actors for the implementation of the six axis of PNH2 • Intersectoral partnerships • Strong prioritization of socioeconomic aspects in certification

Table 5: Identified obstacles and the enabling strategies for GH2 in Brazil

Contrasting the research propositions with the results outlined in this chapter, chapter 5 discusses the socio-technical system of GH2 in Brazil, its transition dynamics and examines the identified obstacles and enablers for a roll-out of such hydrogen technologies in Brazil.

5. Discussion

The outcomes of this research have provided information about the current socio-technical system of hydrogen in Brazil, its likely evolution, and focused on the obstacles and enabling strategies for the development of a green hydrogen economy in Brazil.

This chapter discusses the findings outlined in the last chapter in the light of the theoretical propositions and under consideration of the multi-level-perspective on socio-technical transitions. The first section interprets the socio-technical system of hydrogen in Brazil, outlining the three levels before elaborating on the identified transition pathway. The following three sections discuss the identified obstacles and link them to strategies enabling the development of a green hydrogen economy in Brazil. The research propositions regarding insufficient supporting infrastructure (P4) and coordination challenges (P5) are discussed as part of the other categories, because of their strong linkages and because the results obtained in these categories were less frequently discussed in the obtained data.

Based on the findings and derived from this discussion, *Table 6* at the end of the chapter summarizes the recommended strategic approaches to the market development of GH2 in Brazil.

5.1 The transition in the socio-technical system of H2 in Brazil

This section interprets the results of the case analysis (4.1) of GH2 in Brazil in the light of the landscape level and innovations in the socio-technical regime brought about by emerging innovations. By analyzing these interrelated levels, this section aims to discuss how the development of the socio-technical system of GH2 is unfolding in Brazil.

Landscape level

The macro landscape influencing the socio-technical regime and technological niches of hydrogen in Brazil is consists of a number of forces that shape the trajectory of this transition.

The macroeconomic situation, characterized by high interest rates inhibiting investment activity, poses challenges for financing and resource allocation in the energy sector. Brazil's geopolitical ambiguity in the past years and the recent inauguration of its new government has attracted international attention, creating an environment of uncertainty and also a potential for policy changes that could impact hydrogen initiatives. Additionally, socioeconomic considerations specific to Brazil contribute to the landscape, including factors such as income inequality and the need for job creation, which influence the priorities and approaches to sustainable energy transitions within the country.

In response to the global challenges posed by climate change, Brazil's associated commitments and obligations in international forums, such as its NDC to the United Nations Framework Convention on Climate Change (UNFCCC), exert pressure to manage the adoption of clean energy solutions like green hydrogen.

Further, prevailing trends in the global energy transition present significant implications for Brazil's hydrogen regime. The emergence of new technological pathways and increasing emission standards in global markets call for innovative approaches and solutions. This dynamic landscape not only presents opportunities for technological advancements but also encompasses risks and challenges for Brazil to remain competitive and adapt to evolving market demands. Big exporting industries, such as the steel and the agricultural sector are projected to face increasingly rigorous legislation for the offtaking of their goods and commodities overseas, as exemplified by the CBAM in the EU. Geopolitical events like the Russian invasion of Ukraine, have heightened the perceived necessity of diversifying energy suppliers in many countries. In response, states like Germany are actively exploring new partnerships and alternative energy sources. Brazil, endowed with extensive renewable energy potential, emerges as an appealing prospect as a prospective hydrogen supplier in this shifting global energy panorama.

These influences stemming from the landscape level collectively influence the socio-technical regime of hydrogen in Brazil, influencing policy formulation, technological advancements, investment strategies, and international collaboration. Additionally, these forces influence developments in the technological niches, as innovations increasingly profit from private and public investments, often driven by international players. A thorough comprehension and proper navigation of these landscape dynamics is crucial in positioning Brazil as a relevant player in the global clean energy transition and harnessing the full potential of GH2 as a vital component of the country's sustainable, economic future.

Emerging innovations in the socio-technical regime

Within the socio-technical system of hydrogen in Brazil there are distinctive technological niches that challenge the established regime and contribute to the transition towards a more sustainable energy landscape. These niches encompass both the production and consumption aspects of hydrogen, offering innovative solutions and possibilities.

At the start of the value chain, is still unclear which technological route for production will become dominant. A number of actors favor a technological openness that includes all feasible types of low-carbon hydrogen (e.g., BNDES, 2022; CNI, 2022) and see blue H2 as a technological bridge for a wide-scale adoption of green H2. On the one hand, arguments for such a strategic use of blue hydrogen are the existing and heavily incentivized activities in natural gas extraction (tied to economic development potentials), the corresponding infrastructure for transport and consumption and accompanying legislation. These enhanced starting conditions see blue H2 as being the cheaper alternative at an earlier stage (Gurlit et al., 2021), as CCUS technology could simply be added to processes like Petrobras's gray H2 production. On the other hand, promoting blue H2 as a technological bridge may divert investments from green or moss hydrogen, which are independent of fossil fuels and which are already more sustainable. While it may alleviate existing uncertainty about carbon storage sites in Brazil, investing in CCUS may well prolong fossil fuel dependence. Additionally, blue H2 is not proven to capture all CO2-emissions (Howarth & Jacobson, 2021) and methane leakage during the extraction and transport of natural gas is a further prominent pitfall.

Throughout the interviews and the analysis of relevant literature it became clear that there is no wide consensus on this question, while the federal government has advocated for technological openness and using multiple technological routes.

As uttered by interviewee 2, what may be emerging is an adaptation of production methods to the respective offtaking industry. Hydrogen exported to Europe may be subjected to rather rigid technical and emissions requirements. Greening the existing production of hydrogen in Brazil, and introducing this feedstock in new industries, however, may favor more regulatory flexibility in order to allow for a variety of niche innovations, i.e. production methods, to emerge.

Potential consumers of clean hydrogen and derivatives go beyond, but do not exclude already established consumers. The "new consumers" category also includes companies that are already using hydrogen, but that only do it in very limited scale, such as the steel industry. Established consumers of hydrogen may introduce clean hydrogen as a feedstock into their processes are the refinery sector (largely represented by Petrobras), the petrochemical industry (producing fertilizers and methanol), and the steel industry. As has become clear in this case study, the latter two have enormous potential to green their outputs by introducing ammonia and clean hydrogen into their processes. In Brazil, new consumers may include heavy transport (e.g., in mining), cement and the glass industry. A scenario is likely, where the ramp-up of the consumption in pre-existing consuming industries leads to a diversification of uses in the industry and economies of scale and increased availability of GH2 and to the realization of its introduction in new sectors. *Figure 5* illustrates the three levels as identified by this case study research.

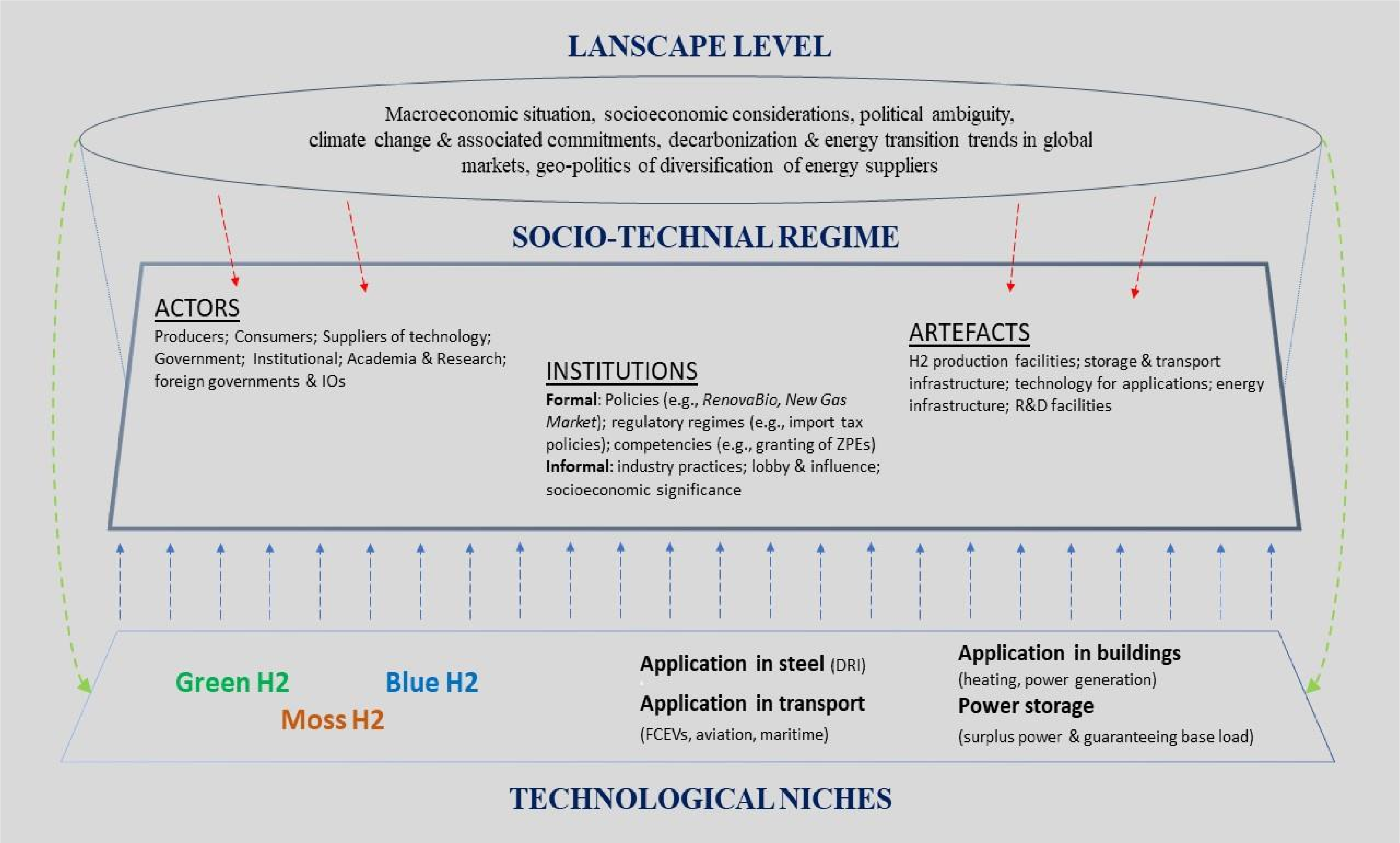


Figure 5: The socio-technical system of hydrogen in Brazil (author's elaboration; based on Geels & Schot, 2007)

A transformation pathway

Section 2.1 reviewed the different pathways for socio-technical transitions according to Geels & Schot (2007). Given the different transition pathways, summarized in *Table 1*, and based on the literature review and the analysis of expert interviewees and case-relevant documents, this research argues that the socio-technical transition pathway towards GH2 in Brazil represents a *Transformation Pathway*.

Here, the modest pressures from the landscape level explained above occur at a moment where niche innovations have not reached market maturity (characterized by the absence of dominant designs, participation of potent actors and a certain degree of early market participation). For any type of low-carbon hydrogen to be considered "mature" it would have to be competitive on the open market. Given the many obstacles outlined in the previous chapter, this is not the case yet.

In response to this combination of modest pressures from the macro-environment and the low maturity of production, storage and transport and application of low-carbon or green H2, regime actors adjust the development and innovation trajectories of the regime to better absorb the landscape pressures. Here, this is shown by the initiatives of both the private and the public sector and their attempts to promote GH2. As stated earlier, actors from the private sector and their representing bodies have appeared as the driving forces to this development so far, which can be linked to their ties to international markets and a higher perceived degree of urgency in the transition.

5.2 Overcoming economic barriers

The findings of this case study indicate that a number of factors perpetuate not only the cost disadvantages of GH2 in Brazil, but also uncertainties and therefore high levels of risks for financial decision-makers, prohibiting FIDs. As with any new technology, the absence of economies of scale prohibits significant reductions in per-unit cost. For green hydrogen specifically, there are merely projections of its price under industrial-scale production in Brazil.

On the one hand, financial decision-makers intending to invest in productive capacity of GH2 are inhibited by the wider economic environment on the landscape level, characterized by high interest rates and hence high cost of capital. This in conjunction with the „Brazil Cost" makes for a situation where financing instruments from the public side or support in accessing such instruments on the international market would be of high impact and importance.

Green finance to spark production for export

Green finance instruments like H2Global aim at helping the market “get over the hump” and use public funds to enable the business between producers and offtaker/consumers of GH2 in a period when natural market forces would not allow it. Even though, the financial situation of the Brazilian state turns the introduction of such an instrument - assuming sufficient funding volumes - less likely, providing favorable conditions for Brazilian companies that seek to bid for long-term offtaking contracts appears to be among the most promising ways of initiating market development through the actual construction of industrial-scale productive capacity of GH2. This would be to develop productive capacity for the export of H2 and derivatives like ammonia, which is most likely to occur at the northeastern industrial like the Port of Pecém and the Port of Suape. Facilitating the creation of export processing zones like the one at the Port of Pecém may help to incentivize investors. State initiatives and international cooperation could further promote matchmaking between international offtakers and Brazilian producers of GH2.

Direct linking of supply and demand in industrial clusters

Further were identified bottlenecks in transport and storage and an offtaking dilemma, where production at scale does not occur because of uncertainties about long-term demand, as such demand is absent, due to uncertainties about price and regulation. Here, supported matchmaking between producers and consumers of GH2 could bring about desired financial investment decisions, as it provides the certainty required by financial decision-makers.

In this scenario, industrial clusters linking renewable energy sources with industrial-scale production and industries using H2 and derivatives as a feedstock would require big joint ventures, regulatory support, and maybe even fiscal incentives. Given the regional differences in RE availability – e.g., the Northeast with wind and sun, the Center and South with Biomass from agriculture – these clusters would leverage local conditions to minimize energy costs and provide industries with opportunities to decarbonize, turn their products more sustainable and, hence, preserve their competitiveness on international markets. It is in Brazil’s interest to turn GH2 into a feedstock that does not merely satisfy industries in other countries but allows for a green reindustrialization of national industries such as fertilizers and steel, as domestic value chains promise the creation of jobs and further economic prosperity.

The continental size of Brazil, challenges in logistics, the offtaking dilemma and technologically different production potentials in different parts of the country make a scenario with distributed generation hubs in a poly-centric hydrogen production system a feasible pathway and one, that allows the country to take advantage of its diverse energy and industry.

Blue H2 as a catalyst for market formation

In the short-term, blue hydrogen could serve as a catalyst for green hydrogen market formation in Brazil, leveraging Petrobras' role as the principle gray hydrogen consumer and utilizing the developing natural gas market to catalyze the H2-market in. By utilizing existing expertise and infrastructure, blue hydrogen can provide a transitional pathway while reducing emissions through carbon capture and sequestration. As the industry gains experience, knowledge transfer to green hydrogen technologies can be accelerated. Public perception can also improve, showcasing commitment to emissions reduction. Government support and collaboration across sectors can establish a hydrogen ecosystem, laying the groundwork for a broader hydrogen economy. However, the shift to green hydrogen should remain as the long-term objective, as there are doubts about the real carbon footprint of blue H2 and its role in perpetuating fossil-fuel dependency.

Tackling the main cost drivers

Of course, reducing renewable energy cost by expanding capacity and tapping into the large existing potentials, particularly in off-shore wind and biogas from biomass, is one of the main levers to turn Brazilian H2 competitive in the long-term. Once proven economically viable, GH2 production cost could also benefit from the domestic manufacturing of necessary equipment like electrolyzers and steam reformers, avoiding high import tariffs on technology. This, in fact, is a feasible way forward as many companies producing such equipment are already present in Brazil (e.g., Siemens Energy, Thyssenkrupp) and the German Neuman & Esser group has already begun the construction of the first plant to produce electrolyzers and steam reformers in Brazil, in the state of Minas Gerais . This financial investment decision can be considered a promising sign.

5.3 Enabling GH2 through institutional support

According to the data collected in this case study, the regulatory framework and related policies do not sufficiently support the development of the GH2 sector in Brazil, as lacking signals from the federal level, insufficiencies in the National Hydrogen Program and uncertainty about technical standards represent significant barriers.

An ambitious hydrogen strategy to realize economic potentials

The absence of a clear federal stance has been identified as a challenging factor, with ambiguous signals about the national vision and desired technological routes and standards leaving market players with uncertainty. The notion was raised that enhancing Brazil's appeal to private investments could be achieved by clear signals from the federal government, endorsing infrastructure development, engaging all relevant stakeholders, and aligning standards with other markets through international collaboration.

Concerns were raised about the lack of concrete ambitions and objectives within the PNH2 when discussing investments and installed capacities or productive volumes, suggesting their absence leaves investors uncertain and inhibits companies from making FIDs. Incorporating specific and measurable objectives, such as an indicator for installed electrolyzer capacity, developed under the engagement of a diverse array of governmental and non-governmental stakeholders, could go a long way in clearly articulating Brazil’s ambitions and reassuring financial decision-makers.

The Triannual Working Plan of the PNH2 has been criticized for initiating developments slowly, resulting in prolonged regulatory uncertainty and a failure to fast-paced international developments in GH2. This is likely a consequence of insufficiently involving relevant stakeholders in policy and regulation development, which ought to be a high priority in order to avoid misalignments with actual market requirements. Accelerating the timelines of the Triannual Working Plan could facilitate faster progress within the GH2 market, increase the program’s adaptability and help in aligning it with international advancements.

A new iteration of the PNH2 should further propose concrete actions to attract investment on the demand side in order to tackle the offtaking dilemma, aiming for a clear assessment of the domestic demand market and define priority sectors, in line with technical and economic feasibility and strategic importance.

Industrial policy to trigger demand and develop domestic industry

Sizing the domestic market should go hand in hand with decarbonization plans for national industries and the transport sector. An added measure to create momentum could be an analysis of the economic development and job creation potential brought about by domestic GH2 value chains, as this may provide additional arguments for making GH2 sector development a major political priority.

The necessity for sound industrial policy, including emission reduction targets for specific sectors like fertilizers, was highlighted. The implementation of a national policy for producing decarbonized fertilizers from GH2 was proposed to enhance supply resilience, with the added benefit of bringing back national fertilizer production to satisfy the Brazilian high-demand market. A strategic focus and regulatory support for the formation geographically dispersed hydrogen generation hubs for local consumption would be an enabling strategy that could mitigate transport costs and associated technological hurdles, whilst securing the economic benefits described earlier.

Opening up existing legislation to include H2

Within the broader regulatory landscape where GH2 competes alongside other energy carriers, the findings showed that including GH2 in regulatory incentives like REIDI and the Lei do Bem, if applicable, could aid in infrastructure development and R&D programs throughout GH2's value chain.

However, tax incentives, akin to those pivotal in the development of Brazil's wind and solar energy sectors (e.g., PROINFA), have not been implemented for GH2, which hampers its ability to compete with other energy carriers on the open market. Experts did, however, also voice their skepticism about tax breaks and described it as ineffective.

Approaches that would bolster GH2's competitiveness are mandatory carbon pricing (i.e., through a carbon tax or a mandatory emission trading system) or other decarbonization frameworks, as they would implicitly help to reward low-carbon energy solutions and put a price on fossil ones.

5.4 Providing the required resource base

The assessment of resource constraints for the development of the GH2 sector in Brazil, resulted in an identification of shortages in qualified labor force and professional training opportunities across the value chain. Additionally, financial resources for R&D appear to be inadequate to satisfy the great needs for innovation.

Cross-sector collaboration for human resources and innovation

Enabling strategies for a qualified labor force in the GH2 value chain and advancing R&D were intertwined, as universities and R&D centers appeared to be important actors for sector development and skilled training. As mentioned earlier, including GH2 initiatives in incentive programs like REIDI could help to satisfy the need for resource allocation to GH2 innovation, especially if accompanied by funding support for private-academic partnerships. A fitting example of such intersectoral collaboration is the Green Hydrogen Hub at the industrial port of Pecém.

A national GH2 research program, involving companies with ANEEL and ANP-managed R&D funds, along with incentives for technical schools, SENAI, research funding, and HR training institutions, is a thinkable way of addressing both R&D and labor and training shortages.

Prioritizing the expansion of REs

In order to avoid undesirable competition for electricity from renewable sources, the focus was on expanding installed renewable energy capacity, notably offshore wind amongst other, to tap into existing potentials, whilst endorsing increased development of the national renewable energy industry, including manufacturing renewable energy equipment, to mitigate costs associated with high import tariffs and vulnerability to international price fluctuations. Further expansion of the RE infrastructure ought to be a priority, particularly in the light of federal ambitions to expand on natural gas, a competing energy carrier.

Recommended strategies to enable the Brazilian GH2 economy

1. Providing institutional and regulatory support for the formation of industrial clusters linking producers and offtakers/consumers of GH2 and leveraging local energy and industry as an opportunity to develop the domestic market, whilst fostering new value creation and decarbonizing industries
2. Facilitating companies' access to green finance instruments and promoting export processing zones in and around industrial ports in the Northeast to enhance the conditions for an industrial-scale production of GH2 and its derivatives for export
3. Linking the developing natural gas market to blue H2 as a path towards accelerating hydrogen market development, using existing expertise and infrastructure and decarbonizing existing gray hydrogen consumption (e.g., Lei do Hidrogênio)
4. Upgrading PNH2 with:
    - ➢ concrete and ambitious targets for Brazilian hydrogen market development
    - ➢ concrete actions to attract investment on the demand side
    - ➢ a clear assessment of the domestic demand market
    - ➢ a definition of domestic priority sectors
    - ➢ accelerated timelines in the Triannual Working Plan
5. Drafting an industrial policy including emission reduction targets for strategic GH2-consuming industries and regulatory support (e.g., fertilizer production) to trigger demand and make a step toward a green reindustrialization in Brazil;
6. Introducing a mandatory carbon pricing mechanism
7. Extending existing regulatory incentives for infrastructure development and R&D (e.g., Reidi & Lei do Bem) to GH2
8. Promoting cross-sector collaboration for R&D initiatives and for the development of the GH2-workforce
9. Expanding existing, developing untapped REs and gradually building up national manufacturing capacity for key technologies, leading to cost reductions and decreased vulnerabilities

Table 6: Recommendations for the market development of GH2 in Brazil

6. Conclusion

This dissertation aims to identify the main obstacles and enabling strategies for the development of a green hydrogen (GH2) economy in Brazil, answering the research question:

> *What are the main obstacles to the development of a green hydrogen economy in Brazil and how could this development be enabled?*

To this end, qualitative data was collected from a series of expert interviews and relevant literature and analyzed through the lens of five theoretical propositions about barriers to the transition to GH2, grounded in the multi-level perspective on socio-technical systems.

It was identified that moderate landscape pressures lead to the first signs of a transformation pathway in the relevant socio-technical regimes for hydrogen. Incumbent actors such as utilities and offtaking industries are engaging increasingly, adjustments are being announced through MoUs and actual projects and no technological niche design has established dominance, as it is still unclear which technological routes for hydrogen production will be prioritized. The main protagonists shaping the first steps of this transition are private (often multinational) companies, industrial ports, sub-national governments and industry associations. Even though activities and discussions on the federal level have started to pick up steam, these developments set Brazil apart from other markets, where the pressures stemming from commitments to the reduction of GHG-emissions have led national governments to be more involved in the earliest stages.

The main economic barriers for the emergence of GH2 identified are the current macroeconomic environment, high investment risks, uncertainty of demand, challenges along the main cost drivers and the limited access to stimulating financial instruments from national and international institutions. Economic performance of green hydrogen represents a significant barrier to its entrance into the socio-technical regime, as it perpetuates high risk-levels for investors to make financial investment decisions and does not allow for demand, i.e. offtaking, to be triggered sufficiently.

In the institutional sphere, insufficiencies in the National Hydrogen Program (PNH2), the omission of H2 from incentivizing regulatory mechanisms and uncertainties about desired technological standards and the prospective domestic market represent major obstacles. The regulatory framework for hydrogen does not provide sufficient clarity about the federal government’s ambitions to provide favorable economic conditions for a development of the

GH2 sector in Brazil. This stands in stark contrast to the regulatory frameworks for competing technologies, such as natural gas, and leads to few actors taking an FDI.

Resource constraints include an insufficiently available qualified labor force, lacking professional training opportunities, inadequate capital allocated for R&D along the GH2 value chain, and the likely competition for renewable energy in a scenario where GH2 production through electrolysis reaches industrial scale.

Given the continental size of the country, the low technological maturity in the transport and storage of H2, insufficient pipeline networks for distribution and bottlenecks in power transmission in the Northeast provide infrastructural bottlenecks that require time and substantial investments to be overcome.

Particularly in policy development, but also in matching supply and offtaking coordination, challenges among actors in the socio-technical system of GH2 become apparent. Insufficient coordination causes misalignments in perceptions and expectations, as exemplified by the Triannual Working Plan and untransparent policy development in the case of PNH2. Future coordination challenges may be linked to the need for large amounts of water in the dry Northeast, likely to arise in the case of large-scale electrolysis.

The discussion of these numerous obstacles and suggested enabling strategies, led to a list of nine recommendations that this research article provides for the market development of GH2 in Brazil.

In order to stimulate the national market, enable domestic value creation and help decarbonizing Brazilian industries, institutional and regulatory support for the formation of industrial clusters linking producers and offtakers of H2 could be an effective approach. Simultaneously, the export of GH2 (in the form of derivatives like ammonia) should be facilitated by providing good conditions to access green finance instruments like H2Global to compensate today’s high production costs and scale up production, while promoting the formation of new export processing zones may attract national and international industries to the ports in the Northeast. Linking the ongoing development of the natural gas market to the production of blue H2 through legislation like the Lei do Hidrogênio would be an adequate bridging strategy towards an accelerated H2 market development, using existing expertise and infrastructure and decarbonizing existing gray hydrogen consumption.

An upgrade of PNH2 should include concrete and ambitious targets for Brazilian hydrogen market development, actions to attract investment on the demand side, a clear assessment of the domestic demand market, a definition of domestic priority sectors and accelerated timelines in the Triannual Working Plan.

A new industrial policy towards a green reindustrialization of Brazil should include emission reduction targets for strategic GH2-consuming industries and regulatory support (e.g., fertilizer production), as a strategy to trigger demand and overcome the offtaking dilemma. Similar in its approach, the introduction of a mandatory carbon pricing mechanism would help to increase demand by raising the competitiveness of GH2 against other, fossil fuel based energy carriers.

Further, existing regulatory incentives (e.g., Reidi & Lei do Bem) should be extended to include GH2 related projects, which would help to stimulate infrastructure development and investments in innovation. R&D and the qualification of a GH2-workforce require cross-sectoral collaboration, such as private-academic research endeavors.

Notably, a Brazilian GH2 economy becomes a more realistic scenario if the existing RE-capacities are further expanded and untapped potentials are accessed, as this will bring down electricity costs, and reduce the competition for renewable energy. Here, gradually building up national manufacturing capacity for key technologies can also lead to cost reductions and decreased vulnerabilities from imports.

This study contributes to the literature by showing that the transition towards GH2 is an adequate case for the use of the MLP as a theory to analyze this particular socio-technical transition in specific geographical markets. Even though the chosen case harbors many favorable characteristics, this case analysis has largely confirmed the MLP’s approach to explaining barriers to sustainability transitions, in that it showed that depending on the specific national context and the concrete emerging technology, some barriers may be more relevant and impactful than others. Further, the findings and strategic recommendations may provide evidence and guidance for policymakers and other actors in the GH2 ecosystem.

This study is limited by the scarcity of applicable data, as GH2 market development is incipient across the globe and scientific analyses of these developments are to this day few in number. A second limitation, the range of interviewed experts is further insufficient to cover all relevant angles of perceiving the transition. Lastly, developments in GH2 are rapid and the accuracy and relevance of the study’s findings may therefore be subjected to changes.

Future research could attempt to replicate and enhance the chosen research design, either taking into account novel developments in the Brazilian GH2-sector at a future point in time or employing MLP theory to analyze barriers and enabling strategies in other promising markets, such as Chile or Argentina. This would provide increasing information to conduct comparative case studies in the future. Given the fact that the whole value chain of an emerging GH2-sector will inevitably imply changes for numerous industries on the demand and the supply side, future analyses may narrow their focus on specific sectors in Brazil, such as the potential for a rebirth of the national fertilizers industry using green ammonia. Such zooming-in may provide a basis for the necessary use-cases and as such go beyond theorical endeavors and provide even more concrete practical implications. Moreover, future research Future sustainability transitions research may also choose to apply *Strategic Niche Management*, *Technological Innovation Systems*, *Transition Management,* to similar cases in order to identify the most applicable framework for the analysis of the socio-technical transition towards GH2.

Bibliography

Agência Minas. (2023). *Minas terá 1ª fábrica de geradores de hidrogênio verde da América Latina*. Www.Agenciaminas.Mg.Gov.Br. https://www.agenciaminas.mg.gov.br/noticia/minas-tera-1-fabrica-de-geradores-de-hidrogenio-verde-da-america-latina

Barreto, L., Makihira, A., & Riahi, K. (2003). The hydrogen economy in the 21st century: A sustainable development scenario. *International Journal of Hydrogen Energy*, *28*(3), 267–284. https://doi.org/10.1016/S0360-3199(02)00074-5

BNDES. (2022). *Hidrogênio de baixo carbono: oportunidades para o protagonismo brasileiro na produção de energia limpa*. https://web.bndes.gov.br/bib/jspui/bitstream/1408/22665/1/PRLiv_Hidrogênio de baixo carbono_215712.pdf

Bockris, J. O. M. (1972). A hydrogen economy. *Science (New York, N.Y.)*, *176*(4041), 1323. https://doi.org/10.1126/SCIENCE.176.4041.1323

Castro, A. (2023, April 19). *Comissão do Hidrogênio Verde aprova plano de trabalho para 2023 — Senado Notícias*. Senado Notícias. https://www12.senado.leg.br/noticias/materias/2023/04/19/comissao-do-hidrogenio-verde-aprova-plano-de-trabalho-para-2023

Chantre, C., Andrade Eliziário, S., Pradelle, F., Católico, A. C., Branquinho Das Dores, A. M., Torres Serra, E., Campello Tucunduva, R., Botelho Pimenta Cantarino, V., & Leal Braga, S. (2022). Hydrogen economy development in Brazil: An analysis of stakeholders' perception. *Sustainable Production and Consumption*, *34*, 26–41. https://doi.org/10.1016/j.spc.2022.08.028

CNI. (2022). *Hidrogênio sustentável : perspectivas e potencial para a indústria brasileira*. https://www.portaldaindustria.com.br/publicacoes/2022/8/hidrogenio-sustentavel-perspectivas-e-potencial-para-industria-brasileira/

Crabtree, G. W., Dresselhaus, M. S., & Buchanan, M. V. (2004). The hydrogen economy. *Physics Today*, *57*(12), 39–44. https://doi.org/10.1063/1.1878333

Deloitte. (2023). *Law 11196/05 – "Lei do Bem."* Www.Deloitte.Com. https://www2.deloitte.com/br/en/pages/tax/solutions/lei-do-bem.html

Dunn, S. (2002). Hydrogen futures: Toward a sustainable energy system. *International Journal of Hydrogen Energy*, *27*(3), 235–264. https://doi.org/10.1016/S0360-3199(01)00131-8

Eicke, L., & De Blasio, N. (2022). Green hydrogen value chains in the industrial sector—Geopolitical and market implications. *Energy Research and Social Science*, *93*. https://doi.org/10.1016/J.ERSS.2022.102847

EPE. (2022). *Balanço Energético Nacional 2021*. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-675/topico-638/BEN2022.pdf

EPE. (2023). *Hidrogênio no Brasil | Potencial técnico de produção de hidrogênio de baixo carbono no Brasil*. Www.Epe.Gov.Br. https://gisepeprd2.epe.gov.br/arcgisportal/apps/storymaps/stories/68332aaa3fc64524a656583e1367daa3

EPE & MME. (2021). *Baseline to support the Brazilian Hydrogen Strategy* (pp. 1–31). https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-569/NT_Hidrogênio_EN_revMAE (1).pdf

Fernandes, G., Henrique De Azevedo, J., Ayello, M., & Gonçalves, F. (2023). Panorama dos desafios do hidrogênio verde no Brasil. In *FGV Energia* (pp. 2–14).

Forbes. (2023). *Brasil tem US$30 bi em projetos de hidrogênio de baixo carbono em estudo*. Www.Forbes.Com.Br. https://forbes.com.br/forbesesg/2023/08/brasil-tem-us30-bi-em-projetos-de-hidrogenio-de-baixo-carbono-em-estudo/

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy*, *31*(8–9), 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Geels, F. W. (2004). From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. *Research Policy*, *33*(6–7), 897–920. https://doi.org/10.1016/J.RESPOL.2004.01.015

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions*, *1*(1), 24–40. https://doi.org/10.1016/J.EIST.2011.02.002

Geels, F. W. (2019). Socio-technical transitions to sustainability: a review of criticisms and elaborations of the Multi-Level Perspective. *Current Opinion in Environmental Sustainability*, *39*, 187–201. https://doi.org/10.1016/J.COSUST.2019.06.009

Geels, F. W., & Kemp, R. (2007). Dynamics in socio-technical systems: Typology of change processes and contrasting case studies. *Technology in Society*, *29*(4), 441–455. https://doi.org/10.1016/J.TECHSOC.2007.08.009

Geels, F. W., & Schot, J. (2007). Typology of sociotechnical transition pathways. *Research Policy*, *36*(3), 399–417. https://doi.org/10.1016/J.RESPOL.2007.01.003

Geels, F. W., Sovacool, B. K., Schwanen, T., & Sorrell, S. (2017). The Socio-Technical Dynamics of Low-Carbon Transitions. *Joule*, *1*(3), 463–479. https://doi.org/10.1016/J.JOULE.2017.09.018

Gibbert, M., Ruigrok, W., & Wicki, B. (2008). What passes as a rigorous case study? *Strategic Management Journal*, *29*(13), 1465–1474. https://doi.org/10.1002/SMJ.722

GIZ, & MME. (2021). *Mapeamento do Setor de Hidrogênio Brasileiro | Panorama Atual e Potenciais para o Hidrogênio Verde*. https://www.energypartnership.com.br/fileadmin/user_upload/brazil/media_elements/Mapeamento_H2_-_Diagramado_-_V2h.pdf

Gordon, J. A., Balta-Ozkan, N., & Nabavi, S. A. (2023). Socio-technical barriers to domestic hydrogen futures: Repurposing pipelines, policies, and public perceptions. *Applied Energy*, *336*, 120850. https://doi.org/10.1016/J.APENERGY.2023.120850

Griffiths, S., Sovacool, B. K., Kim, J., Bazilian, M., & Uratani, J. M. (2021). Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options. *Energy Research and Social Science*, *80*. https://doi.org/10.1016/J.ERSS.2021.102208

Grin, J., Rotmans, J., & Schot, J. (2010). Transitions to Sustainable Development: New Directions in the Study of Long Term Transformative Change. In *Transitions to Sustainable Development: New Directions in the Study of Long Term Transformative Change* (1st ed.). Routledge. https://doi.org/10.4324/9780203856598/TRANSITIONS-SUSTAINABLE-DEVELOPMENT-JOHAN-SCHOT-JOHN-GRIN-JAN-ROTMANS

Gurlit, W., Guillaumon, J., Aude, M., & Ceotto, H. (2021). *Green Hydrogen: an opportunity to create sustainable wealth in Brazil and the world*. 14. https://www.mckinsey.com/br/en/our-insights/hidrogenio-verde-uma-oportunidade-de-geracao-de-riqueza-com-sustentabilidade-para-o-brasil-e-o-mundo

H2Gobal Stiftung. (2022). *The H2Global Instrument*. https://www.h2global-stiftung.com/project/h2g-mechanism

Heid, B., Sator, A., Waardenburg, M., & Whilthaner, M. (2022). Five charts on clean hydrogen and net zero | McKinsey. In *McKinsey & Company*. https://www.mckinsey.com/capabilities/sustainability/our-insights/five-charts-on-hydrogens-role-in-a-net-zero-future#/

Howarth, R. W., & Jacobson, M. Z. (2021). How green is blue hydrogen? *Energy Science & Engineering*, *9*(10), 1676–1687. https://doi.org/10.1002/ESE3.956

Hydrogen Council, & McKinsey & Company. (2023). Hydrogen Insights 2023: An update on the state of the global hydrogen economy, with a deep dive into North America. In *Hydrogen Council*. https://hydrogencouncil.com/en/hydrogen-insights-2023/?utm_medium=DSMN8&utm_source=LinkedIn&utm_user=14419233730045594

HyResource. (2023, March). *National Hydrogen Strategies – HyResource*. Research.Csiro.Au. https://research.csiro.au/hyresource/policy/international/

IEA. (2019). The Future of Hydrogen. In *International Energy Agency*. https://www.iea.org/reports/the-future-of-hydrogen

IEA. (2022a). *Electrolysers - Technology Deep Dive*. https://www.iea.org/reports/electrolysers

IEA. (2022b). *Global Hydrogen Review 2022*. https://www.iea.org/reports/global-hydrogen-review-2022

IEA. (2022c). *Renewable Energy Market Update* . https://www.iea.org/reports/renewable-energy-market-update-may-2022

IEA. (2023). *CO2 Emissions in 2022*. https://www.iea.org/reports/co2-emissions-in-2022

IPEA. (2022). *Panorama do Hidrogênio no Brasil*. https://doi.org/10.38116/td2787

IRENA. (2020). *Green hydrogen: A guide to policy making*. https://www.irena.org/publications/2020/Nov/Green-hydrogen

IRENA. (2021). *Making the breakthrough: Green hydrogen policies and technology costs*. www.irena.org

IRENA. (2022). *World Energy Transitions Outlook 2022: 1.5°C Pathway*. https://www.irena.org/Digital-Report/World-Energy-Transitions-Outlook-2022

IRENA. (2023). *Creating a global hydrogen market: Certification to enable trade*. https://www.irena.org/Publications/2023/Jan/Creating-a-global-hydrogen-market-Certification-to-enable-trade

Kemp, R. (1994). Technology and the transition to environmental sustainability: The problem of technological regime shifts. *Futures*, *26*(10), 1023–1046. https://doi.org/10.1016/0016-3287(94)90071-X

Kemp, R., Schot, J., & Hoogma, R. (1998). Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. *Technology Analysis and Strategic Management*, *10*(2), 175–198. https://doi.org/10.1080/09537329808524310

Köhler, J., Geels, F. W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M. S., … Wells, P. (2019). An agenda for sustainability transitions research: State of the art and future directions. *Environmental Innovation and Societal Transitions*, *31*, 1–32. https://doi.org/10.1016/J.EIST.2019.01.004

Loorbach, D., Frantzeskaki, N., & Avelino, F. (2017). Sustainability Transitions Research: Transforming Science and Practice for Societal Change. *Https://Doi.Org/10.1146/Annurev-Environ-102014-021340*, *42*, 599–626. https://doi.org/10.1146/ANNUREV-ENVIRON-102014-021340

Markard, J., Raven, R., & Truffer, B. (2012). Sustainability transitions: An emerging field of research and its prospects. *Research Policy*, *41*(6), 955–967. https://doi.org/10.1016/J.RESPOL.2012.02.013

McDowall, W. (2014). Exploring possible transition pathways for hydrogen energy: A hybrid approach using socio-technical scenarios and energy system modelling. *Futures*, *63*, 1–14. https://doi.org/10.1016/J.FUTURES.2014.07.004

MME. (2021). *PNH2 - Programa Nacional do Hidrogênio: Proposta de Diretrizes* (Vol. 1, pp. 1–24). https://www.gov.br/mme/pt-br/assuntos/noticias/mme-apresenta-ao-cnpe-proposta-de-diretrizes-para-o-programa-nacional-do-hidrogenio-pnh2/HidrognioRelatriodiretrizes.pdf

MME. (2022). *PNH2 - Programa Nacional do Hidrogênio: Plano de Trabalho Trienal (2023-2025)*. http://antigo.mme.gov.br/c/document_library/get_file?uuid=1385f73a-16c2-9bc3-66cf-bc45c1e0ada7&groupId=36070

Muhammed, G., & Tekbiyik-Ersoy, N. (2020). Development of Renewable Energy in China, USA, and Brazil: A Comparative Study on Renewable Energy Policies. *Sustainability 2020, Vol. 12, Page 9136*, *12*(21), 9136. https://doi.org/10.3390/SU12219136

Noussan, M., Raimondi, P. P., Scita, R., & Hafner, M. (2021). The role of green and blue hydrogen in the energy transition—a technological and geopolitical perspective. *Sustainability (Switzerland)*, *13*(1), 1–26. https://doi.org/10.3390/SU13010298

Nurdiawati, A., & Urban, F. (2022). Decarbonising the refinery sector: A socio-technical analysis of advanced biofuels, green hydrogen and carbon capture and storage developments in Sweden. *Energy Research and Social Science*, *84*. https://doi.org/10.1016/J.ERSS.2021.102358

Panos, E., Densing, M., & Volkart, K. (2022). Energy. *Our World in Data*, *9*, 28–49. https://doi.org/10.1016/j.esr.2015.11.003

Ritchie, H., Roser, M., & Rosado, P. (2022). Energy. In *OurWorldInData.org*. https://ourworldindata.org/energy

Sawaya, A., Ferreira, N., Fiorini, R., Fantoni, R., & et al. (2022). *The green hidden gem – Brazil's opportunity to become a sustainability powerhouse* . https://www.mckinsey.com/br/en/our-insights/all-insights/the-green-hidden-gem-brazils-opportunity-to-become-a-sustainability-powerhouse#/

Tarvydas, D. (2022). The role of hydrogen in energy decarbonization scenarios - Views on 2030 and 2050. In *Publications Office of the European Union*. https://doi.org/10.2760/899528

The White House. (2023). *Building a Clean Energy Economy: A Guidebook to the Infaction Reduction Act's investments in clean energy and climate action*. https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf

Veiga, J. (2022). *REIDI, você sabe o que é?* Www.Migratio.Com.Br. https://migratio.com.br/reidi-voce-sabe-o-que-e/

Verbong, G. P. J., & Geels, F. W. (2010). Exploring sustainability transitions in the electricity sector with socio-technical pathways. *Technological Forecasting and Social Change*, *77*(8), 1214–1221. https://doi.org/10.1016/J.TECHFORE.2010.04.008

Yap, J., & McLellan, B. (2023). A Historical Analysis of Hydrogen Economy Research, Development, and Expectations, 1972 to 2020. *Environments - MDPI*, *10*(1). https://doi.org/10.3390/environments10010011

Yin, R. K. (2017). *Case study research and applications: design and methods* (Sixth edit). SAGE Publications, Inc. https://uk.sagepub.com/en-gb/eur/case-study-research-and-applications/book250150

Annex

A. Model of the semi-structured interview guide & questionnaire (Portuguese)

INTRODUÇÃO

Boa tarde e obrigado por tomar este momento para falar comigo.

Meu nome é Max Thomsen e sou aluno do Duplo-Mestrado em Administração na FGV EBAPE no Brasil e na Universidade Católica de Lisboa em Portugal.

CONTEXTO

Esta pesquisa é para a minha tese de mestrado e como parte desse processo estou entrevistando diferentes atores relevantes para o setor de hidrogênio verde no Brasil. Eu identifiquei você como um especialista na área.
Minha pesquisa está focada na identificação dos atores e processos relevantes para o desenvolvimento de uma economia brasileira de hidrogênio verde, a fim de identificar os principais gargalos e viabilizadores para o avanço desta tecnologia.
Para este fim, estou usando a *perspectiva multinível às transições sociotécnicas* para entender as dinâmicas chaves.

PRIVACIDADE

Seu nome não será ligado a nenhum dos seus comentários e eu vou alterar qualquer dado pessoal ou profissional que possa identificá-lo nas transcrições para garantir que o que você me disser permanecerá estritamente confidencial. Se em algum momento você não quiser responder a uma pergunta por qualquer motivo, por favor, me avise e eu vou omitir a pergunta. Além disso, se você tiver alguma preocupação em algum momento durante a entrevista ou em algum momento depois a entrevista, me avise e trataremos dessas preocupações de maneira apropriada.

Gostaria de gravar a entrevista de hoje para poder me concentrar totalmente em nossa conversa. Possivelmente tomarei notas durante toda a entrevista para manter ela no caminho certo. Ninguém além de mim terá acesso à gravação e assim que terminarmos a gravação será transcrita sem suas informações e então a gravação será apagada.

Você concorda com esse procedimento?

A ENTREVISTA

A entrevista consiste em 7 perguntas guias e vai levar 30 a 45 minutos. Você também pode ter algumas informações ou ideias adicionais que eu não tenha pensado ou que não sejam abordadas em minhas perguntas, portanto, sinta-se encorajado a elaborar e compartilhar comigo o que considerar relevante.

Como eu só vou defender a minha tese em outubro deste ano, terei prazer em compartilhar o resultado com você depois disso, caso você esteja interessado.

Você tem alguma pergunta ou há mais alguma coisa que gostaria de saber antes de iniciarmos a entrevista? Obrigado por sua participação!

Perguntas

Abertura

Para começar, por favor, se apresente e explique como surgiu o seu envolvimento com a temática hidrogênio verde?

Pergunta 1

Da sua perspectiva, quais são os principais atores no ecossistema do hidrogênio (verde) no Brasil? (**nomes concretos**)

Como você vê o papel específico da sua indústria?

Pergunta 2

Por favor, descreva os principais obstáculos ou gargalos que você vê para o desenvolvimento de uma economia de hidrogênio verde no Brasil. De que forma os stakeholders relevantes representam barreiras para a adoção dessa tecnologia? **(Exemplos concretos?)**

Pergunta 3

Por favor elabore o papel de diferentes formas de gerar hidrogênio para facilitar o desenvolvimento do setor de hidrogênio verde no Brasil. Da sua perspectiva, quais são as rotas tecnológicas mais promissores? **(Exemplos concretos?)**

Pergunta 4

No lado dos potenciais consumidores de H2V e derivados, quais deveriam ser os setores prioritários no Brasil?
De que forma os atores já estabelecidos, como as empresas de energia ou os possíveis consumidores de hidrogênio verde, reagem a essa inovação emergente? **(Exemplos concretos?)**

(Priorização da demanda nacional ou internacional?)

Pergunta 5

Por favor, aborde a estrutura regulatória atualmente em andamento para apoiar o desenvolvimento do setor de hidrogênio verde no Brasil (*PNH2*). Que mudanças ou acréscimos você acha necessários para promover melhor o desenvolvimento do mercado? **(Exemplos concretos?)**

Pergunta 6

Olhando para inovações no âmbito do hidrogênio verde no Brasil, quais são os atores mais ativos e promissores? São mais os atores estabelecidos com grandes capacidades de P&D ou também existem novas iniciativas com um potencial disruptivo?

Final

Resumindo, quais são as mudanças tecnológicas, políticas, econômicas e sociais mais importantes que você acha que são essenciais para permitir o desenvolvimento de uma economia de hidrogênio verde no Brasil? **(Exemplos concretos?)**

Tem mais alguma consideração que você queria fazer?

Obrigado pelo seu tempo!

RECORDING ENDS