UNIVERSITY OF SÃO PAULO
INSTITUTE OF ENERGY AND ENVIRONMENT
GRADUATE PROGRAM IN ENERGY

SABRINA FERNANDES MACEDO

EXPLORING POSSIBLE TRANSITION WAYS FOR THE USE OF HYDROGEN AS AN ENERGY SOURCE IN THE BRAZILIAN ELECTRIC SECTOR

SÃO PAULO
2022

SABRINA FERNANDES MACEDO

EXPLORING POSSIBLE TRANSITION WAYS FOR THE USE OF HYDROGEN AS AN ENERGY SOURCE IN THE BRAZILIAN ELECTRIC POWER SECTOR

M.Sc. Dissertation presented to the Graduate Program in Energy, at the Institute of Energy and Environment, University of São Paulo, to obtain degree of Master in Energy Science.

Supervisor: Prof. Dr. Drielli Peyerl

Original Version

SÃO PAULO

2022

FICHA CATALOGRÁFICA

Macedo, Sabrina Fernandes.
Exploring possible transition ways for the use of hydrogen as an energy source in the Brazilian electric sector. / Sabrina Fernandes Macedo; orientadora: Drielli Peyerl. —São Paulo, 2022.
80 f.: il; 30 cm.

Dissertation (Master of Sciences) – Graduate Program in Energy – Instituto de Energia e Ambiente da Universidade de São Paulo.

1. Hydrogen. 2. Electric Power Sector. 3. Energy Transition
4. Public Policy – Brazil. I. Title.

Elaborado por Maria Penha da Silva Oliveira CRB-8/6961

MACEDO, S. F. **Exploring possible transition ways to the use of hydrogen as an energy source in the Brazilian Electric Power Sector**. 2022. 80p. M.Sc. Dissertation (M.Sc. in Energy Science) – Graduate Program on Energy Science, University of São Paulo, São Paulo, 2022.

Approved in:

Dissertation Examination Committee

Prof. Dr. ____

Institution: ____

Judgment: ____

Prof. Dr. ____

Institution: ____

Judgment: ____

Prof. Dr. ____

Institution:____

Judgment: ____

Prof. Dr. ____

Institution:____

Judgment: ____

ACKNOWLEDGMENT

The author thanks the support of the Postgraduate Program in Energy of the Institute of Energy and Environment of the University of São Paulo (PPGE IEE/USP) for all the learning and structure provided.

The author thanks the support and guidance of Profª. Drª. Drielli Peyerl.

The author is grateful to Professor Evandro Mateus Moretto, Professor Carla de Abreu D'Aquino and Dr. Donato da Silva Filho for accepting the invitation.

ABSTRACT

MACEDO, S. F. **Exploring possible transition ways for the use of hydrogen as an energy source in the Brazilian Electric Power Sector**. 2022. 89p. M.Sc. Dissertation (M.Sc. in Energy Science) – Graduate Program on Energy Science, University of São Paulo, São Paulo, 2022.

The next step of the global energy transition will probably be based on the hydrogen economy in order to guarantee a sustainable future. Therefore, this study examines the possibilities for expanding the hydrogen market in the Brazilian electric power sector in a model that will contribute the country to take full advantage of competitive features. Thus, this work is divided into two articles which answer this main goal. The first paper analyzes the economic feasibility of renewable hybrid systems for hydrogen production and storage in the Brazilian electric power sector. Thus, to evaluate this proposal, the methodology used is based on economic cost analyses of the two largest wind and solar photovoltaic plants in the country. In conclusion, it was found that the number of hours of electricity available for hydrogen production directly influences its cost. However, full dedicated plants producing green hydrogen have shown economic feasibility when the hydrogen is exported or used in other sectors, so trading hydrogen was found more profitable than transforming it back into power. The model also concludes that wind and solar hybrid systems for hydrogen production and storage are still not economically viable in Brazil. The second paper aims to assess countries with most effective hydrogen strategies, bringing up lessons for Brazil. This work main question is how Brazil can accelerate its hydrogen economy. To answer this question, the methodology applied is based on identify policy front-runners and potential leading markets, where three countries were selected: Germany, Netherlands and Australia. Then, the analysis was carried out first by outlining six pillars that are supporting countries to thrive in hydrogen market. Then a survey was conducted in order to gather enough information of how the selected countries are engaging in each pillar. Finally, a critical analysis is conducted in order to sort out lessons to learn for Brazil. It was found that: (i) Brazil must stablish a regulatory framework providing legal and regulatory security to investors; (ii) Brazilian government should promote strong public polices; (iii) Brazil shall make concrete alliances with front-runners countries; (iv) renewable potential is not the only factor that determine high potential hydrogen producers, factors like: existing infrastructure, soft factors (e.g. government support, businesses friendliness, political stability) and potential demand for hydrogen, are also major determinants. Finally, a discussion will be made covering the results extracted from the two papers, pointing out the characteristics that Brazil has as favourable to achieving a Hydrogen-based economy and essential requirements to enable the grow of hydrogen production, cooperating in the transition to a low-carbon economy.

Keywords: Hydrogen, Electric Power Sector, Energy Transition, Public Policy, Brazil.

RESUMO

MACEDO, S. F. **Explorando possíveis caminhos de transição para o uso do hidrogênio como fonte de energia no Setor Elétrico Brasileiro**. 2022. 89p. Dissertação de Mestrado (Mestrado em Ciência de Energia) – Programa de Pós Graduação em Ciência de Energia, Universidade de São Paulo, São Paulo, 2022.

O próximo passo da transição energética global provavelmente será baseado na economia do hidrogênio para garantir um futuro sustentável. Portanto, este estudo examina as possibilidades de expansão do mercado de hidrogênio no Brasil em um modelo que permita ao país aproveitar ao máximo os recursos competitivos para beneficiar sua sociedade. Assim, este trabalho está dividido em dois artigos, os quais respondem ao objetivo geral. O primeiro artigo analisa a viabilidade econômica de sistemas híbridos renováveis para produção e armazenamento de hidrogênio no setor elétrico brasileiro. Assim, para avaliar esta proposta, a metodologia utilizada baseia-se em análises de custo econômico das duas maiores usinas eólicas e solares fotovoltaicas do país. Em conclusão, verificou-se que o número de horas de energia elétrica disponível para a produção de hidrogênio influencia diretamente no seu custo. No entanto, plantas totalmente dedicadas à produção de hidrogênio verde mostraram viabilidade econômica quando o hidrogênio é exportado ou usado em outros setores, de modo que o comércio de hidrogênio foi considerado mais lucrativo do que transformá-lo novamente em energia. O modelo também conclui que os sistemas híbridos eólico e solar para produção e armazenamento de hidrogênio ainda não são economicamente viáveis no Brasil. O segundo artigo visa avaliar países com estratégias de hidrogênio mais eficazes, trazendo lições para o Brasil. A questão principal deste trabalho é como o Brasil pode acelerar sua economia de hidrogênio. Para responder a esta pergunta, a metodologia aplicada baseia-se na identificação de políticas públicas e potenciais líderes mercados, onde foram selecionados três países: Alemanha, Holanda e Austrália. Em seguida, a análise foi realizada primeiramente delineando seis pilares que estão apoiando países a prosperarem no mercado de hidrogênio. Então, foi realizada uma pesquisa para coletar informações sobre como os países selecionados estão se engajando em cada pilar. Por fim, é realizada uma análise crítica a fim de levantar lições a serem aprendidas pelo Brasil. Constatou-se que: (i) o Brasil deve estabelecer um marco regulatório que proporcione segurança jurídica e regulatória aos investidores; (ii) o governo brasileiro deve promover políticas públicas sólidas; (iii) o Brasil deverá fazer alianças concretas com os países de vanguarda; (iv) o potencial renovável não é o único fator que determina o potencial para produção de hidrogênio, fatores como: infraestrutura existente, fatores como apoio do governo, relações de confiança entre empresas ou governos, estabilidade política, além de demanda potencial de hidrogênio, também são fatores importantes. Por fim, será feita uma discussão abrangendo os resultados extraídos dos dois trabalhos, apontando características que o Brasil tem como favoráveis para alcançar uma economia baseada em hidrogênio e quais os requisitos essenciais para viabilizar o aumento da produção de hidrogênio, cooperando assim para a transição para uma economia de baixo carbono.

Palavras-chave: Hidrogênio, Setor Elétrico, Transição Energética, Políticas Públicas, Brasil.

LIST OF TABLES

LIST OF FIGURES

SUMMARY

1. INTRODUCTION

To mitigate climate change, the global energy system must undergo a deep transformation from a system that is largely based on fossil fuels to one based on renewable sources.. Furthermore, the Paris Agreement signed in 2016, adopted by 196 Parties, aims to limit global warming to two degrees Celsius below pre-industrial levels (UNFCCC, 2015). This Agreement has accelerated and encouraged the Parties to achieve ambitious targets to reduce or even zero greenhouse gas emission rates. In this context, renewable sources have gained great space, as pointed out by IRENA's annual report (IRENA, 2020a). In 2019, new renewable sources represented 81% of the total global energy expansion (IRENA, 2022a). Wind and solar photovoltaic sources are expected to increase substantially by 2050, and their current share of 7% and 3% to reach 35% and 25%, respectively (IRENA, 2019a). However, a system dominated by renewable energy presents some challenges; as the share of variable renewable energy increases, the system requires a balance of supply and demand.

The Brazilian electric matrix has experienced great growth in renewable sources in the last few years, mainly coming from wind and solar energy projects. In 2010, wind energy represented only 0.3% of the total electric matrix generation in the country, while in 2021, this percentage reached around 10,6%, and solar energy has also been gaining ground, currently representing 2,5% of the total generated and it is expected to grow in the coming years (ONS, 2022).

Brazil´s Northeast Submarket stands out with more than 85% of the country's wind generation capacity, with a higher concentration in the states of Bahia and Rio Grande do Norte (ANTUNES CAMPOS; RAFAEL DO NASCIMENTO; RÜTHER, 2020; ONS, 2021a). The expansion of renewables can cause critical problems such as constrained-off or curtailment, which is a generation reduction demanded by the centralized operator. This event is liable to occur when there is congestion in the transmission grid or wind energy exceeds the difference between the load demand and the minimum generation necessary to maintain the system's stability (MENEZES; SORIANO; DE AQUINO, 2021). Besides, with the increase in the participation of Wind Power Plants and, more recently, Photovoltaic Power Plants, there is an increase of imbalance of generation and load, implying the need for additional flexibility to keep the balance of generation-load. (NASCIMENTO et al., 2021).

According to PDE 2031 (Ten-Year Energy Plan), the photovoltaic (PV) solar and wind sources will probably add around 9 GW to the installed capacity already being implemented until the end of 2031. The generation of renewables (wind and solar PV) is predominant in the Northeastern region of Brazil, and according to records of energy auctions, the Northeast presents 75% of the total renewable plants (EPE; MME, 2021). The fact that wind and solar PV plants are sources of clean and renewable energy has led to their expansion in the national electricity supply. Simultaneously, the electric power sector has experienced the growth of intermittent sources of uncontrollable nature, challenging to keep the system reliability and meet peak demand (BELANÇON, 2021).

Based on the context mentioned above, hydrogen has been seen as one of the leading energy carriers capable of achieving emission reduction goals, as it can be used directly as a low or zero-carbon energy source (depending on its production process). Hydrogen can be introduced in sectors that are difficult to electrify and as a vector for energy storage, enabling greater entry of renewable variables such as wind and solar PV. Thus, Hydrogen is seen as a resource capable of promoting the coupling of the fuel sector, electric, industrial and other markets (EPE, 2021a). According to (EPE, 2021a), currently, Hydrogen production is based on the following technologies:

(i) Brown Hydrogen: produced from gasification of coal;

(ii) Gray Hydrogen: production by steam reform using fossil fuels, mainly natural gas, and if coupled with Carbon Capture Use and Storage (CCUS) technology, it produces the so-called Blue Hydrogen;

(iii) Green Hydrogen: produced from electrolysis using energy from renewable sources; and

(iv) Turquoise Hydrogen: produced by thermal cracking of methane generating carbon (C) and not of carbon dioxide (CO2), provided that the heat source is carbon neutral.

It is highlighted that the production of green hydrogen is still expensive since it uses technologies that are still emerging in the market and does not have scale production since the electrolysis process to produce green hydrogen represents only 2% of the world's production (IEA, 2019a). The production of Blue Hydrogen from natural gas using CCUS, is also very expensive but less than green hydrogen. The production of Gray Hydrogen, without CCUS technology, is currently the cheapest way to produce hydrogen in most parts of the world. However, currently, green hydrogen is still 2 to 3 times more expensive than Blue Hydrogen (IRENA, 2020b). Hydrogen storage and transportation costs are also critical and need to be scaled up to foster competitiveness in using green hydrogen.

Hydrogen is usually stored and transported in compressed or liquid gas due to its low density. Most of the production is consumed *on-site* (85%) or transported by trucks or pipelines (15%) (MAYYAS; WEI; LEVIS, 2020b). Also, storage can be carried out in salt caves and depleted gas or oil reservoirs, enabling large-scale and long-term storage, with lower costs than tanks. Transmission and distribution can be done through hydrogen blends in the natural gas pipelines. Still, this issue requires studies on the gas limit that can be injected without harming the network or the final consumer, thus requiring regulation of the conditions for this mixture (DANTAS; SILVA; THOMAS, 2020).

Also, the massive expansion of renewable variable sources brings challenges to the system regarding energy security and operational flexibility to maintain the balance between demand and supply (SINSEL; RIEMKE; HOFFMANN, 2020). Green hydrogen can play a key role in meeting these challenges through short and long-term energy storage (CHANDRASEKAR; FLYNN; SYRON, 2021b). However, to continue on the energy transition path towards a low or zero-carbon economy based on hydrogen production, will require technological innovation, supporting polices, design and market regulation, and the main challenge regarding the competitiveness of using this energy compared to other sources (HYDROGEN COUNCIL, 2020).

Furthermore, hydrogen can allow the expansion of renewables, as it has the potential to soften the variable production of energy from wind and solar photovoltaic sources. Through hydrogen energy from renewables can be stored, and it is on the go to become the lowest cost option for storing large amounts of electricity for days, weeks or even months (IRENA, 2019b).

Also, green hydrogen production could help with the curtailment of electrical systems caused by renewable sources. However, it would not be possible to produce large amounts of Hydrogen considering only the energy available in curtailment events, where the electrolysers would operate around 10% of the time. This would make it difficult to gain competitiveness in Hydrogen production, even considering the electric energy zero value for the process. This scenario can change if the price of electrolysers is reduced, but this should only happen using electrolysers on the scale. (IEA, 2019a; IRENA, 2019b).

Based on the aforementioned, the development of this dissertation has the purpose of exploring what are the challenges and possibilities of expanding the hydrogen market in the Brazilian electric power sector in a model that enlightens actions that the country should take to move towards the green energy transition, taking full advantage of its competitive features. To come up with this objective central questions were raised:

(i) Is it economically feasible to produce green hydrogen in Brazil through the energy from curtailment events from existing power plants connected to the SIN? Will the economic cost be competitive considering new wind or solar hybrid systems working fulltime for hydrogen production and storage?

(ii) What can Brazil do to accelerate the hydrogen economy based on lessons to learn from other countries?

To answer these questions and the central objective, two papers were built in a complementary way. The first one, which is presented in chapter 2, provides a deep economic analysis of considering renewable hybrid systems for green hydrogen production and storage. The second paper, presented in chapter 3, brings insights from international strategies and market, helping to draw a convenient path for Brazil to thrive in a hydrogen economy. The last chapter presents the conclusions that cover the results from both papers answering the research gaps.

This dissertation is the main result of the master's course held by the Graduate Program in Energy at the University of São Paulo carried out by the author. Although the Program requires the presentation of the dissertation combined with **only one scientific paper** published, accepted or sbmitted in a qualified journal, this study presents a second one deepening the research results of the first. The first one was accepted and published in the qualified international journal: International Journal of Hydrogen Energy[1]. In addition to this, the student during the period of the course produced other publications that subsidized its execution. The complete list of publications and events can be found in Appendix I.

[1] MACEDO, S. F.; PEYERL, D. Prospects and Economic Feasibility Analysis of Wind and Solar Photovoltaic Hybrid Systems for Hydrogen Production and Storage: A Case Study of the Brazilian Electric Power Sector. **International Journal of Hydrogen Energy**, Volume. 47, Issue 19 March 2022. https://doi.org/10.1016/j.ijhydene.2022.01.133

2. PROSPECTS AND ECONOMIC FEASIBILITY ANALYSIS OF WIND AND SOLAR PHOTOVOLTAIC HYBRID SYSTEMS FOR HYDROGEN PRODUCTION AND STORAGE: A CASE STUDY OF THE BRAZILIAN ELECTRIC POWER SECTOR[2]

Abstract: The work aims to verify the economic feasibility of renewable hybrid systems for hydrogen production and storage in the Brazilian electric power sector. The methodology applied is based on economic cost analyses of the two largest wind and solar photovoltaic plants in the country. As a result, the number of hours of electricity available for hydrogen production directly influences its cost. However, fully dedicated plants to produce green hydrogen have shown economically feasible to the exporter or other sectors, being trading hydrogen is more profitable than transforming it back into power. The model also concludes that wind and solar hybrid systems for hydrogen production and storage are still not economically viable in Brazil. The CAPEX of electrolysers and their operating losses are still very significant. Finally, hydrogen production and storage become economically feasible only from plants operating above 3000 h and for electrolysers with a CAPEX of USD 650/kWe.

Keywords: Green hydrogen, Hybrid system, Electric power sector, Economic costs, Brazil.

2.1. INTRODUCTION

Hydrogen has emerged as a key factor in the global transition to a net-zero economy (BARRETO; MAKIHIRA; RIAHI, 2003; VAN RENSSEN, 2020). In particular, green hydrogen has become one of the most sustainable long-term hydrogen supply options (IRENA, 2019b). Green hydrogen is currently recognized as a clean energy carrier (CHANDRASEKAR; FLYNN; SYRON, 2021b; HYDROGEN COUNCIL, 2020) produced by electrolysis using electricity from renewables to split water into hydrogen and oxygen (IRENA, 2020b; WANG-HELMREICH; LOCHNER, 2012). Electricity can be stored through this process by converting it into hydrogen (Power-to-Hydrogen) (HEUSER et al., 2019). The integration of renewable energy sources and hydrogen systems offers new pathways to achieving global targets to the zero-carbon economy (DINCER; ACAR, 2018; SAEEDMANESH; MAC KINNON; BROUWER, 2018), balancing the power grid and tackling intermittency of Variable Renewable Energy (VRE) (CHEN; LU; XINGA, 2021; SAEEDMANESH; MAC

[2] This paper was accepted and published with contributions from Drielli Peyerl in the International Journal of Hydrogen Energy. Cite this paper as:
MACEDO, S. F.; PEYERL, D. Prospects and Economic Feasibility Analysis of Wind and Solar Photovoltaic Hybrid Systems for Hydrogen Production and Storage: A Case Study of the Brazilian Electric Power Sector. International Journal of Hydrogen Energy, Volume. 47, Issue 19 March 2022. https://doi.org/10.1016/j.ijhydene.2022.01.133

KINNON; BROUWER, 2018) through energy storage (CHANDRASEKAR; FLYNN; SYRON, 2021b; HYDROGEN COUNCIL, 2020). That can facilitate integrating high VRE shares and avoid generation surplus curtailment (CHEN; YANG; HU, 2021; RABIEE; KEANE; SOROUDI, 2021; YU et al., 2019). In addition, the green hydrogen produced can be used across multiple sectors or reconverted back into power through fuel cells, increasing the power grid flexibility (BØDAL; KORPÅS, 2020; WANG et al., 2018). The future benefits of green hydrogen production include energy security, mitigating greenhouse gases (GHG), economic growth, and industrial competitiveness (ASKARZADEH; COELHO, 2015; IRENA, 2020b; SAWLE; GUPTA; BOHRE, 2018). On the other hand, green hydrogen faces globally barriers that prevent its full contribution to the energy transition, such as high production costs, lack of dedicated infrastructure, energy losses, tax regimes, deployment policies, trade agreements and financial regulation (IRENA, 2020b, 2021).

In the case of the production of green hydrogen, the costs are between USD 2.50-6.80/kg, while the current price of grey hydrogen production at USD 1-1.80/kg and blue hydrogen at USD 1.40-2.40/kg (IEA, 2021a; IRENA, 2019a, 2020a). The most attractive production markets for green hydrogen are those with abundant, low-cost renewable resources (VAN DE GRAAF et al., 2020; ZHAO et al., 2019). In parts of the Middle East, Africa, Russia, the United States and Australia, green hydrogen can be produced for EUR 3 to EUR 5/kg (IEA, 2021a; IRENA, 2019b, 2020b). While in Europe, production costs can vary from EUR 3 to EUR 8/kg (IEA, 2021a; IRENA, 2019b, 2020b) . Furthermore, green hydrogen has become viable due to the increasing drop-in renewable energy costs and the integration of energy systems (IRENA, 2020b). Some studies, for example, already have demonstrated the feasibility of a levelized cost of hydrogen production through a renewable hybrid system (ABDIN; MÉRIDA, 2019; KHOUJA, 2021; MCDONAGH et al., 2020). An offshore wind hybrid system associated with hydrogen production only, given 10% curtailment, has shown a levelized cost of hydrogen of EUR 3.77/kg (MCDONAGH et al., 2020). On the other hand, (KHOUJA, 2021) has found a levelized hydrogen cost of 4.07 USD/kg. Also, (GUTIÉRREZ-MARTÍN; AMODIO; PAGANO, 2021) shows that costs for off-grid hydrogen production connected to the solar photovoltaic (PV) systems are around 6–7 EUR/kg. It is worth highlighting that in the previous studies, the hydrogen produced is used in other sectors and not transformed back into electric power.

The potential of the low-cost and large-scale production of green hydrogen have been assessed in different regions and countries (DELPIERRE et al., 2021; IRENA, 2016; KUDRIA et al., 2021; TOUILI et al., 2020; XIANG et al., 2021). Brazil has great wind and solar potential to produce green hydrogen, which needs to be better explored and deepened (EPE, 2020a; IEA, 2021b; KELMAN et al., 2020). Also, the Brazilian electricity generation mix is one of the cleanest globally, with 85% from renewable sources (EPE, 2021b), with hydropower accounting for 64% of the total, solar 1,7% and wind 9,2% considering 2020 data (EPE, 2021b). In the general context, the country has a well-established renewable industry developed over several years, including an established supply chain and specialised workforce (AQUILA et al., 2017). Brazil also has the potential to create both a local market, in particular, to feed industrial sectors that consume large amounts of energy and/or to use in transport sectors, as well as for the international market, which should create an important demand for this type of fuel in the coming years (KELMAN et al., 2020; MME, 2021a). Therefore, the country can become a competitive hydrogen producer by combining these resources (MME, 2021a).

This work aims to verify the economic feasibility of wind and solar PV hybrid systems in the National Interconnected System (SIN) for hydrogen production and storage in the Brazilian electric power sector. As part of this research, the guiding questions are: Is it economically feasible to produce green hydrogen in Brazil through the energy from curtailment events from existing power plants connected to the SIN? Will the economic cost be competitive considering new wind or solar hybrid systems working full time for hydrogen production and storage? To answer these questions, the two largest Brazilian renewable energy generating plants (Baixa do Feijão wind and Sertão Solar Barreiras PV power plants) were selected as case studies. In addition, the input data of the two case studies allowed applying an economic cost model and developing four hypothetical scenarios close to reality. It highlights that there are studies about renewable hybrid systems mainly to decentralised power generation in the country but not specifically linked to hydrogen (LYSENG et al., 2018; SILVA; DE OLIVEIRA MARCO; SEVERINO, 2010; SILVA; SEVERINO; DE OLIVEIRA, 2013). Some studies also relate hybrid systems with hydrogen to other sources (e.g., hydropower and wind power) or point to economic projections of hydrogen production (DO SACRAMENTO et al., 2013; EZAR NADALETI; ALVES LOURENÇO; AMERICO, 2021; NADALETI; BORGES DOS SANTOS; LOURENÇO, 2020). Therefore, the novelty of this work shows the actual costs of implementing the wind and PV solar hybrid system for both hydrogen production and storage in the Brazilian electric power sector, becoming one of the first studies about this subject in the country. It highlights that other case studies can reapply the economic cost model developed. At last, all the results from this article can support policymakers in establishing a national hydrogen economy and the green hydrogen market across borders.

2.2. HYBRID SYSTEM

Several studies have demonstrated the feasibility of hybrid systems with combined solar PV, wind power, fuel cell, electrolyser, and hydrogen storage systems (BHUYAN; HOTA; PANDA, 2018a; CALDERÓN et al., 2011b; CEYLAN; DEVRIM, 2021b; HASSANZADEHFARD et al., 2020b; OKUNDAMIYA, 2020b; PEPPAS et al., 2021b). However, according to (ACUÑA; PADILLA; MERCADO, 2017a; AL-GHUSSAIN; AHMED; HANEEF, 2018a; MAZZEO; MATERA; OLIVETI, 2018a; OKUNDAMIYA, 2020b), PV and wind hybrid system coupled with battery is more feasible and has higher efficiency than without energy storage. On the other hand, as reported by (MAZZEO et al., 2021a), there is a time trending of publications related to hybrid systems coupled to hydrogen systems. Even though the battery is the most widely used stored system for grid connection, with a small percentage, hydrogen tanks have been used with fuel cells to form a hydrogen system (MAZZEO et al., 2021a).

The schematic of the wind and solar PV hybrid system for hydrogen production and storage, proposed in Fig. 1, consists of electricity supply (wind or solar PV), electrolyser, hydrogen storage tank for a long time energy storage, fuel cell and a power inverter (Direct Current (DC)/Alternating Current (AC)) (MAYYAS; WEI; LEVIS, 2020b). Besides using batteries as enabling technologies to facilitate the integration of high shares of VRE and avoid curtailment of the generation surplus, and the possibility of use of other technologies as compressed air energy storage (LUND; SALGI, 2009b) or the concept of smart energy (LUND et al., 2016a), electricity can be stored by being converted into hydrogen (IRENA, 2019c). Still, hydrogen has been demonstrated to be the best option for long term and massive storage, as it has a lower loss rate than batteries (ABDIN; MÉRIDA, 2019; IEA, 2019b; MAYYAS; WEI; LEVIS, 2020b). There are four types of electrolyser: Solid Oxide in the early commercialisation stage; Alkaline and Polymer Electrolyte Membrane (PEM), which are already commercial; and Anion Exchange Membrane (AEM) currently at lab scale (MAYYAS et al., 2019a). The PEM model is adopted for this work as it is better suited to a VRE source (CHANDRASEKAR;

FLYNN; SYRON, 2021b) and has an excellent time response (MOHAMMADI; MEHRPOOYA, 2018a). The energy flowing during transients can be absorbed by the PEM electrolyser, enhancing the efficiency of the project (FALCÃO; PINTO, 2020a; HERNÁNDEZ-GÓMEZ; RAMIREZ; GUILBERT, 2020b). The hydrogen produced can be stored in tanks or geological formations without losing its stored energy capacity (MAYYAS; WEI; LEVIS, 2020b). Conventional tanks, at output pressure from the electrolyser (30 bar for PEM technologies), can be applied without using a hydrogen compressor (SCHALENBACH et al., 2013). Conventional tanks also can maximise flexibility, as mechanical compression can limit the speed at which electrolyser output can change (ZOULIAS; LYMBEROPOULOS, 2007).

Several studies have demonstrated the feasibility of hybrid systems with combined solar PV, wind power, fuel cell, electrolyser, and hydrogen storage systems (BHUYAN; HOTA; PANDA, 2018b; CALDERÓN et al., 2011a; CEYLAN; DEVRIM, 2021a; HASSANZADEHFARD et al., 2020a; OKUNDAMIYA, 2020a; PEPPAS et al., 2021a). However, according to (ACUÑA; PADILLA; MERCADO, 2017b; AL-GHUSSAIN; AHMED; HANEEF, 2018b; MAZZEO; MATERA; OLIVETI, 2018b; OKUNDAMIYA, 2020a), PV and wind hybrid system coupled with battery is more feasible and has higher efficiency than without energy storage. On the other hand, as reported by (MAZZEO et al., 2021b), there is a time trending of publications related to hybrid systems coupled to hydrogen systems. Even though the battery is the most widely used stored system for grid connection, with a small percentage, hydrogen tanks have been used with fuel cells to form a hydrogen system (MAZZEO et al., 2021b).

The schematic of the wind and solar PV hybrid system for hydrogen production and storage, proposed in Figure 1, consists of electricity supply (wind or solar PV), electrolyser, hydrogen storage tank for a long time energy storage, fuel cell and a power inverter (Direct Current (DC)/Alternating Current (AC)) (MAYYAS; WEI; LEVIS, 2020b). Besides using batteries as enabling technologies to facilitate the integration of high shares of VRE and avoid curtailment of the generation surplus, and the possibility of use of other technologies as compressed air energy storage (LUND; SALGI, 2009a) or the concept of smart energy (LUND et al., 2016b), electricity can be stored by being converted into hydrogen (IRENA, 2019d). Still, hydrogen has been demonstrated to be the best option for long term and massive storage, as it has a lower loss rate than batteries (ABDIN; MÉRIDA, 2019; IEA, 2019c; MAYYAS; WEI; LEVIS, 2020a). There are four types of electrolyser: Solid Oxide in the early commercialisation stage; Alkaline and

Polymer Electrolyte Membrane (PEM), which are already commercial; and Anion Exchange Membrane (AEM) currently at lab scale (MAYYAS et al., 2019b). The PEM model is adopted for this work as it is better suited to a VRE source (CHANDRASEKAR; FLYNN; SYRON, 2021a) and has an excellent time response (MOHAMMADI; MEHRPOOYA, 2018b). The energy flowing during transients can be absorbed by the PEM electrolyser, enhancing the efficiency of the project (FALCÃO; PINTO, 2020b; HERNÁNDEZ-GÓMEZ; RAMIREZ; GUILBERT, 2020a). The hydrogen produced can be stored in tanks or geological formations without losing its stored energy capacity (MAYYAS; WEI; LEVIS, 2020a). Conventional tanks, at output pressure from the electrolyser (30 bar for PEM technologies), can be applied without using a hydrogen compressor (SCHALENBACH et al., 2013). Conventional tanks also can maximise flexibility, as mechanical compression can limit the speed at which electrolyser output can change (ZOULIAS; LYMBEROPOULOS, 2007).

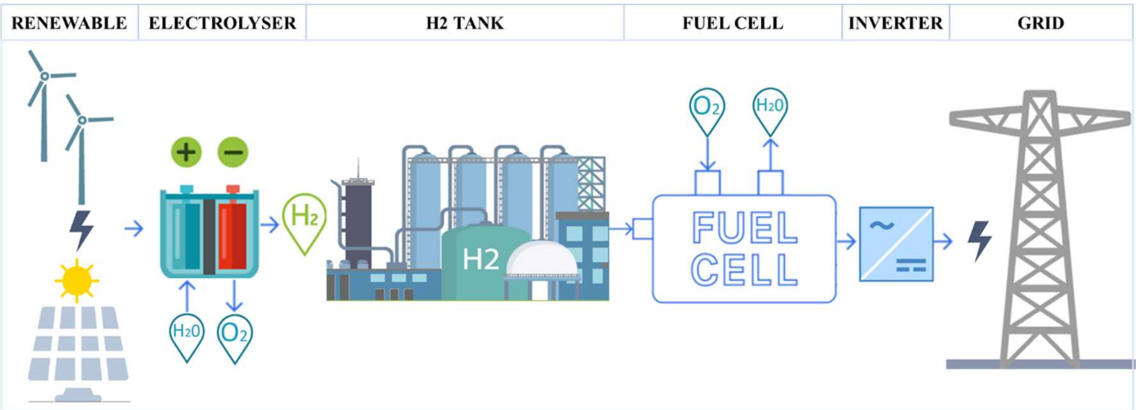

Figure 1: Schematic wind and solar PV hybrid systems for hydrogen production and storage (IRENA, 2020c).

The fuel cell converts hydrogen and oxygen into water and electricity. This electricity can be delivered to the grid after going through an inverter DC/AC (MAYYAS; WEI; LEVIS, 2020b; ZOULIAS; LYMBEROPOULOS, 2007). Fuel cells can achieve high efficiencies over 60% and have higher efficiency in part-load than full load, making them particularly attractive for flexible operations such as load balancing (IEA, 2019b). Fuel cells can be used for stationary applications in backup generation, large-scale power plants or microgrids (IRENA, 2020b). Polymer electrolyte membrane fuel cell (PEMFC) and solid oxide fuel cell (SOFC) are most used (ABDIN; MÉRIDA, 2019; BORNAPOUR et al., 2020). However, molten carbonate fuel cells (MCFCs) are used in the Megawatts (MW) scale for power generation, resulting in a relatively large size (ABDIN; MÉRIDA, 2019; BORNAPOUR et al., 2020). Besides, hydrogen-based storage options suffer from low round-trip efficiency in converting electricity through electrolysis into hydrogen, then hydrogen back into electricity, around 60% of the original electricity is lost (EIA, 2020). In light of this, the hydrogen produced can be combined with other usages, as exported to different sectors as industrial and transport (IEA, 2019b). However, it is worth highlighting that the feasibilities of hydrogen are different if one takes a broader cross-sectoral smart energy systems approach as worked by (LUND et al., 2017; THELLUFSEN et al., 2020).

2.3. BRAZILIAN ELECTRIC POWER SECTOR AND RENEWABLE DEVELOPMENT

The Brazilian electricity sector is organized by (i) the National Electricity Agency (ANEEL), which is the sector's regulator; (ii) the Energy Research Company (EPE), which has provided the sector's energy planning and; (iii) the National System Operator (ONS), which is responsible for the operation of the generation and transmission facilities of the SIN (EPE, 2021c; ONS, 2019). The SIN consists of four subsystems: South, Southeast/Midwest, Northeast (NE), and most North regions (ONS, 2019). The transmission system's exchange limits determine the line that divides each subsystem (BAYER; BERTHOLD; MORENO RODRIGO DE FREITAS, 2018). However, some country areas are still disconnected from the SIN for technical or economic reasons (LIMA et al., 2020). Also, the Brazilian electricity power sector is formed by two trading environments: (i) the Free Contracting Environment (ACL), which is the market segment subject to freely negotiated bilateral agreements; and (ii) the Regulated Contracting Environment (ACR), which is organised around centralised auctions led by ANEEL (BRASIL, 2004; GLORIA; LEITES, 2018; VIANA; RAMOS, 2018). It is highlighted that the ANEEL electricity auctions for utility supply adequacy have become Brazil's main power purchasing method (BRASIL, 2004; GLORIA; LEITES, 2018; VIANA; RAMOS, 2018). Three kinds of auctions are relevant for renewable projects: (i) Auction for new power generation projects (LEN), which can be carried out from 3 to 7 years before the start of energy supply; (ii) Alternative generation projects (LFA), which can be carried out from 1 to 3 years before the start of energy supply and, (iii) Reserve energy (LER) (BAYER; BERTHOLD; MORENO RODRIGO DE FREITAS, 2018). LEN and LFA have a 15-years minimum and 30-years maximum supply term, and LER has 15-

years minimum and a 35-years maximum supply term (VIANA; RAMOS, 2018). At last, it highlights the Alternative Sources Incentive Program (PROINFA), which aimed to diversify the Brazilian mix electricity generation sources, promote supply security, enhance regional and local characteristics, and reduce GHG emissions (DUTRA; SZKLO, 2008; SOLIANO PEREIRA, 2009). Figure 2 shows the development of renewables in Brazil through these processes.

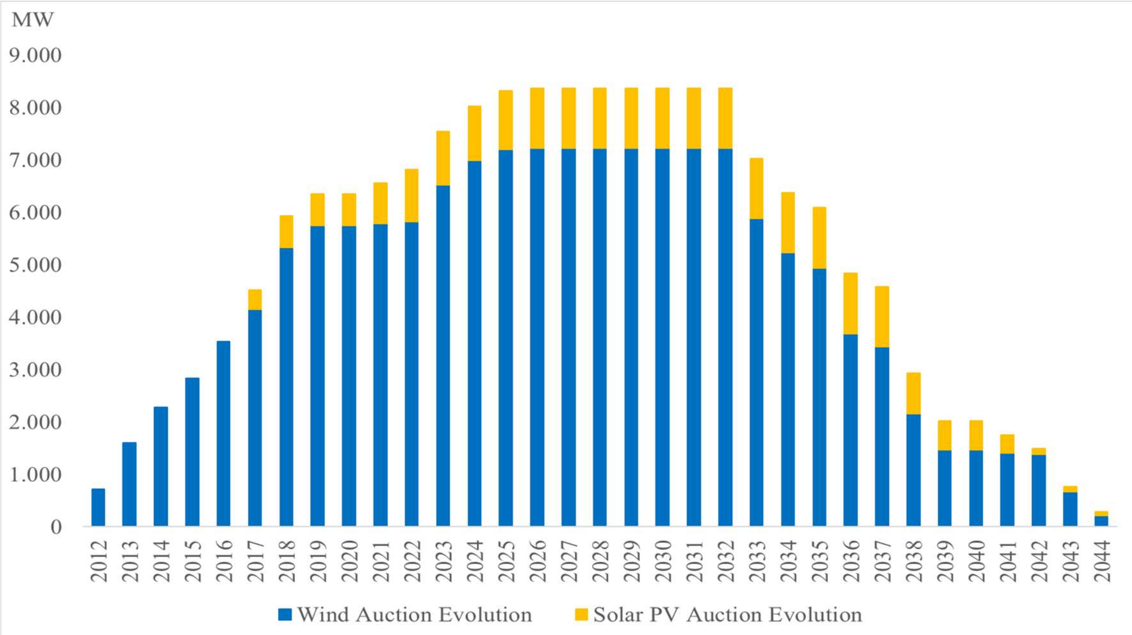

Figure 2: Progress of contracting in expansion auctions by renewable energy source (CCEE, 2021a; EPE, 2016).

Wind and Solar PV are taking place through ANEEL auctions, bringing huge investments and reducing energy prices, as shown in Figure 3 (CCEE, 2021a, 2021b). Over recent years, particularly in the NE region, renewables sources have demonstrated strong growth, increasing the importance of this generation to meet the market needs (EPE, 2021d). According to (DO NASCIMENTO CAMELO et al., 2018), wind projects have raised investments of USD 19,6 billion and solar USD 5,0 billion, and it is forecasted to increase 6 Gigawatts (GW) capacity on the electricity mix by 2030 (EPE, 2020b).

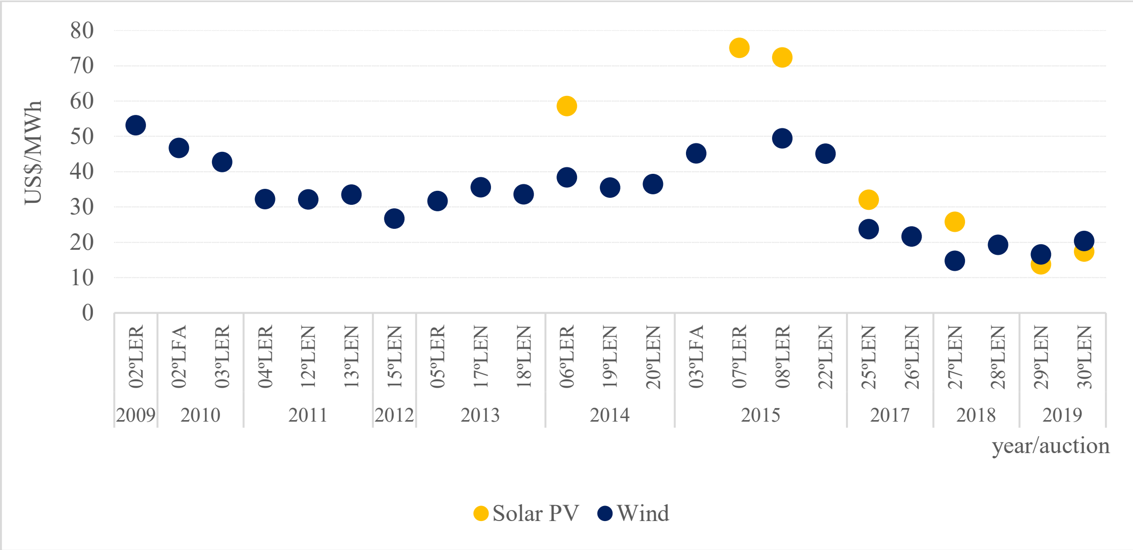

Figure 3: Average sale price per renewable sources auction of the Brazilian electricity sector (US$/MWh*) (CCEE, 2021a, 2021b, 2021c).

*Considering the Broad National Consumer Price Index (IPCA) of Apr/2021 price index for readjustments.

Figures 4 and 5 show the wind and solar PV expansion in the country, mainly in the NE region.

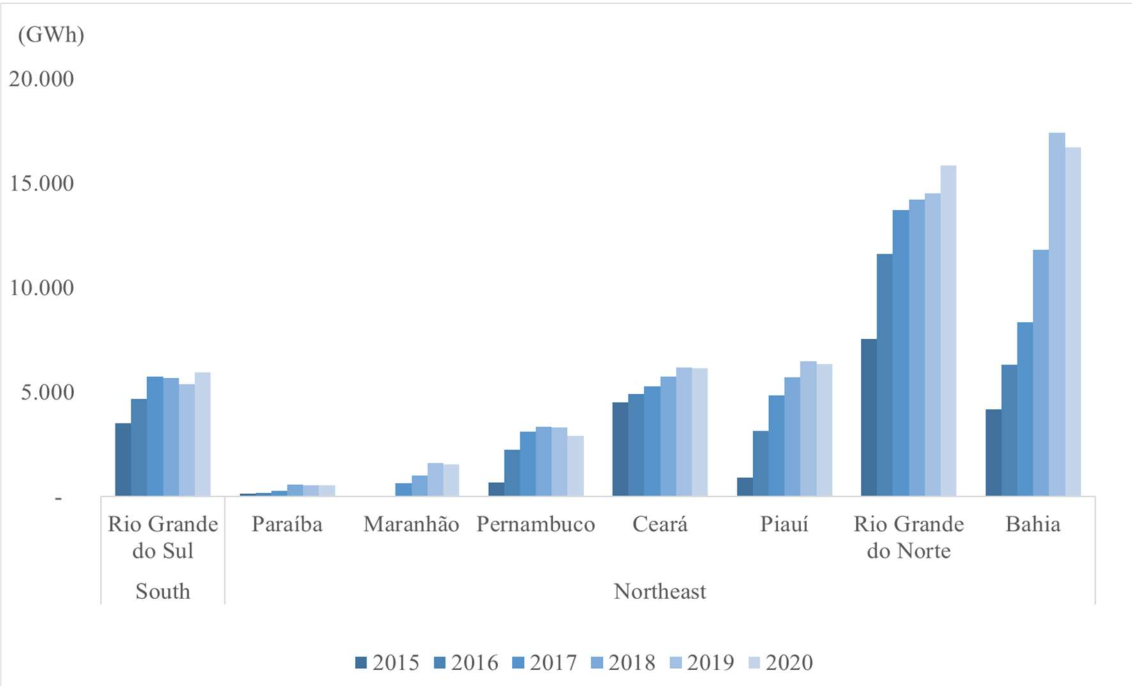

Figure 4: Brazil wind energy generation by subsystem and state (ONS, 2021b).

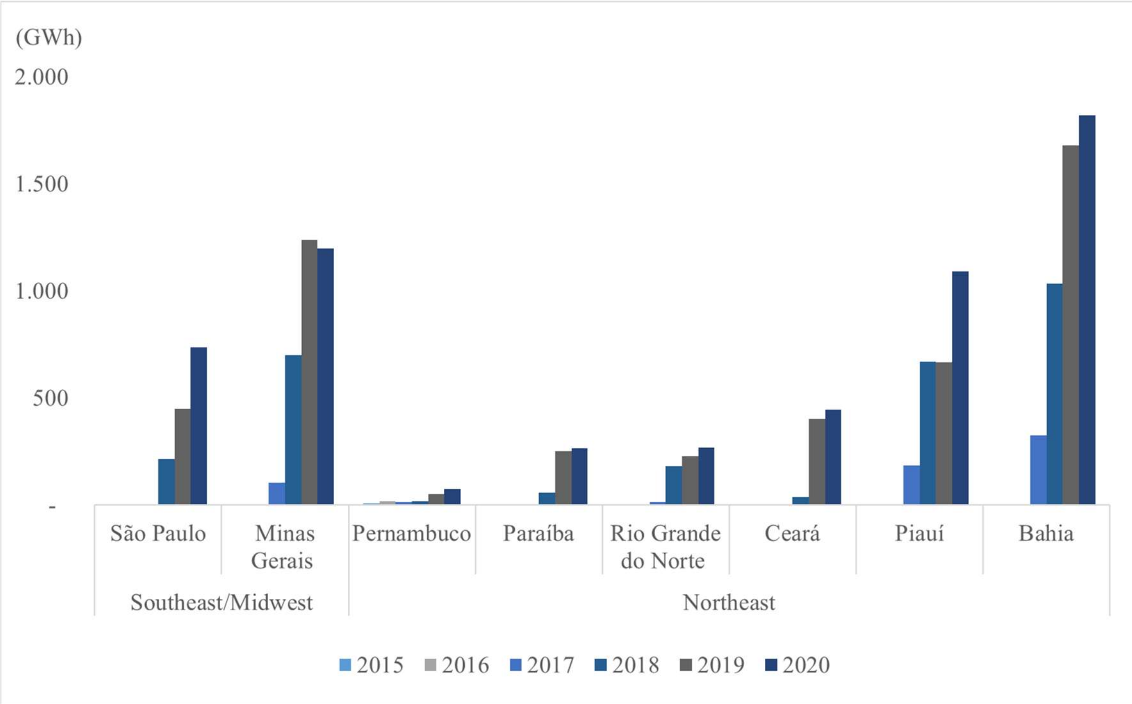

Figure 5: Brasil solar PV energy generation by subsystem and state (ONS, 2021c).

The rise in renewable energies implies the quality of the power delivered without significant interruptions and reliability of the system, as approached by (AKEYO; PATRICK; IONEL, 2020). According to (REN et al., 2017), attending peak load and quantifying the risk associated with renewables penetration is necessary to keep the system reliable. However, external factors such as seasonality, interannual and hourly variability have still impacted the total energy capacity through renewable sources (PFENNINGER, 2017). In the case of wind and solar generation, there are strong differences in supply curve and consumer demand curve patterns (DENHOLM; HAND, 2011). As the Brazilian NE Subsystem presents the most wind and solar power generation, Figure 6 compares this region's hourly load curve and renewable generation during August 2020, period this of the greater intermittence of the renewables (PRADO, 2021). Besides, the second semester shows high wind speed records in the NE region, allowing wind power plants to generate large amounts of energy (CAMELO et al., 2018).

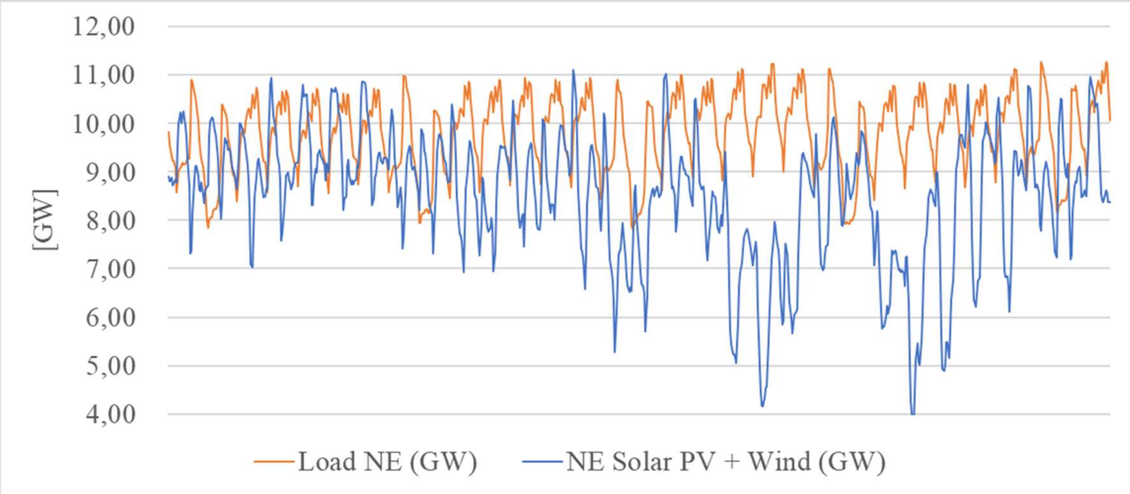

Figure 6: Hourly load of NE compared to wind and solar PV generation and the region (period August 2020) (ONS, 2021a).

As explained in (MME; EPE, 2014), the NE Subsystem presents features that differentiate it from other Brazilian regions, leading the ONS to adopt certain operating policies to ensure SIN security. One big issue is curtailment, defined as a generation reduction of the centralised operator demands about scheduling due to transmission network limitations, operational reserve requirements, or over-load generation (DE LIMA, 2021). The regulation for this issue is the Normative Resolution nº 927, 2021, which attends wind projects and proposes a refund for frustrated generation valued by the market price (MORAIS, 2021). However, it considers refundable only the frustrated generation related to unavailability of external equipment to the plant, with a duration above 78 hours per year (MORAIS, 2021). Curtailment is being addressed from a regulatory perspective, but the physical matter still needs to be addressed (ANEEL, 2019a).

The regulation for hybrid systems in Brazil covers only the combination of two or more sources of energy production, as provided by the Normative Resolution 954, published in December 2021 (BRASIL, 2021). Still, the Normative Resolution does not consider storage systems (ANEEL, 2020). Apart from the SIN, hybrid and storage systems were enabled to enroll in the isolated system's (IS) auction in 2019 for the state of Roraima, which can be used as a reference in later events (ANEEL, 2019b). The law enabling these solutions for the SIN is expected to come into force foreseeable, provided by Senate Bill 232/2016. It will include projects with storage systems working as a power product, and the government will establish guidelines for bidding (BRASIL, 2016). In

July 2021, the Brazilian government also presented the Hydrogen National Program (PNH2) guidelines, aiming to demonstrate the country's strategies for developing the hydrogen economy (MME, 2021a). The PNH2 also seeks to map existing laws and regulations to support and promote hydrogen as an energy and fuel vector in the Brazilian energy matrix (MME, 2021a) . According to (CHAVES; DORES; DE CASTRO, 2021), the production and industrial uses of hydrogen in Brazil are relatively consolidated. However, for enabling the large-scale use of hydrogen, public incentive policies in stimulating the hydrogen economy are considered essential for reducing technical, regulatory, economic costs and socio-environmental barriers (PEYERL, 2018).

2.4. METHODOLOGY

The two largest Brazilian renewables (wind and solar) energy generating plants were selected as case studies. Both power plants are located in the NE subsystem of the SIN (See Figure 7). The complex Sertão Solar Barreiras PV power plant is situated in the city of Barreiras (Bahia state) and is the only winning solar power plant of the 25th LEN (ANEEL, 2021; CCEE, 2021d). This complex consists of four solar power plants, Sertão Barreiras I to IV, each with a 26,66 MW nominal power and 6,8 MW firm energy certificate (ANEEL, 2021). In total, 339,120 modules were installed, and the complex has been generating 230 GWh annually, presenting an average capacity factor of 28% (ONS, 2021a; PORTAL SOLAR, 2020). The total investment was about USD 0,3 billion, and Operation and Maintenance (O&M) was estimated at USD 12/kW/year (EPE, 2020a). The plant started its operation in November 2019 with a 20-years Power Purchase Agreement (PPA) (CCEE, 2021e; PORTAL SOLAR, 2020), investing in training and developing capacity, building programs in local communities to work during the construction as an opportunity to generate new sources of income (SANTOS, 2020). The second case study is the wind power complex Baixa do Feijão located in the city of Jandaíra (Rio Grande do Norte state). Seven plants form the complex: Baixa do Feijão I to IV, Aroeira, Jericó and Umbuzeiro, counting 15 turbines each, presenting a total of 210 MW nominal power and 92,8 MW of the firm energy certificate. Therefore, part of the complex (Baixa do Feijão I to IV) was a winning project of the 13th LEN and part of the 18th LEN for utility supply, having a 20-years PPA, with the operation started respectively in 2016 and 2017 (THE WIND POWER, 2021). The investment was about USD 0,24 billion, according to the results of the bids data and O&M estimated in

USD19/kW/year (EPE, 2020a). The complex has generated 736 GWh annually, presenting an average capacity factor of 42% (ONS, 2021a).

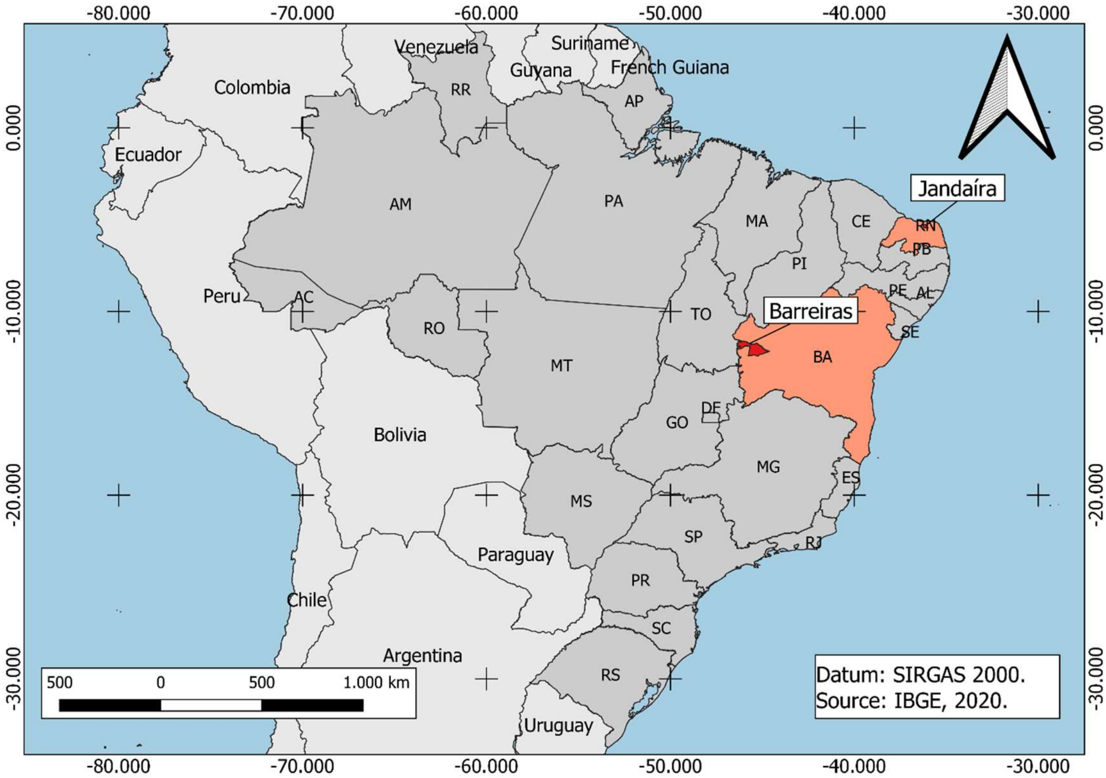

Figure 7: Geographic location of Sertão Solar Barreiras PV (Barreiras) and Baixa do Feijão wind (Jandaíra) power plants in Brazil (IBGE, 2020).

As the case studies are connected on-grid with their full capacity sold in a PPA, the amount of hydrogen possible to be produced will be tied to curtailment periods that each plant would be exposed. There is no curtailment power index in Brazil, as pointed out by (RIBEIRO et al., 2019), although the SIN availability is being used to measure (BRAZIL, 2021; MORAIS, 2021). In the NE subsystem, the availability of the SIN achieved 93,65% in 2020 and dropped to 91,80% (ONS, 2021d). During this period, the plants may be prevented from generating in parts or completely (CCEE, 2021d).

The ONS, ANEEL and Chamber of Electric Energy Commercialization (CCEE) provided the data to calculate the hydrogen production of the case studies selected in this paper (ANEEL, 2021; CCEE, 2021f; ONS, 2021a). The hourly power generation of the chosen plants are available on the ONS platform, and the auctions data are available on ANEEL and CCEE platforms. It was possible to gather technical details about the power plants through that. Also, on the ONS platform, it was possible to obtain reports of the SIN Performance Index, which indicate the availability of the grid for power flow.

2.4.1. Modeling process

(1) Wind and solar power into the electrical grid at the time t

Real data was collected from the ONS (ONS, 2021a) of energy generation integrated into the grid from the wind power plant complex Baixa do Feijão and from the solar PV complex Sertão Solar Barreiras hourly throughout the year 2020. The power onto the electrical grid is given by Ptg at time t:

$$P_{tg} = OPP(t)$$

Eq.1

Where OPP(t) is the power output of the power plant at time t. The hourly generating features of the plants is presented in Figure 8.

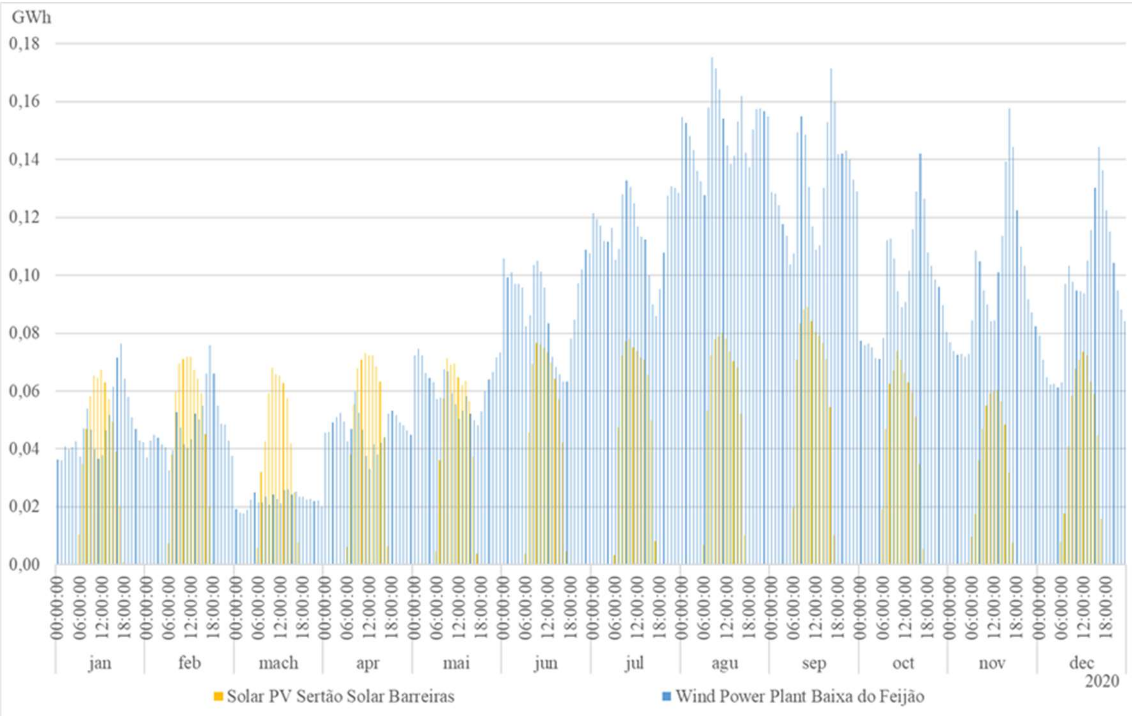

Figure 8: Case studies average generation integrated energy into the grid by the hour in 2020 (ONS, 2021a).

(2) Curtailed Period Considered

Considering the unavailability of 8.2% measure in 2020 for the NE Subsystem (ONS, 2021c), it was adopted in this study that, as 2020 had 8,784 hours, the total curtailment period was 720 hours. Therefore, it was considered the maximum curtailed period for each case study.

(3) Curtailed Power Driven to the Electrolyser for hydrogen production

The plants can be curtailed in parts or totally. Figure 9 was built to demonstrate the permanence energy generation curve of the case studies. Based on this curve, it was possible to range the possible sizes of electrolysers for the power plants.

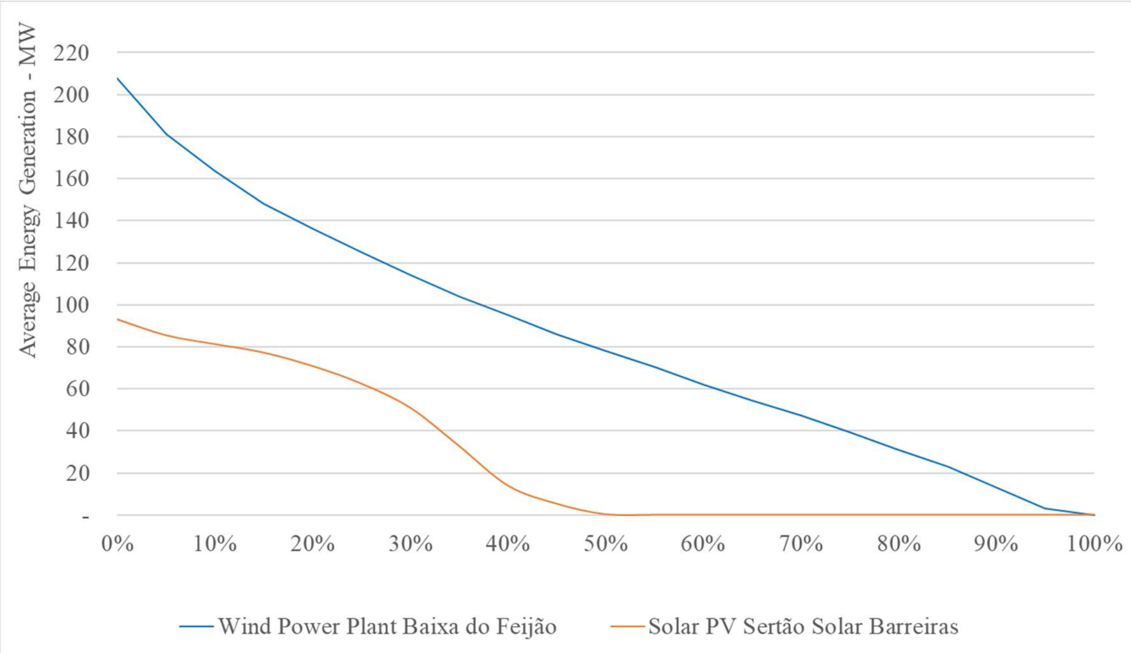

Figure 9: Average energy generation curve of the case studies in 2020.

The size of the electrolysis plant should be given at different electrolyser rated power, from 1 MW to 90 MW. This range is based on the firm energy certificate of the case studies (DINH et al., 2020; ZHANG; WAN, 2014b). Following six premises: (i) Intermittent operation without any other power source supply when curtailed power was not enough for starting electrolyser; (ii) hydrogen production is proportional with electrolyser power; (iii) average energy consumption μ is 39,5 kWh/kg (MCDONAGH et al., 2020); (iv) Annual working hours 720h (NE Subsystem average unavailability); (v) lifetime of 20 years and; (vi) green hydrogen price of USD 4,2/kg (IRENA, 2019a).

Eqs. 2 and 3 determine the energy viable from the power plant, driven to the electrolyser (ZHANG; WAN, 2014b).

$$P_{t,c} = OPP(t)$$

Eq.2

$$E_{H2} = P_{H2_{plant}} \times T_{P_{t,c} \geq P_{H2_{plant}}} + E_{t,c_{25\% P_{H2pla}} < P_{t,c} < P_{H2pla}}$$

Eq.3

Where $P_{t,c}$ is the power of curtailment of the power plants, E_{H2} is the energy used for electrolyser system; $P_{H2_{plant}}$ is the electrolyser rated Power; $T_{P_{t,c} \geq P_{H2_{plant}}}$ is the total time when $P_{t,c} \geq P_{H2_{plant}}$; and $E_{t,c_{25\% P_{H2pla}} < P_{t,c} < P_{H2pla}}$ is assumed curtailed energy of the whole plant when $25\% P_{H2pla} < P_{t,c} < P_{H2pla}$.

Finally, Eq. 4 can lead to the amount of hydrogen that can be produced (DINH et al., 2020).

$$W_{H2}\,(t) = \frac{E_{H2}}{\mu}\left[\frac{kg}{hour}\right]$$

Eq.4

Where W_(H2) (t) is the amount of hydrogen that can be produced per hour from curtailment, and μ is the electrolyser average energy consumption.

2.5. ECONOMIC COSTS

As mentioned in the Introduction (FALCÃO; PINTO, 2020a), green hydrogen production is currently expensive (IRENA, 2020b). The electricity input is the major cost, followed by electrolysers' efficiency and capital cost (LONGDEN et al., 2020). Despite the market availability and maturity, PEM and alkaline water electrolysers are considered highly expensive from Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) prospective than fossil fuel-based hydrogen production (IRENA, 2020b). As stated by (IRENA, 2020b), electrolyser CAPEX, electricity price and operating hours are the main parameters determining the cost of producing green hydrogen. The hydrogen production by water electrolyser presents a global average parameter as shown in Table 1. Still, to reach these numbers, it is considered full load hours of electricity, with a capacity factor around 5000 hours/year and an electricity price in the long-term of USD 18/MWh to USD 63/MWh (IEA, 2019b). Some studies stand that costs could be cut by 40% in the short-term and up to 80% in the long-term (IRENA, 2020b). As reported by (IRENA, 2020b), green hydrogen can achieve cost competitiveness with blue hydrogen through large scale hybrid solar PV and wind power plants in favorable geographic locations, reaching a capacity factor of 5000 hours per year.

Parameter	Unit	2021	2030	Long term
CAPEX	USD/kWe	1100	650	200
Efficiency (Lower Heating Value - LHV)	%	60	68	74
Annual OPEX	% of CAPEX	1,5	1,5	1,5
Stack lifetime (operating hours)	hours	90000	90000	150000

Table 1: Water electrolysis parameters (CHRISTENSEN, 2020; IRENA, 2019d).

Hydrogen can provide strategic opportunities for storing large amounts of energy over longer durations, for example, when seasonal storage of energy is needed (CMS, 2020). On the other hand, as operating hours is an important issue, producing hydrogen only from curtailed electricity, which today implies in few hours (considering the case studies that count with the maximum of 60 hours per month), the investment can be cost dominant, suggesting barriers for the establishment of hybrid projects with hydrogen.

This work considers the hydrogen cost production (CP_{H2}) as Eq. 5:

$$CP_{H2} = \frac{PP_{CAPEX} + PP_{OPEX} + EL_{CAPEX} + EL_{OPEX} + TK_{CAPEX} + TK_{OPEX}}{W_{H2}}$$

Eq. 5

Where:

PP_{CAPEX} = Power Plant CAPEX [USD]

PP_{OPEX} = Power Plant OPEX [USD]

EL_{CAPEX} = Electroliser CAPEX [USD]

EL_{OPEX} = Electroliser OPEX [USD]

TK_{CAPEX} = Storage Tank CAPEX [USD]

TK_{OPEX} = Storage Tank OPEX [USD]

W_{H2} = Hydrogen Production [kg]

The payback period by simple methods of the hybrid hydrogen system that has been proposed is calculated by Eq. 6:

$$Payback\ Period = \frac{Initial\ Investment\ Cost}{Annual\ Operating\ Savings}$$

Eq. 6

Where Initial Investment Cost consists of electrolyser, hydrogen storage system, fuel cell; and Annual Operating Savings is the net income from hydrogen after maintenance cost (ZHANG; WAN, 2014a). Other premises for the hybrid system are the cost for a high-pressure steel tank at 30 bar, which is around USD 300/Kg and operating costs are estimated at 1.5% of initial CAPEX, having a lifetime of 20 years (LEEUWEN; ZAUNER, 2018). Also, it was adopted that the thank size is proportional to the electrolyser hydrogen capacity in kg of hydrogen during 15 hours. The CAPEX for hydrogen fuel cells is USD 1,600/kW for a 1 MW PEMFC unit, and its capacity corresponds to 3-1 of the electrolyser plant capacity (IEA, 2019c).

2.6. RESULTS AND DISCUSSION

The simulation results were carried out considering a hypothetical hybrid system based on the Baixa do Feijão wind and Sertão Solar Barreiras PV power plants data with a green hydrogen production and storage system in Brazil, from four points of view:

i. The analysis plans to produce green hydrogen from the existing power plants, storing and selling it to other sectors. Table 2 brings the simulation results, considering curtailed periods of 720 hours. The system CAPEX for electrolyser below 4MW as exposed in (ABDIN; MÉRIDA, 2019) may be stable in USD 875/kWe. The payback period is reaching 16 years assuming this configuration, and the cost production is above USD 50/kg of hydrogen, way above USD 4,20/kg found in the literature for plants working full-time (producing hydrogen full-time period not just during curtailment periods) (IEA, 2019b; IRENA, 2020b).

$P_{H2plant}$ [MW]	E_{H2} [MW]	W_{H2} [kg]	Electrolyzer Cost [USD/MW]	Hydrogen cost production [USD/kg]	Payback [Year]
1	720	18,462	1,325,000	79.19	25.75
2	1,427	36,594	1,025,000	63.2	19.07
3	2,160	55,385	900,000	55.83	16.3
4	2,880	73,846	875,000	54.45	15.8
13	9,360	240,000	875,000	54.45	15.8
22	15,840	406,154	875,000	54.45	15.8
30	21,600	553,846	875,000	54.45	15.8
40	28,377	727,625	875000	55.17	16.06
47	33,840	867,692	875,000	54.45	15.8
54	38,880	996,923	875,000	54.45	15.8
62	44,640	1,144,615	875000	54.45	15.8
70	50,400	1,292,308	875,000	54.45	15.8
78	56,160	1,440,000	875,000	54.45	15.8
86	61,904	1,587,282	875,000	54.46	15.8
95	68,400	1,753,846	875,000	54.45	15.8

Table 2: Simulation results for a curtailment period of 720 hours.

ii. The analysis considers the existing power plants and the hydrogen system connected to a fuel cell. Following the same premises as in case (i), the payback returns negatively. The main point is that the CAPEX to introduce fuel cells to the project is considerably high. In addition, the model emphasises the competitiveness of hydrogen sales over electricity, taking an electricity price of USD 35/MWh (LEEUWEN; ZAUNER, 2018). Table 3 shows the difference between the amount of hydrogen produced versus price and the amount of electricity produced, and sales price.

Hydrogen		Electricity	
Output [kg]	Sale [USD]	Output [MWh]	Sale [USD]
18,462	77,538	325	11,375

Table 3: Amount of hydrogen produced versus sales price and amount of electricity produced versus sales price.

iii. The analysis of hydrogen cost production for the hybrid system, working full-time for hydrogen production, considered the cost of investment of the case studies and the implementation of the hydrogen production and storage system. In this scenario, the number of hours increases and the cost of electrolyzers decrease, respectively, simulating the behavior of this hypothetical hybrid system in a future situation of competitive prices of electrolysers and plants dedicated to hydrogen production. Table 4 brings the simulation results for the case studies. This finding is related to the different capacity factor and the investment of each particular power plant.

Power Plant	**WH_2 [kg]**	**EH_2 [MWh]**	**PH_2_plant (MW)**	**Electrolyzer Cost [USD/MW]**	**Hydrogen cost production**	**Payback**
Baixa do Feijão wind	18871795	736000	90	1100000	19,4	5
	18871795	736000	90	900000	18,4	5
	18871795	736000	90	650000	17,2	4
	18871795	736000	90	200000	15,0	4
Sertão Solar PV Barreiras	5897436	230000	27	1100000	57,9	2
	5897436	230000	27	900000	57,0	1
	5897436	230000	27	650000	55,8	1
	5897436	230000	27	200000	53,7	1

Table 4: Simulation results for case studies working full time for hydrogen production and storage.

iv. The analysis brings the hydrogen production and storage system in a range of production hours and for different electrolysers CAPEX. The simulation results show that for hours above 3000 and electrolyzers under USD 650/kWe, the system starts to be economically feasible, with the cost of production following what is found in the literature (USD 4,2/kg). Fig. 10 presents the results.

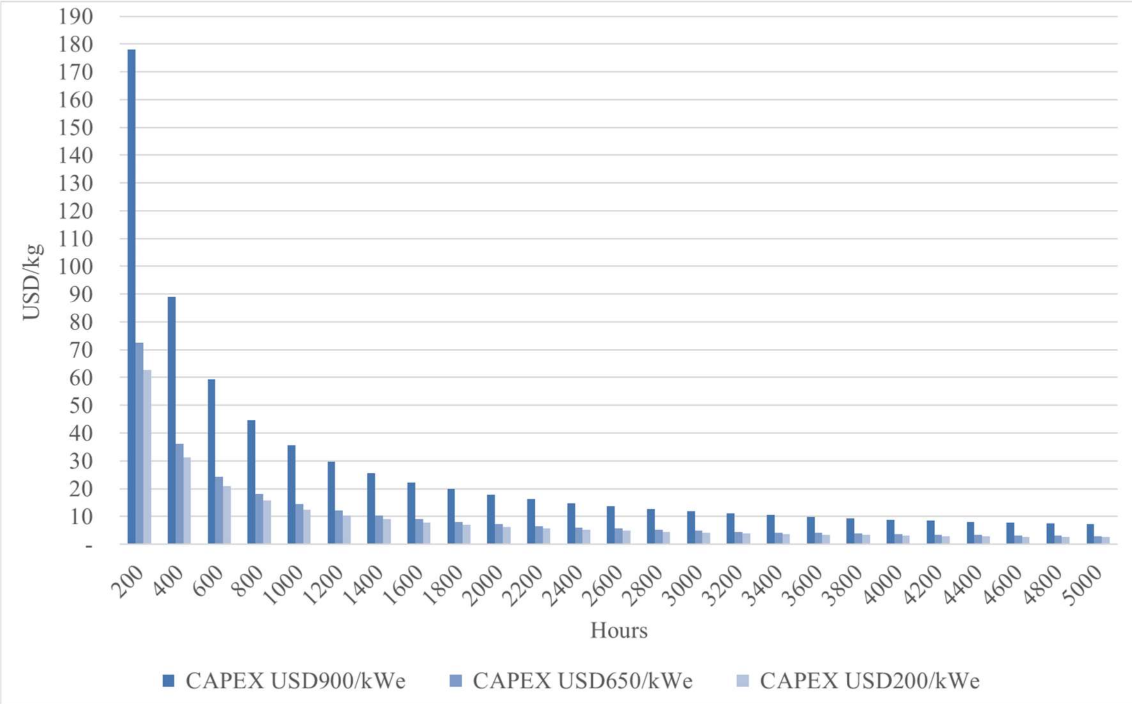

Figure 10: Hydrogen cost per kg as a CAPEX function.

2.7. CONCLUSION

First, the capacity factor of the wind power plants, on average, become superior then the capacity factor of the solar power plants in Brazil. The model concludes that the solar and wind hybrid system for hydrogen production and storage is not yet viable in Brazil. In addition, the CAPEX of electrolysers and storage tanks and their operating losses are key points for the deployment of these systems.

Furthermore, the model still concludes that trading hydrogen is more profitable than transforming it back into power. One of these reasons is that the CAPEX is still highly expensive to the system. Besides, hydrogen-based storage options suffer from low round-trip efficiency in converting electricity through electrolysis into hydrogen, then hydrogen back into electricity. Hydrogen production becomes economically feasible only from plants operating from 3000 hours and for electrolysers with a CAPEX of USD650/kWe.

3. LESSONS TO LEARN FROM THE DEVELOPMENT OF GREEN HYDROGEN ECONOMY IN SELECTED COUNTRIES TO BRAZIL[3]

Abstract: This paper aims to assess countries with most effective hydrogen strategies, bringing up lessons for Brazil in the context of energy transition. This work main question is how Brazil can accelerate its hydrogen economy. To answer this question, the methodology applied is based on identify policy front-runners and potential leading markets, where three countries were selected: Germany, Netherlands and Australia. Then, the analysis was carried out first by outlining six pillars that are supporting countries to thrive in hydrogen market. Then a survey was conducted in order to gather enough information of how the selected countries are engaging in each pillar. Finally, a critical analysis is conducted in order to sort out lessons to learn for Brazil. It was found that: (i) Brazil must stablish a regulatory framework providing legal and regulatory security to investors; (ii) Brazilian government should promote strong public polices; (iii) Brazil shall make concrete alliances with front-runners countries; (iv) renewable potential is not the only factor that determine high potential hydrogen producers, factors like: existing infrastructure, soft factors (e.g. government support, businesses friendliness, political stability) and potential demand for hydrogen, are also major determinants.
Keywords: Green Hydrogen, **Market, Public Policies, Energy Transition.**

3.1. INTRODUCTION

Brazil has been establishing bases for its hydrogen strategy since 2002, but only in 2021 the subject gained traction, when the EPE published in February 2021 the document Basis for the Consolidation of the Brazilian Hydrogen Strategy. Right after the National Energy Policy Council (CNPE) launched the proposal of guidelines for the National Hydrogen Program (PNH2) in July 2021 (EPE, 2021e, 2021a). The program includes six strategic axes: (i) strengthening of scientific and technological bases; (ii) training of human resources; (iii) energy planning; (iv) legal and regulatory-normative framework; (v) market opening and growth and competitiveness; and (vi) international cooperation (MME, 2021a). In June 2022 CNPE approved the program (MATTOS, 2022). Meanwhile, the draft bill 725/2022 was presented as "Hydrogen Law", including the fuel in the existing "Petrol Law", suggesting that the hydrogen would be regulated by

[3] This paper will be submitted to a journal with contributions from Drielli Peyerl.

National Petroleum Agency (ANP) (BOECHEM, 2022). The draft classifies as sustainable hydrogen the one produced with electricity provide by solar, wind, biomass, biogas and hydro power plants. Also proposes to regulate the activity of the whole hydrogen chain. In addition, the draft suggests that, by 2032, a minimum percentage of 5% of hydrogen will be added to the gas network and increasing to 10% by 2050. Within these percentages, 60% must be sustainable hydrogen in the first period (until 2032) and from 2050, the share must raise to 80% (PRATES, 2022).

The last step taken towards a green hydrogen market, was the acceptance of the proposal presented by CCEE (Brazil's power clearing house) in September 2022, on hydrogen certificate protocols in the International Council on Large Electric Systems (CIGRE) (CCEE, 2022; PIERRY, 2022). CCEE will be responsible for leading a global working group on renewable energy and hydrogen certification, positioning Brazil at the forefront of this new business. The Chamber will begin to debate internationally which attributes will be considered to define hydrogen as renewable and which are the minimum criteria to be considered in a certification of this product. The work will be carried out together with members from other interested countries. CCEE will also launch, later this year (2022), a simplified certification model to meet Brazilian projects that are already underway and will define a definitive version, together with CIGRE, by 2023 (CCEE, 2022).

Many of the hydrogen production projects in Brazil are concentrated in ports of the Northeast region, mainly in Pecém in Ceará, Suape in Pernambuco and Açu in Rio de Janeiro (CHIAPPINI, 2021). In February 2021, the government of the state of Ceará, in partnership with the Federation of Industries of Ceará (Fiec), Federal University of Ceará (UFC) and Pecém Complex (CIPP S/A), presented a project called The Green Hydrogen Hub (MME, 2021b). Considered as the first hydrogen hub in formation in the country, the port in Ceará has considerable competitive advantages, such as being closer to the international markets, having sea routes 12 days away from the Port of Rotterdam, which owns 30% of Pecém and where the future flow of green hydrogen in Europe will take place (FAERMAN, 2021). The country has been prospected by international companies and institutions for implementing projects for hydrogen production. Also considering Brazil's renewable potential, these circumstances bring up possibilities for the country to become a hydrogen exporting hub.

This paper aims to assess selected countries with most effective strategies for developing a hydrogen economy, bringing up lessons for Brazil. This work main question is: How can Brazil accelerate its hydrogen economy? To answer this question, based on (IRENA, 2022b), it was selected three countries (Germany, Netherlands and Australia) that are presenting significant shares of stimulus funds to move towards a low carbon economy, betting on hydrogen to support their low carbon economy goal. Then, a framework was built in order to assess key pillars of hydrogen development in those countries. There are studies about hydrogen economy development in Brazil, but without looking at international breakthroughs that can guide the country (DA SILVA CÉSAR et al., 2019; LO FARO; CANTANE; NARO, 2022; RAMOS et al., 2022). Therefore, the novelty of this work is a framework to analyze nations' current and planned visions for what will become one of the most influential energy markets in the 21st century, hydrogen. It will provide deep insight into countries that can help the Brazilian government and the private sector to take efficient actions based on international experience.

This paper consists of four parts: (i) methodology used for countries selection and to build the framework; (ii) international experience according to features raised in the framework; (iii) results and discussion; (iv) final remarks, given an overview of the issues above.

3.2. MATERIAL AND METHODS

According to (IRENA, 2022b), a growing number of countries and companies are engaged in intense competition for leadership in clean hydrogen technologies, to identify policy front-runners and potential leading markets. Thus, to identify leaders, three metrics were used: **national hydrogen strategies, investments** and **projects development**. The pipeline of announced electrolysers projects reached over 260 GW globally by October 2021, in half of the world's announced megawatt-scale projects, Europe is surging ahead, driven largely by strong momentum of rapidly reduce dependence on Russian fossil fuels and accelerating Europe's clean energy transition (EUROPEAN COMMISSION, 2022a; IRENA, 2022b). The largest volumes of clean hydrogen are projected to come from Europe and Oceania, most of them using renewables (IRENA, 2022b). By early August 2021, governments had allocated at least USD 65 billion in targeted support for clean hydrogen over the next decade, with **Germany** making the most significant commitments in Europe. Following are **Australia** and **Netherlands** allocating huge investments in low carbon energy sources (IRENA, 2022b).

The analysis was carried out first by outlining pillars that are supporting countries to thrive in hydrogen market. Based on (CRANMORE PARTNERS AND ENERGY ESTATE, 2021; IEA, 2019b; IRENA, 2020b, 2022b; MME, 2021a) it was possible to raise six key features of countries which are leading the hydrogen economy establishment:

(i) setting **national targets and strategies** in order to guide initiatives in an emerging technology;

(ii) hydrogen projects need a market environment supported by **legal and regulatory**, mitigating risks;

(iii) **technology** leadership, public and private support for research and development (R&D), pilot projects or even scale projects;

(iv) **infrastructure**, the readiness of countries' hydrogen **transportation** infrastructure for massive scale up of hydrogen production and use, including **pipelines**, **storage** facilities or potential, and for **export** producers, existing ammonia or LNG infrastructure that may be leveraged towards green hydrogen transport, **hubs** concentrating hydrogen production, storage, usage and export;

(v) **potential end use**, size of sectors (**industry**, **transport**, **heating**, **power generation**) that can switch for using clean hydrogen, local demand (e.g. hydrogen hubs);

(vi) **potential cost reduction**, economies of scale, efficiency.

Secondly, having built the framework embracing the key pillars for hydrogen development, a survey was conducted in order to gather enough information of how the selected countries are engaging in each pillar. Finally, a critical analysis is conducted in order to sort out lessons to learn for Brazil. Figure 2 summarizes the methodological procedures of this work.

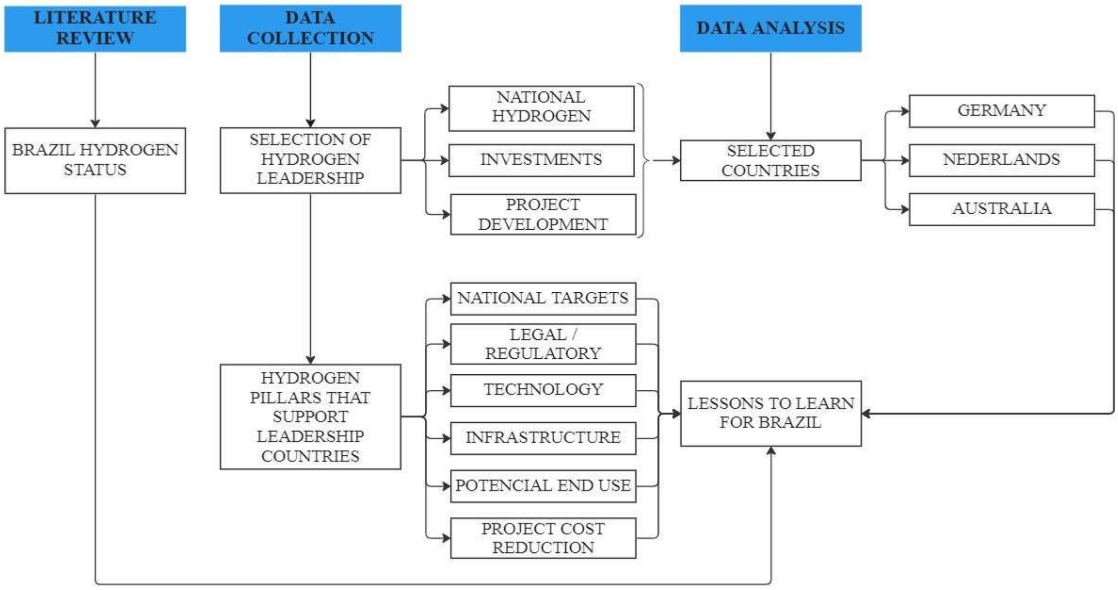

Figura 1- Methodology

3.3. INTERNATIONAL EXPERIENCE

3.3.1. National targets

Germany is still heavy reliant on fossil fuels for domestic power supply. In 2021, 28% of the power mix was generated using lignite and hard coal, natural gas contributed with 15.4% and the combined share of renewables stood at 41%, with wind the most prominent of Germany's renewable energy sources (ALVES, 2022). Most of the hydrogen used in German industry is produced from natural gas (55TWh), whilst only 7% (3.85TWh) of current demand is provided by green hydrogen from electrolysis (FEDERAL MINISTRY FOR ECONOMIC AFFAIRS AND ENERGY, 2020; VON BURCHARD, 2021). To enlarge renewable energy share, jointly with EU, Germany has updated its NDC in 2020 to reduce emissions by 38% from 2005 levels by 2030 (EUROPEAN COUNCIL, 2020). Within the G20, Canada, the European Union, France, Germany, Japan, the Republic of Korea and the United Kingdom have passed laws on net zero emissions (IRENA, 2022a). In June 2021 the country adopted a major new climate legislation, setting higher emissions reduction targets for 2030 (at least 65%) and 2040 (at least 88%), with the goal of achieving greenhouse gas neutrality by 2045 (FEDERAL MINISTRY OF FINANCE, 2021). Furthermore, a €8 billion climate action program for 2022, will finance additional measures to further reduce greenhouse gas emissions.

Germany was one of the first countries to launch a National Hydrogen Strategy in 2020 (FEDERAL MINISTRY OF FINANCE, 2021), focusing on green hydrogen, considering that only hydrogen produced from renewable energy is sustainable in the long term (FEDERAL MINISTRY FOR ECONOMIC AFFAIRS AND ENERGY, 2020; RINGSGWANDL et al., 2022). The strategy shown that the Federal Government expects that around 90 to 110 TWh of hydrogen will be needed by 2030. To cover part of this demand (14TWh of green hydrogen), a 5GW generation capacity from offshore and onshore renewable plants will be needed (FEDERAL MINISTRY OF FINANCE, 2021). A further 5GW of domestic electrolyser capacity is foreseen by 2035 or 2040 (FEDERAL MINISTRY OF FINANCE, 2021). To ensured that the demand for electricity that is created by the electrolysers will not increase carbon emissions, the Federal Government has included a monitoring mechanism to track the development of green hydrogen demand in detail (FEDERAL MINISTRY OF FINANCE, 2021).

Offshore wind energy will play an important role, the Federal Government will work with the North and Baltic See border states to push forward hydrogen production by establishing a reliable regulatory framework for offshore wind energy (FEDERAL MINISTRY FOR ECONOMIC AFFAIRS AND ENERGY, 2020). Despite German´s efforts, the domestic generation of green hydrogen will not be enough to cover all the expected demand, increasing the need for imports (FEDERAL MINISTRY FOR ECONOMIC AFFAIRS AND ENERGY, 2020). To meet this needs Germany is looking for opportunities to broaden the debate on the topic. E.g., the country is engaging several African countries to explore and develop a hydrogen economy that makes use of the continent's resource potential to support sustainable economic development (IRENA, 2022a). In Brazil, Germany has established the Brazil-Germany Alliance for Green Hydrogen, seeking for hydrogen trade opportunities between both countries (BRASILALEMANHA, 2021).

Netherlands most important energies sources are natural gas and oil. Its current energy mix is 38% of natural gas, 35% of oil, 11% of coal, 5% of biofuels and waste, and 11% from nuclear, wind, solar, hydropower and geothermal (INTERNATIONAL TRADE ADMINISTRATOR, 2021). Netherlands is a signatory to the UNFCCC Paris Climate Agreement and it´s Nationally Determined Contribution (NDC) are attached to the European Union´s (EU) targets (EUROPEAN COUNCIL, 2020). In the EU´s NDCs, updated in December 2020, the target for increasing renewable energy in final energy consumption has been set to reach 32% from 2005 levels by 2030. Breaking down the goals, Netherlands in its National Energy and Climate Plan (NECP) is responsible to reduce its emissions in 36% compared to 2005, asset in the Effort Sharing Regulation (ESR)[4] (EUROPEAN COMMISSION, 2019; EUROPEAN COUNCIL, 2020; INTERNATIONAL ENERGY AGENCY, 2020). In addition, in March 2020, the EU communicated a long-term strategy to the UNFCCC for EU-wide carbon neutrality by 2050, along with, the Netherlands intent to support EU in that goal (EUROPEAN COUNCIL, 2020).

Most of the Hydrogen in the Netherlands is being produced from natural gas, yet the country´s main objective is to produce hydrogen from renewable energy resources (EUROPEAN COUNCIL, 2020). The Dutch aims for low-carbon hydrogen to play a major role in supporting the achievement of emission reduction targets and the country has already started a strong policy push through its Hydrogen Strategy (EUROPEAN COMISSION, 2020). Additionally, according to the National Climate Agreement, launched in 2019, it is expected that until 2030, electrolysis capacity will be scaling up to 3 - 4 GW (NETHERLANDS MINISTRY OF ECONOMIC AFFAIRS AND CLIMATE POLICY, 2019).

Australia energy mix data from 2020 shown oil and coal, representing 32% and 30% respectively, followed by natural gas counting of 29%, biofuel and waste representing 4,5%, renewables (wind, solar, etc) 3% and hydro 1% of the mix (IEA, 2022). Considering annual electricity generation in 2021, renewables represented 32,5% of the total, with wind representing 36% of the total renewable generation (CLEAN ENERGY COUNCIL, 2022). Australia is the world´s largest liquified natural gas (LNG) exporter, planning to be a major hydrogen producer and exporter in the world (AGUILERA; INCHAUSPE, 2021; LEWIS, 2022).

The country first NDC submitted target to reduce emissions by 26% to 28% below 2005 levels by 2030 (AUSTRALIAN GOVERNMENT, 2016). In June 2022, the government updated its NDC, committing to reduce greenhouse gas emissions by 43% below 2005 by 2030 and reaffirms the target adopted in its 2021 NDC to achieve net zero emissions by 2050 (AUSTRALIAN GOVERNMENT, 2016, 2021c). Meanwhile, in September 2020 the First Low Emissions Technology Statement announced measures to support low emissions technologies, particularly in hard-to-abate sectors, and the

[4] Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013.

establishment of Australia's first regional hydrogen export hub to boost hydrogen industry (AUSTRALIAN GOVENMENT, 2021). Moreover, in order to position the country as a large-scale producer and exporter of hydrogen to Asia and beyond, the Statement set the goal for clean hydrogen production price under A$2 per kilogram (AUSTRALIAN GOVENMENT, 2021).

3.3.2. Legal & Regulatory drivers

In **Germany**, there is no specific regulation for hydrogen projects, being subject to existing regulation for gas and electricity market, under the command of the Federal Network Agency (BNetzA) (VON BURCHARD, 2021). However, Germany has a strong Hydrogen Strategy and several of its 16 state governments have defined hydrogen strategies or roadmaps (e.g., Baden-Württemberg, Bavaria, five north German coastal states together, North Rhine-Westphalia) (HODGES et al., [s.d.]). The national strategy points out that the key element to enable hydrogen technologies are regulatory sandboxes (FEDERAL MINISTRY FOR ECONOMIC AFFAIRS AND ENERGY, 2020), which allow experimentation of novel technologies that cannot operate within existing regulatory frameworks, by allocating specific areas for this experimentation (FUHRMANN; EMEA & RUSSIA DEPT. GLOBAL ECONOMIC & POLITICAL STUDIES DIV.; MITSUI & CO. GLOBAL STRATEGIC STUDIES INSTITUTE, 2020). The 'Regulatory Sandboxes for the Energy Transition' is a funding instrument within the framework of the Federal Government's Seventh Energy Research Program, provided by the Federal Ministry for Economic Affairs and Energy (FEDERAL MINISTRY FOR ECONOMIC AFFAIRS AND CLIMATE CHANGE, 2021). The goal of the regulatory sandboxes is to speed up the transfer of innovation for key enabling technologies, particularly in the field of hydrogen, helping these technologies become quickly marketable, also bringing up Power-to-X technologies that are already close to market to an industrial scale (FEDERAL MINISTRY FOR ECONOMIC AFFAIRS AND CLIMATE CHANGE, 2021).

Furthermore, two transitional laws for the development of green hydrogen in German have been improved, which are The Renewable Energy Sources Act (EEG 2021) and The Energy Industry Act (EnWG 2021) (RINGSGWANDL et al., 2022). The EEG objective the development of renewable sources (RES), containing definition for green hydrogen and support schemes for the called EEG surcharge, which directly affects the electricity price paid consumers, also affect the cost of electricity used for green hydrogen production (RINGSGWANDL et al., 2022).

Under the amendment of the EEG 2021, it was included requirements for green hydrogen exception of surcharge payments, since green hydrogen shall be produced electrochemically by exclusive consumption of renewable electricity and limited to 5000 full-load hours of a calendar year, for facilities taken into operation before first January 2030 (FEHLING, 2022). In addition, 80% of the electricity used must be from renewable power plants located in the German price zone and does not receive any other subsid under existing schemes of the EEG or of the Act on Combined Heat and Power Generation (CHP Act) (ENERGYPARTNERSCHAFT DEUTSCHLAND-CHINAR, 2022; FEHLING, 2022).

The EnWG provides an overall framework for a functioning and competitive energy market, regulating the operation of energy networks (electricity and gas) and the tasks of transmission and distribution system operators (TSOs and DSOs) (RINGSGWANDL et al., 2022). The amendment of the EnWG 2021 regarding to the hydrogen network regulation was based on the following approaches: Opt-in regulation of hydrogen networks and vertical unbundling (HRITSYSHYNA; HUTAREVYCH, 2021). Meaning that the network operator which has a hydrogen pipeline is entitled to declare the hydrogen pipeline for the purpose of the opt-in regulation, so this option is a right and not an obligation. According to the opt-in regulation, the network operator can receive the return of its costs, profiting through the network tariffs paid by customers. Choosing the opt-in regulation, the hydrogen infrastructure must comply with the rules of legal unbundling which means independence from production, storage, and supply of green hydrogen, also implicating in accounting unbundling and no-discriminatory access to the grid for third parties (CLIFFORD CHANCE, 2021; HRITSYSHYNA; HUTAREVYCH, 2021; RINGSGWANDL et al., 2022). The application of new regulations will only apply to networks solely used for the transport of hydrogen, in situations where hydrogen is injected into natural gas pipelines (blending), which is already possible under certain circumstances, the existing regulation apply to natural gas networks (CLIFFORD CHANCE, 2021; HRITSYSHYNA; HUTAREVYCH, 2021). It should be noted that hydrogen networks must be subject to regulation under the updated EU Gas Directive. However, until adjustment of the EU Gas Directive, Germany decided to implement the mentioned regulations for the transition period (CLIFFORD CHANCE, 2021).

Netherlands has no specific legislation for hydrogen production, regardless of the process used, it is considered as a traditional chemical production facility. This places a disproportionate burden on environmentally friendly production methods, as it subjects them to the same requirements as industrial, emitting processes and it is considered as any other inorganic gas production facility. This increases the costs for developers and delays the deployment of hydrogen technology (VAN DER MEER; PEROTTI; DE JONG, 2020)).

Furthermore, local hydrogen production and storage is legally considered as hydrogen production in general, as an industrial gas, being considered a chemical process involving emissions. As a result, even for small scale production, the permitting requirements will be subject to Risk Assessments (SEVESO), Health and Safety requirements (ATEX), Integrated Environmental obligations (IED), Environmental Impact Assessment procedures (SEA and EIA). In addition, the production of hydrogen by electrolysis is not distinguished from other means of producing hydrogen (VAN DER MEER; PEROTTI; DE JONG, 2020).

However, The Dutch Government released its Hydrogen Strategy in 2020, having the policy agenda based in four pillars:

1. Legislation and Regulation
2. Cost reduction and scaling up green hydrogen
3. Sustainability of final consumption
4. Supporting and flanking policy

The Strategy on legislation and regulation highlights the use of existing gas grid, alongside the national network operators and the cross borders network operators Gasunie and Tennet. The government will review how part of the gas grid can be used for the transport and distribution of hydrogen. The National Climate Agreement mandates that statutory and regulatory flexibility can be created for experiments to allow regional and national network operators to gain experience in the transport and distribution of hydrogen. A process has been initiated to enable this plan through the General Administrative Order on ‘Temporary Tasks’ under the current Gas Act (GOVERNMENT OF THE NETHERLANDS, 2020).

Regarding to safety risks, this will preferably be implemented based on international and European guidelines and standards. Also, at the start of 2020, the Netherlands launched the four-year Hydrogen Safety Innovation Program, which will be implemented as a public-private partnership between the national government, network operators, emergency services, knowledge institutes and companies. The program identifies hydrogen safety issues, proposing policies and agreements that allow these issues to be adequately addressed (GOVERNMENT OF THE NETHERLANDS, 2020).

Australia has no specific regulation for hydrogen production, transport or storage, the current gas definitions regarding quality and value will therefore not support an emerging hydrogen market (BRUCE S et al., 2018; ROWELL et al., 2022). However, there are numerous regulatory frameworks that would apply to the development of a hydrogen project and the 2021–2022 Federal Budget includes AUD 2.4 million to support hydrogen-related legal reforms (ROWELL et al., 2022). The South Australia government announced on May 2022 plans to develop new legislation for license and regulate the production of hydrogen in South Australia. The scope of the new law will cover manufacturing of all forms of hydrogen, including green hydrogen made from renewable energy, and blue hydrogen manufactured from methane in conjunction with carbon capture and storage to permanently sequester the associated carbon dioxide emissions (REUTERS, 2021).

In a national level, in August 2021, Energy Ministers agreed that the national gas regulatory framework should be amended to bring hydrogen, biomethane and other renewable gas blends within its scope. The improvements are initially focusing on hydrogen blends and renewable gases that can be used in the exiting natural gas appliances (AUSTRALIAN GOVERNMENT, 2022). In March 2022, AEMC (Australian Energy Market Commission) released a draft report outlining recommendations to support the development of a national regulatory framework. The draft mention that low-level hydrogen blended gases and renewable gases can be safely supplied to existing distribution systems and used in appliances in homes and businesses (CSIRO, 2022c). The AEMC expects approve the final draft rules before the Energy Ministers by the end of 2022 (JOHNSON; KNOWLMAN, 2022).

3.3.3. Technology

Germany has an advanced hydrogen research landscape, seeking to become a global leader and exporter of green hydrogen technology. The country has a global market share of 20% in electrolysers implementation, led by Thyssenkrupp subsidiary Uhde (HUBER, 2021). Within Europe, Germany alone has the majority of European fuel cell and hydrogen technology demonstration projects. Currently 30 small-scale pilot projects that use renewable energy to produce green hydrogen are in operation across the country (GERMANY TRADE & INVEST, 2022). Overall technologies, according to S&P Global Platts data, Germany has 124 hydrogen production locations at various stages of completion (GERMANY TRADE & INVEST, 2022). A network of laboratories around Germany isn't just looking for novel technologies concerning hydrogen and fuel cells, the labs are testing them in real-world situations on an industrial scale (GERMANY WORKS, 2020).

Besides, Germany benefiting from the European program Important Projects of Common European Interest (IPCEI), made to support clean energy projects. Germany has shortlisted 62 hydrogen production and infrastructure projects as part of the IPCE covering the whole value chain from electrolysers to pipelines (KURMAYER, 2021). European Commission Vice President (Margrethe Vestager) announced in July 2022 the approval of 41 "IPCEI Hydrogen" projects, including four from Germany (FEDERAL MINISTRY FOR DIGITAL AND TRANSPORT, 2022). Additionally, more than eight billion euros in funding is available for hydrogen projects, provided by the federal and state governments (FEDERAL MINISTRY FOR DIGITAL AND TRANSPORT, 2022; KURMAYER, 2021). Since the start of Russia's war against Ukraine (Feb. 2022), the reliance on Russian gas is contested, highlighting the importance of projects as IPCEI Hydrogen, which is also part of the German National Hydrogen Strategy (FEDERAL MINISTRY FOR ECONOMIC AFFAIRS AND ENERGY, 2020; FUHRMANN; EMEA & RUSSIA DEPT. GLOBAL ECONOMIC & POLITICAL STUDIES DIV.; MITSUI & CO. GLOBAL STRATEGIC STUDIES INSTITUTE, 2020).

Germany's largest energy group E.ON (EONGn.DE) on signed in a memorandum of understanding with the green power arm of Australian miner Fortescue Metals (FMG.AX). The agreement will explore ways to ship up to 5 million tonnes of green hydrogen generated via wind and sun in Australia to Europe by 2030, but starting as soon as 2024, helping wean itself off Russian gas (IPHE, 2022; STEITZ, 2022).

German's Hydrogen Strategy aims to foster the development and diffusion of technologies such as power-to-gas and power-to-liquid that convert surplus electricity derived from renewable energy sources into hydrogen, gaseous fuels, and liquid fuels (FEDERAL MINISTRY FOR ECONOMIC AFFAIRS AND ENERGY, 2020; FUHRMANN; EMEA & RUSSIA DEPT. GLOBAL ECONOMIC & POLITICAL STUDIES DIV.; MITSUI & CO. GLOBAL STRATEGIC STUDIES INSTITUTE, 2020). The strategy is focusing on green hydrogen technology, furthermore Germany not only has a strong government subsidy framework, pledging €7 billion to expand domestic green hydrogen pilots, but it also invests €2 billion in hydrogen exports abroad through international partnerships (IHS MARKIT - S&P GLOBAL, 2022). However, as shown by (KURMAYER, 2022; THE ENERGY MIX, 2022) the currently German government is not in favour of subsidy for blue hydrogen even though it could bridge green hydrogen future.

Netherlands hydrogen production is mature and developed, been carried out for over 50 years. Hydrogen is mainly produced by the chemical and the petrochemical industry (centralized production), used as a feedstock (a chemical element) and recently used as energy carrier (VAN DER MEER; PEROTTI; DE JONG, 2020). The government recognises the importance of supporting research and demonstration projects as well as scaling-up and roll-out process for low-carbon hydrogen deployment (GOVERNMENT OF THE NETHERLANDS, 2020).

The TNO Faraday Lab localised in Pette, is one of Europe's largest hydrogen research facilities, involved in over 50 projects along the entire hydrogen value chain (NETHERLANDS ENTERPRISE AGENCY, 2021; TNO, 2022). In this lab, researchers and a wide range of industry partners are working to optimise existing electrolysis technologies such as PEM, alkaline, SOEC and AEM, focusing on improving efficiency, boosting production capacity and finding robust, cheaper alternatives to the rare materials used in current electrolysers (NETHERLANDS ENTERPRISE AGENCY (RVO); FME; TKI NEW GAS, 2021).

Gasunie, the operator of the national gas transmission grid, in its annual report for 2020, shown that blue hydrogen can put forward the development of the hydrogen market in the short term. To boost the transition to hydrogen as a clean fuel, the Dutch see blue hydrogen as an essential intermediate step (NETHERLANDS ENTERPRISE AGENCY (RVO); FME; TKI NEW GAS, 2021). Companies like BP, Shell and Exxon Mobil want to make large-scale blue hydrogen production possible (PETERS, 2021). However, for the longer term, in agreement with the Dutch government, green hydrogen is the final goal (GASUNIE, 2021).

A range of projects are being conducted in Netherlands as described in (DE LAAT, 2020; ISPT, 2022; NORTH SEA WIND POWER HUB, 2021; NS ENERGY, 2022; POSHYDON, 2022; PRICEWATERHOUSECOOPERS ADVISORY N.V., 2021), aiming to promote a climate-neutral economy based on hydrogen. Many of these projects at first are focusing on blue hydrogen, anticipating the arrival of green hydrogen.

Australia is building a pipeline of technologies needed to meet its Paris Agreement target of emissions reductions beyond 2030. The Government supports clean energy technology, including hydrogen, through the Australian Research Council, the CSIRO, the Australian Renewable Energy Agency (ARENA), the Clean Energy Finance Corporation and the Northern Australia Infrastructure Fund. Having committed over AUD146 million to hydrogen projects across the entire supply chain (COAG ENERGY COUNCIL HYDROGEN WORKING GROUP, 2019). Australia fixed ambitious targets to increase hydrogen penetration in the domestic market and export to Japan, China, and South Korea. The country's national hydrogen strategy emphasizes creating a strong hydrogen value chain to capitalize on abundant renewable resources (KAR et al., 2022). Furthermore, The Australia's Technology Investment Roadmap identified clean hydrogen as priority low emission technology. This roadmap shown the importance of stablishing a regional hydrogen hub co-locating domestic hydrogen users, also with an export focus to create global hydrogen supply chain linkages(AUSTRALIAN GOVENMENT, 2020).

On this path, the Australian´s green hydrogen firm Hysata has launched a ground-breaking electrolyser technology, which can produce green hydrogen at 98% efficiency, while the typical operation is at 75% or less (HODGES et al., [s.d.]; HYSATA, 2022; PEKIC, 2022). High energy efficiency contributes to making renewable hydrogen cost competitive, also making the Australian hydrogen cost production target well below AUD2/kg close to reality (USD1.50/kg) (HYSATA, 2022).

Considering the large capacity to harness solar energy, excellent wind resources, especially on the southern and western coastlines and hydroelectric resources in Tasmania, Victoria and New South Wales, based on the quality of wind, solar and hydro resources, Geoscience Australia estimates that about 11% of Australia (872,000 square kilometers) could be highly suitable for green hydrogen production (NETHERLANDS ENTERPRISE AGENCY (RVO); FME; TKI NEW GAS, 2021). Australia has led the world for many years in high efficiency photovoltaic (PV) device technology (ARENA, 2022). Leveraging this expertise, the country launched the initiative Solar 30 30 30, with the goal of achieving 30% efficiency at 30 cents per installed capacity of solar photovoltaic plants by 2030. Led by ARENA, the initiative will help drive costs down to achieve the goal of ultra low-cost solar technology. As clean electricity cost is critical for clean hydrogen production, this technology should have a major contribution to reducing cost of the hydrogen value chain (AUSTRALIAN GOVERNMENT, 2021a, 2021b).

It is worth to mention that Australia can take advantage of carbon capture and storage technologies to produce low-emissions hydrogen from coal and natural gas, as the country has depleted oil and gas reservoirs, that hydrogen gas could be injected and compressed in underground salt caverns to enable seasonal storage. As an example, the Mallowa Salt, in the Canning Basin is the most extensive halite unit in Australia with thicknesses up to 700-800 meters, that may enable hydrogen storage (COAG, 2019; FEITZ; TENTHOREY; COGHLAN, 2019). As stated in The Australia's Technology Investment Roadmap, off-grid gas with CCS, and coal gasification with CCS might be the lowest cost clean hydrogen production methods in the short-term, although renewable production methods will come down in cost as clean hydrogen demand grows (AUSTRALIAN GOVENMENT, 2020).

In April 2021, the Australian Government announced that the 2021-22 budget will include AUD565.8 million to support the establishment of low emissions international technology partnerships and initiatives with key trading and strategic partners (CSIRO, 2022c). This commitment include programs as: (i) The Declaration of Intent between the Government of Australia and the Government of Germany on the Australia-Germany Hydrogen Accord; (ii) The Australian Clean Hydrogen Trade Program (ACHTP) which the first round will focus on the export of clean hydrogen to Japan under the program Japan-Australia Partnership on Decarbonisation through Technology; (iii) The British and Australian Governments alliance focusing on research and development across six key technologies, including clean hydrogen. These partnerships target making low emissions technologies such as hydrogen cheaper than high emitting alternatives (CSIRO, 2022c).

3.3.4. Infrastructure

The German´s IPCEI program is being substantial for the development of sustainable green hydrogen economy by providing investment support across the entire hydrogen value chain, with projects on an industrial scale, both nationally and across Europe (LOWER SAXONY STATE CHANCELLERY, 2022). The state of Lower Saxony is benefiting far more than average from this program. The federal and state governments are funding twelve projects that will help with hydrogen production, **storage, transportation**, and importation. State officials also have stated that domestic hydrogen production cannot function without some external supply. Therefore, it is essential that the **terminals being built to import** liquefied natural gas (LNG) can be converted to import green gas in the future (DOKSO, 2022). Lower Saxony has a fortunate location on the coast with seaports, a well-developed gas network, large cavern **storage** facilities and the enormous potential of renewable energies, the region can become a important **hub**, not just for local use but for the German and European hydrogen economy (LOWER SAXONY STATE CHANCELLERY, 2022).

Through the program, it is being proposed the creation of more than 500 km of hydrogen **transport infrastructure** in Lower Saxony, largely through the rededication of existing natural gas pipelines, but also through the construction of new hydrogen **pipelines** as well as the conversion of caverns for natural gas **storage** (LOWER SAXONY STATE CHANCELLERY, 2022).

German´s Hydrogen Strategy acknowledges its role as a long-term net importer and consequently places clear emphasis on building EU and global green hydrogen networks. Germany's geographical attributes support its aspirations to lead the EU's energy transition, the country holds 42% of Europe's onshore and offshore salt cavern hydrogen **storage** potential, essential to seasonal energy balances (CRANMORE PARTNERS AND ENERGY ESTATE, 2021).

Netherlands is the second largest hydrogen producer (fossil-fuel based) in Europe, and as the quantities are large, several production centres are connected with dedicated hydrogen pipelines (VAN DER MEER; PEROTTI; DE JONG, 2020). The country today operates more than 1,000km of dedicated hydrogen pipelines, connected to industrial sites in Belgium and France (CRANMORE PARTNERS AND ENERGY ESTATE, 2021; NETHERLANDS ENTERPRISE AGENCY (RVO); FME; TKI NEW GAS, 2021). Also, the country has one of the world's densest and most sophisticated natural **gas grids**, including 136,000 km of pipelines and over 7 million connections, reaching into almost every Dutch home and business (NETHERLANDS ENTERPRISE AGENCY (RVO); FME; TKI NEW GAS, 2021). This **infrastructure can be used for hydrogen transport**, not just by mixing hydrogen into the natural gas flow, but by replacing it. In the province of Zeeland, a 12-km-long industrial **gas pipeline transports** around 400,000 tonnes of hydrogen per year, and nearly a dozen pilot projects are underway in residential areas to replace natural gas with hydrogen using the existing infrastructure. One of the key policies on the Dutch climate agenda is that over 2 million homes must have switched to natural gas alternatives by 2030 (CRANMORE PARTNERS AND ENERGY ESTATE, 2021; NETHERLANDS ENTERPRISE AGENCY (RVO); FME; TKI NEW GAS, 2021).

Gasunie, a Dutch and European gas infrastructure company, to follow the demand for more renewable energy, it is determined to execute company's transition towards hydrogen usage. The company has decades of knowledge, expertise, and experience in natural gas transportation and will also use part of its existing infrastructure for hydrogen (GASUNIE, 2021).

The existing natural gas infrastructure also offers opportunities for **storage**. For example, in the north of the country, the Dutch have been storing natural gas in huge salt caverns with a capacity of hundreds of millions of cubic metres. Pilot projects are carried out to demonstrate that hydrogen can be safely stored there as well. Also, Dutch researchers and industry specialists are already examining the technical and economic feasibility of storing hydrogen in empty gas fields, both on land and in the North Sea (NETHERLANDS ENTERPRISE AGENCY (RVO); FME; TKI NEW GAS, 2021). They are also developing special hydrogen tanks that enable hydrogen to be stored at very high pressure or extremely low temperatures, paving the way for safe and cost-effective **transport by road, rail or ship**. Dutch companies are even focusing on binding hydrogen with other materials, such as nitrogen, carbon dioxide or toluene, to create a carrier liquid that is much easier to transport, sometimes even in existing oil tankers (NETHERLANDS ENTERPRISE AGENCY (RVO); FME; TKI NEW GAS, 2021).

Some of Europe's busiest transport corridors converge on the Netherlands, thanks to **excellent road, rail and inland shipping infrastructure**, as well as **pipeline connections** with much of Europe. The port of Rotterdam is the **largest port** for oil and liquefied natural gas in Europe and is working with industrial partners to build up a similar position for hydrogen. Several multinationals are already building electrolysers in Rotterdam, and work has started on a dedicated hydrogen pipeline infrastructure (NETHERLANDS ENTERPRISE AGENCY (RVO); FME; TKI NEW GAS, 2021).

Porthos, which stands for Port of Rotterdam CO_2 Transport Hub and Offshore Storage, is developing a **backbone infrastructure** to transport CO_2 produced from refineries, chemical, and hydrogen plants in the Port of Rotterdam, via undersea pipeline and store it in empty gas fields beneath the North Sea (PETERS, 2021; PORTHOS, 2022). The H-Vision project, a joint venture between TNO and industry in Rotterdam, associated with Porthos project, will initially be applied to existing refineries (GOVERNMENT OF

THE NETHERLANDS, 2020). The project plan to capture residual gases from refining and transport them by pipeline to a central plant, where they will be used to make low-carbon hydrogen. That hydrogen is then returned to the refineries to be used as a fuel to generate high-temperature heat. The CO2 resulting from the production of hydrogen is captured directly and then transported to depleted gas fields (H-VISION, 2021a, 2021b). The first plant, with a capacity of approximately 750 MW, will be completed by 2027. The second one will increase the total capacity to over 1,500 MW, planned to be completed by 2032 (H-VISION, 2021a).

On the path of scaling up production, an expressive project is the Hydrohub. Which is a large consortium of research and industry partners, jointly to produce an advanced design for a 1-GW green hydrogen plant, which will use alkaline water electrolysis (AWE) and polymer electrolyte membrane (PEM) water electrolysis, expected to start commissioning in 2030 (ISPT, 2022).

As pointed out in the Netherlands Hydrogen Strategy (GOVERNMENT OF THE NETHERLANDS, 2020), offshore wind farms will play an important part in the roll-out of large-scale green hydrogen production. However, relatively large volumes of renewable power are needed to produce green hydrogen and reach the Dutch target of electrolysis capacity. The North Sea Wind Power **Hub** (NSWPH) is an ambitious new approach to the challenge of integrating renewable energy (NORTH SEA WIND POWER HUB, 2021). In this project, a hub-and-spoke concept is used, consisting of modular hubs in the North Sea connecting offshore wind farms with bordering North Sea countries and facilitating sector coupling through power-to-Hydrogen conversion (DE LAAT, 2020; NORTH SEA WIND POWER HUB, 2021). While there is not enough renewable electricity to produce green hydrogen on an industrial scale, blue hydrogen is predicted to pave the way to green (H-VISION, 2021b).

In an optimistic scenario, where the Netherlands hits the target set in the Dutch Climate Agreement (including having 3-4GW of installed electrolysis capacity by 2030), the report HyWay 27 suggests a model made up of various hydrogen supply and demand hubs and pipeline connections between these hubs. The hubs represent five industrial clusters, two export locations, and one storage location (PRICEWATERHOUSECOOPERS ADVISORY N.V., 2021). Den Helder was added as a blue hydrogen production location, considering the project H2Gateway with hydrogen produced from natural gas, and the released CO_2 captured and stored in the empty gas fields below the North Sea (DE LAAT, 2022).

Despite large-scale production initiatives, as demonstrated in the studies II3050 and HyWay 27, the north-western Europe will not be able to meet its own demand for green hydrogen in the future, meaning that importing green hydrogen will also be necessary (GASUNIE, 2022).

Australia's key element for hydrogen development will be to create **hubs**, as large-scale demand clusters (COAG, 2019). Hubs will make the development of infrastructure more cost-effective, promote efficiencies from economies of scale, foster innovation, and promote synergies from sector coupling. These will be complemented and enhanced by other early steps to use hydrogen in transport, industry and gas distribution networks and integrate hydrogen technologies into the power systems in a way that enhances reliability (COAG, 2019) .

According to the National Strategy, to enable the rollout of hydrogen, seven prospective locations across Australia have been identified as potential **hubs**, including: Bell Bay (TAS), Darwin (NT), Eyre Peninsula (SA), Gladstone (QLD), Latrobe Valley (VIC), Hunter Valley (NSW), and Pilbara (WA) (COAG, 2019; MINISTRY OF INDUSTRY ENERGY AND EMISSIONS REDUCTION, 2021).

The Eyre Peninsula Gateway project is an industrial-scale green hydrogen and ammonia production complex being established by H2U, the initial demonstrator stage will feature a 100 MW electrolysis plant and up to 40,000tpa green ammonia plant in 2024 (GOVERNMENT OF SOUTH AUSTRALIA, 2022; HANCOCK; WOLLERSHEIM, 2021). The export stage will expand to a 1.5GW electrolysis and synthesis plant to produce up to 800,000tpa of green ammonia in 2026 (GOVERNMENT OF SOUTH AUSTRALIA, 2022; HANCOCK; WOLLERSHEIM, 2021). In addition, this stage will include the establishment of an **export terminal** to serve the emerging market in North Asian and Europe, with a view of commissioning the Export Terminal by the end of 2025 and transitioning to industrial-scale production operations from 2026 (GOVERNMENT OF SOUTH AUSTRALIA, 2022; NEW SOUTH WALLES GOVERNMENT, 2021).

The Tasmanian Government is developing a proposal for a green hydrogen export hub at Bell Bay (NEW SOUTH WALLES GOVERNMENT, 2021). Bell Bay has good attributes to become a green hydrogen hub with its advanced manufacturing zone, renewable energy availability, advanced infrastructure, water availability and **port** access (AUSTRALIAN GOVERNMENT, 2021a; POWELL, 2022). The hub is expected to establish the right environment and infrastructure necessary for operations to start unlocking the potential for large-scale green hydrogen exports and supporting domestic market activation in Tasmania and on the mainland. There is significant interest in Bell Bay from some of Australia's largest potential hydrogen producers, including Fortescue Future Industries, Woodside Energy, Origin Energy and ABEL Energy (POWELL, 2022).

Total Eren plans to develop a project called H2 Hub, located in Darwin. The aim is to produce over 80,000 tons of renewable hydrogen per year through a 1 GW electrolyser, powered by 2 GW of renewable energy from a solar power plant (ARNOLD, 2022; PARKES, 2022).

The Hydrogen Park Gladstone (HyP Gladstone) project, located in South Australia, consists of green hydrogen produced using a 175kW Nel C30 proton exchange membrane electrolyzer using water and renewable electricity. Renewable hydrogen is blended with natural gas in volumes of up to 10% and supplied to around 770 nearby homes and businesses through the **existing gas network**, being Australia's first renewable hydrogen production facility (AUSTRALIA GAS INFRASTRUCTURE GROUP (AGIG), 2022; CSIRO, 2022b).

The Hydrogen Energy Supply Chain (HESC) trial project in the Latrobe Valley intends to produce liquefied hydrogen from the region's brown coal to be transported to Japan for use in fuel cell electric vehicles and power generation (LATROBE CITY, 2022). For the pilot phase, carbon credits are purchased for the CO2 produced, and a **carbon capture and storage** system will be implemented for the commercial phase (HYDROGEN ENERGY SUPPLY CHAIN PROJECT, 2022).

The production of hydrogen has been part of the Hunter region for decades, and with it a suite of specialised skills and expertise. The production has been handled using traditional steam reforming technology to produce derivative products such as ammonia, fertilisers and explosives for the resources and associated sectors (HUNTER HYDROGEN TASKFORCE, 2021). Australian upstream and utility firm Origin Energy and Australian chemical and explosives firm Orica will study plans to develop a hydrogen **hub** in the Hunter Valley region of New South Wales (NSW), which is Australia's largest thermal coal-producing area. This hub would produce renewable hydrogen from sustainable sourced water and renewable electricity from Origin's portfolio, using a grid-connected 55MW electrolyser (MORRISON, 2022). In addition, the Hunter boasts a deep-water international **port** connected to Australia's energy trading partners, having a vital role in accelerating the domestic growth cycle by supporting innovation and deployment of cutting-edge hydrogen technologies with export potential (HUNTER HYDROGEN TASKFORCE, 2021). The New South Wales Government (NSW) also is promoting discussions among several companies to progress the concept of a hydrogen hub in the Illawarra / Port Kembla; according to (NEW SOUTH WALLES GOVERNMENT, 2021) this region is set to become a hydrogen superpower, with an ambitious plan to build Australia´s first 5GW scale green hydrogen hub (CSIRO, 2022a; NEW SOUTH WALLES GOVERNMENT, 2021).

The Pilbara is an energy-intensive mining region with substantial energy demand and carbon emissions (BP). This west region of Australia, called the Asian Renewable Energy Hub (AREH), is expected to be capable of producing around 1.6 million tonnes of green hydrogen or 9 million tonnes of green ammonia per annum (BP, 2022).

The South Australian Government is investing more than half a billion dollars to accelerate new hydrogen projects, **shipping infrastructure** and modelling tools for investors and developers, objecting scale-up renewable hydrogen production for export and domestic consumption (REUTERS, 2021). According to the Government, South Australia's total renewable energy in operation or commissioned is close to 4.5GWwith an additional 17GW underdevelopment (GOVENMENT OF SOUTH AUSTRALIA, 2021). One key project is Santos' Moomba carbon capture and storage (CCS), presenting up to 2Mtpa potential for blue hydrogen, it will be one of the largest CCS projects in the world and one of the lowest cost projects, estimate at AUD30 per tonne, counting with AUD15 million Government support (GOVENMENT OF SOUTH AUSTRALIA, 2021). Santos has access to the **existing pipeline** to Port Bonython, enabling permanent CO2 **storage** in the Cooper Basin (GOVENMENT OF SOUTH AUSTRALIA, 2021). Hydrogen, made from natural gas, presents a major opportunity for both Santos and Australia to produce a low-carbon and reliable fuel that will help Australia and the world to lower carbon emissions (HANCOCK; WOLLERSHEIM, 2021). Blending up to 10% of hydrogen into the existing natural gas network could be the first step in providing lower carbon energy to Australian homes and industries. Natural gas combined with CCS technology can speed up a hydrogen economy at a more affordable price. Through its existing assets and capabilities, Santos is extremely well-placed to develop low-carbon hydrogen at scale (HANCOCK; WOLLERSHEIM, 2021).

Australia is one of the world's largest exporters of coal and natural gas, thus the country should think about an **export** alternative of energy, and hydrogen would be a suitable one, as the current infrastructure used for gas can also be used for hydrogen (YUSAF et al., 2022).

3.3.5. Local demand

Germany´s demand for hydrogen for **industrial** processes is already substantial and amounts to about 55 TWh, which is currently served by hydrogen produced using methane steam reforming (ENERGYPARTNERSCHAFT DEUTSCHLAND-CHINAR, 2022). Germany is the 10th world's largest oil refiner, thus, there is a potential for electrolytic hydrogen to replace dedicated hydrogen production from natural gas or coal. Currently, Shell operates a 10MW proton exchange membrane (PEM) electrolyser in Rheinland **refinery** in Germany; it can produce 1,300 tonnes of hydrogen a year, supplying around 1% of the refinery's hydrogen needs (CRANMORE PARTNERS AND ENERGY ESTATE, 2021; SHELL, 2022). Germany is a world's top 10 steel manufacturing, having room to create demand for green hydrogen (CRANMORE PARTNERS AND ENERGY ESTATE, 2021). In October 2022, the European Commission has approved, under EU State aid rules, a €1 billion subside to help Salzgitter Flachstahl GmbH ('Salzgitter') decarbonise its **steel** production processes by using hydrogen. The measure contributes to the achievement of the EU Hydrogen Strategy and the European Green Deal targets while helping reduce dependence on imported Russian fossil fuels and fast forward the green transition, in line with the REPowerEU Plan. REPowerEU is about rapidly reducing our dependence on Russian fossil fuels by fast-forwarding the clean transition and joining forces to achieve a more resilient energy system and a true Energy Union (EUROPEAN COMMISSION, 2022b).

Germany is also a large **ammonia** producer; due to disruption to Russian gas supplies, German´s BASF, the world's largest chemical company, SKW Piesteritz, Germany's biggest ammonia maker and Ineos are on the edge of not ruling out production cuts. Fertiliser giant Yara, which runs Germany's third-largest ammonia production site in the northern town of Brunsbuettel, said its output across Europe was currently 27% below capacity due to the surge in gas prices (BURGER, 2022). This urgency for the independency of international natural gas occasionally can foster replacement for green hydrogen.

Germany, in conjunction with the EU, is focusing on concluding long-term cooperation frameworks with trusted partners via binding or non-binding agreements that support the purchasing of gas, hydrogen and clean energy project development

(EUROPEAN COMMISSION, 2022b). For example, several African countries have already engaged to explore and develop a hydrogen economy that uses continent's resource potential to support sustainable economic development (IRENA, 2022b).

About **transportation**, it is worth mentioning that the world´s first hydrogen-powered passengers **trains** are already running in Germany. Five of these zero-emissions trains began running in the second half of 2022 in Lower Saxony, a state in the northern part of the country. And over the next year, the regional rail line intends to replace all its diesel-powered trains with this new alternative. It is planed that 14 new trains will be in service soon, the line will become the first route to run exclusively on hydrogen, according to a statement from Alstom, the France-based company that developed the trains. The trains can run at speeds of up to 86 miles per hour, can travel 1,000 kilometers on a single tank of hydrogen, and there is a **hydrogen filling station** along the tracks. The state plans to eventually phase out all 126 of its trains that run on diesel (KUTA, 2022). The project benefits from the support of the German Ministry of Economy and Mobility and its development were funded by the German government as part of the National Innovation Program for Hydrogen and Fuel Cell Technology. Alstom currently has four contracts for hydrogen fuel cell-powered regional trains, two are in Germany, this one mentioned in the region of Lower Saxony, and the second for 27 trains in the Frankfurt metropolitan area (ALSTOM, 2022; AUSTOM, 2022; LOWER SAXONY STATE CHANCELLERY, 2022).

The building sector accounts for 16 % of Germany's total CO2 emissions in 2021, due to the use of fuels for **heating** and hot water generation. The German Hydrogen Strategy explicitly specifies the use of hydrogen in the heating market as one of its essential goals (FEDERAL MINISTRY FOR ECONOMIC AFFAIRS AND ENERGY, 2020). Thus, blending hydrogen in the natural gas network can enable the use of hydrogen in the building sector. There are demonstrating projects across the country to demonstrate technical feasibility by blending different shares of hydrogen into the distribution grid, e.g., the project of Netze BW in Germany, which plan to demonstrate a blend of up to 30 % hydrogen in the gas grid by 2023 (KNOSALA et al., 2022).

Netherlands' Government states that once there are clear rules for the market and successful steps have been taken in scaling up production, resulting in cost reductions, this will lead to a clearer picture for potential customers as to what extent hydrogen could be beneficial to them as a tool to achieve sustainability improvements (GOVERNMENT

OF THE NETHERLANDS, 2020).

According to (FUEL CELLS AND HYDROGEN 2 JOINT UNDERTAKING (FCH 2 JU), 2020), to cover the estimated hydrogen demand from new uses and from the substitution of fossil-based hydrogen, 2 to 9 GW of dedicated renewable electricity capacity would have to be installed to produce green hydrogen via electrolysis by 2030. In this scenario, part of the 2030 hydrogen demand would still be covered by fossil-based hydrogen produced via steam-methane reforming of fossil fuels (FUEL CELLS AND HYDROGEN 2 JOINT UNDERTAKING (FCH 2 JU), 2020).

The Gasunie annual report suggests that by 2030, **domestic demand** for natural gas will have dropped by a quarter, and the role of natural gas is expected to partially be replaced by green gas and hydrogen (GASUNIE, 2021). Over the next ten years, millions of existing homes are expected to switch to sustainable alternatives, and hydrogen may be a more feasible solution, as the existing gas infrastructure could be adapted to distribute hydrogen. The Netherlands has a strong ecosystem of central **heating** boiler manufacturers who are investing heavily in transitioning from natural gas to hydrogen. Several of them have marketed models suitable for gas mixtures with up to 30% of hydrogen, and also have showcased 100% hydrogen boilers. Others are working on technology that would allow existing gas-fueled central heating boilers to be retrofitted for use with hydrogen (NETHERLANDS ENTERPRISE AGENCY (RVO); FME; TKI NEW GAS (TOP SECTOR ENERGY), 2022).

Considering the **transport** sector, the Netherlands intends to achieve 50 refuelling stations, 15,000 fuel cell vehicles and 3,000 heavy-duty vehicles by 2025 and 300,000 fuel cell vehicles by 2030 (GOVERNMENT OF THE NETHERLANDS, 2020). Through the Sustainable Procurement Programme, the national government and regional authorities will act as launching customers, as subsidy schemes for zero emissions urban logistics and heavy-duty transport are being developed under the framework of the National Climate Agreement (GOVERNMENT OF THE NETHERLANDS, 2020).

The Dutch large inland **shipping sector** is set with a goal to introduce 150 hydrogen-powered barges over the next 10 years, and as part of a pan-European project initiated by the province of Zuid-Holland, hydrogen fueling stations will be built along the shipping corridor between Rotterdam and Genoa. The construction of the first barge has started and is set to be operational in 2023, an important step towards a carbon-neutral maritime sector (NETHERLANDS ENTERPRISE AGENCY (RVO); FME; TKI NEW GAS (TOP SECTOR ENERGY), 2022).

Dutch **industry** has a substantial market share in Europe's ammonia production and refinery capacity. These industries use fossil-based hydrogen, which could be replaced by renewable or low-carbon hydrogen (FUEL CELLS AND HYDROGEN 2 JOINT UNDERTAKING (FCH 2 JU), 2020). The report Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU), based on the Netherlands´s NECPs, points out that the use of renewable hydrogen is foreseen in methanol production (up to 7%) and ammonia production (up to 5%). Also estimates the substitution of up to 2% of the conventional steel production by renewable hydrogen-based steelmaking, and the introduction of 11,530 to 50,230 (in a high scenario) of stationary fuel cells for Micro CHP (Combined Heat and Power) production is foreseen (FUEL CELLS AND HYDROGEN 2 JOINT UNDERTAKING (FCH 2 JU), 2020).

In the **power sector**, as variable renewable energy is taking place, the Dutch are working on the technology to convert gas and coal power plants to run on (carbon-neutral) hydrogen, as well as on the storage solutions needed to create large hydrogen buffers. Other innovations include flexible electrolysers that can be used for grid balancing, frequency containment or emergency power systems. In addition, the existing natural gas infrastructure also offers opportunities for storage in order to help bridge seasonal variations in the availability of renewable power or to balance the power grid (NETHERLANDS ENTERPRISE AGENCY (RVO); FME; TKI NEW GAS, 2021).

Australian Government launched in December 2021 report State of Hydrogen, showing the development of Australia's hydrogen industry since the release of the National Hydrogen Strategy, pointing to Australia´s hydrogen use opportunities (CSIRO, 2021b). Australia's most developed areas of hydrogen demand are ammonia production and blending into gas networks (AUSTRALIAN GOVERNMENT, 2021a).

Australia´s national hydrogen strategy includes both export and domestic opportunities (AGUILERA; INCHAUSPE, 2021). As state in Australia's Gas Vision 2050 report (ENERGY NETWORK AUSTRALIA, 2022) reaching 100% of hydrogen in networks will be achieved in two stages. The first one is to blend at least 10% into the network, engaging with customers, including assessments of infrastructure suitability, scaling up hydrogen production and developing a local manufacturing capability for hydrogen appliances including **heating** appliances. According to (SANDRI et al., 2021), numerous trials are being undertaken in Australia, funded by the gas industry and the national government to test domestic appliances and heating with hydrogen, also injecting hydrogen into natural gas for use in homes. The second stage would involve making infrastructure modifications to ensure safe operation, replacing natural gas appliances with hydrogen appliances and replacing the fuel in pipelines and networks with hydrogen (ENERGY NETWORK AUSTRALIA, 2022). Gas networks are targeting 100% hydrogen in some regions by 2030 (AUSTRALIAN GOVERNMENT, 2021a).

Ammonia production is currently the largest use for hydrogen in Australia, used for manufactory products such as fertilizers, industrial chemicals, explosives and plastic. Nine projects are being developed in Australia, ranging from small-scale pilot projects to large-scale developments. For example, the Australian Government, through ARENA, is providing up to AUD 42.5 million to Engie Renewables Australia for a 10 MW electrolyser project. The project will produce renewable hydrogen at Yara Pilbara Fertilizers' ammonia facility in Karratha, Western Australia (AUSTRALIAN GOVERNMENT, 2021a).

In the **industrial heating** business is possible to highlight the Company Grange Resources, which is Australia´s premier producer of iron ore pallets, located in Tasmania. The Company was selected to undertake a study to explore the potential to use hydrogen for industrial heating at the pellet plant(AUSTRALIAN GOVERNMENT, 2021a; GRANGE RESOURCES, 2022).

The **power sector** is advancing quickly, two new hydrogen-ready gas generators reached a final investment decision in NSW, Snowy Hydro's 660 MW in Kurri Kurri gas generator and Energy Australia's 316 MW Tallawarra B dual fuel capable gas/hydrogen power plant located in the Illawarra region, besides other projects that are also in the pipeline (AUSTRALIAN GOVERNMENT, 2021a; CSIRO, 2021a; SNOWY HYDRO, 2020). However, electricity grid support has shown limited activity underway to test whether hydrogen can provide frequency control ancillary services (FCAS) (AUSTRALIAN GOVERNMENT, 2021a).

To foster the **transport sector**, the Australian Government has launched The Future Fuels Fund aiming to address barriers to the roll-out of new vehicle technologies, including hydrogen vehicles, also embracing refilling stations for hydrogen fuel cell vehicles (GRANGE RESOURCES, 2022). Currently, four refuelling stations and approximately 30 vehicles are in operation. It is worth mentioning that Hyzon Motors and Fortescue Metals are collaborating on hydrogen-powered buses for mining applications (AUSTRALIAN GOVERNMENT, 2021a).

3.3.6. Potential cost reduction

Germany considers two main approaches to support green hydrogen development, through OPEX (operating) and CAPEX (capital) costs, according to the current stage of the country's regulatory process (HUBER, 2021).

Germany adopted a surcharge payments exemption for green hydrogen to decrease operating costs under EEG 2021. This surcharge payments exemption decreases the electricity price for hydrogen production and, as a result, helps reduce operating costs. The surcharge payment exemption for electricity consumed in a green hydrogen production facility will apply from 1 January 2022. The main purpose of the surcharge payments exception is accelerating the growth of hydrogen market to reach the National Hydrogen Strategy goals (APPUNN; ERIKSEN; WETTENGEL, 2021; VON BURCHARD, 2021).

As a supportive scheme for CAPEX costs, Germany has started the process of obtaining funding under the European initiative of IPCEI. The projects, which are expected to receive funding under IPCEI, concern the production of green hydrogen (electrolyser capacity of 2 GW) and hydrogen infrastructure (pipelines up to 1700 km), as well as the production of fuel cell systems and vehicles (EUROPEAN PARLIAMENTARY RESEARCH SERVICE, 2020).

The expected project costs that will be funded by the German government total EUR 8 billion, and the funding will cover the investment costs of the project. However, it is also anticipated that projects and their funding under the IPCEI will trigger further investments in the sector of up to EUR 33 billion, of which EUR 20 billion is expected from the private sector (KURMAYER, 2021).

In addition to the IPCEI, Germany envisages a new contractual framework for a subsidy payment to the consumers of green hydrogen like steel plants that would be connected with the price of a ton of CO2 according to the EU Emission Trading System (ETS) (GERMANY TRADE & INVEST, 2022). This approach is called the "Carbon Contract for Difference" (CCfD) regime to support the avoidance of GHG emissions by the consumer together with hydrogen (APPUNN; ERIKSEN; WETTENGEL, 2021; VON BURCHARD, 2021).

Germany considers supportive schemes not only for capital and operational costs, but also for markets and different sectors and industries before and after 2030. According to a roadmap for the submission and development of schemes to support the hydrogen industry, the initial phase up to 2030 requires particularly strong involvement of government measures to support hydrogen supply and demand. From 2030 onward, it is expected that the gap between the cost of renewable and fossil fuel-generated hydrogen will narrow significantly, and liquid hydrogen market participants will be able to cover the gap to a large extent on their own .

Netherlands Government´s supporting measures to provide the development of hydrogen production projects are based on the Stimulation of Sustainable Energy Production and Climate (SDE++) scheme, an operating subsidy (NETHERLANDS ENTERPRISE AGENCY, 2021). The subsidy mainly compensates for the difference between the cost price of sustainable energy or the reduction in CO_2 emissions and the real revenue, being allocated for periods of 12 or 15 years .(NETHERLANDS ENTERPRISE AGENCY, 2021)

Costs of green hydrogen production are expected to fall with the scaling-up process, higher electrolysis efficiency and price development of the renewable electricity used. According to the Dutch Hydrogen Strategy, the government is considering the options available to realise scaling up and cost reduction by linking the development of offshore wind energy and hydrogen via integrated tenders and through a blending obligation (GOVERNMENT OF THE NETHERLANDS, 2020).

In an international context, The North Seas Energy Cooperation (NSEC) supports and facilitates the development of offshore grid development and the large renewable energy potential in the region. The work programme for 2020-2023 put a particular emphasis on developing concrete cross-border offshore wind and grid projects (hybrid projects), with the potential to reduce costs and space of offshore developments (EUROPEAN COMISSION, 2020). As mentioned in the Hydrogen Strategy, The Netherlands will promote exploring offshore hydrogen cooperation, among others as part of the North Sea Energy Cooperation program to accelerate the development of green hydrogen (GOVERNMENT OF THE NETHERLANDS, 2020).

Achieving the **Australian** Government's target of AUD 2.00 per kilogram of hydrogen will require cost reductions across the supply chain (AUSTRALIAN GOVERNMENT, 2021a). The National Hydrogen Strategy supports the creation of hydrogen hubs to foster a competitive clean hydrogen industry in Australia. Hubs are regions where hydrogen users, producers and potential exporters are co-located. This lowers infrastructure needs and reduces costs, making the hub model an efficient approach to producing hydrogen at scale and increasing demand (AUSTRALIAN

GOVERNMENT, 2022).

Hydrogen technology breakthroughs are occurring, and uptake is driving cost reductions. The hydrogen scale is driving supply chain costs down rapidly (COAG, 2019). According to the report State of Hydrogen, cost competitiveness is advancing quick, thus, clean hydrogen costs are expected to decline to between AUD 2 and AUD4 by 2030 (AUSTRALIAN GOVERNMENT, 2021a).

Australian Government plan to invest in strategic international partnerships to make low emissions technologies cheaper than high emitting alternatives (AUSTRALIAN GOVERNMENT, 2021b). Looking for partner countries to work on cost-reduction solutions, Australia signs a letter of intent with India on new renewable energy technology, focusing on the manufacture and deployment of ultra-low-cost solar and clean hydrogen.

3.4. LESSON TO LEARN FOR BRAZIL

Based on the research done embracing the international experience of selected countries the following paragraphs bring outstanding features that Brazil should note for its hydrogen market development.

In Brazil, there is no specific regulation for the production, storage and transport of hydrogen for energy uses or for the hydrogen market (EPE, 2021a; MAUR; LEITE; SCH, 2021). Despite being working on the issue since 2002, the country has not come up with its Hydrogen Strategy or specific regulation for hydrogen and the governance. Exploring the international experience of the selected countries, it is possible to notice that hydrogen front-runners have published its Hydrogen Strategies pushing the current momentum that hydrogen is having worldwide. Even though they have not presented specific regulations for hydrogen, they are implementing regulations for the transition period, e.g. Germany launched the program 'Regulatory Sandboxes for the Energy Transition', having the goal of speeding up key enabling technologies, particularly in the field of hydrogen, to become quickly marketable. The selected countries also highlight the importance of hydrogen blending in the existing natural gas network and the need for research and pilot projects to determine that hydrogen can be safely supplied by existing distribution systems and used in appliances in homes and businesses. Therefore, regulatory flexibility can be created for experiments, allowing regional and national network operators to gain experience in the transport and distribution of hydrogen.

Observing hydrogen technology development, the elected countries present numerous programs to support and stimulate laboratories and small-scale projects. In each county, the Government provides funds through programs and policy support to help with hydrogen production, storage, transportation, and import/export. Consequently, private companies are stimulated to take advantage of these programs and add their own investment, so the total investment in the hydrogen field can more than double. The countries are also strongly considering existing infrastructures that is used to transport, ship and storage natural gas to run on hydrogen. Hubs are being prospected as an efficient arrangement where hydrogen users (demand), producers and potential exporters are co-located. It was also noted that European countries, especially Germany, are looking for long-term cooperation frameworks with trusted partners that support the purchasing of gas, hydrogen and clean energy project development, aiming to diversify energy suppliers.

It was possible to recognize that large markets are well positioned to set standards and other rules of the game if their strategies and plans are well operationalized. Brazil is following behind in this run. When looking at world´s ranking (CRANMORE PARTNERS AND ENERGY ESTATE, 2021; IRENA, 2022b) Brazil appears as having great potential to be a hydrogen production leader, but in criteria such as regulatory and legal framework, public support and technology and projects development, the country does not thrive.

3.5. CONCLUSION

Observing the relationship between the policy front-runners and leading markets, it is possible to see that their ambitions for hydrogen plans, combined with their market size and additionally the European recently need in diversifying energy suppliers, are contributing to their leadership. These large markets can influence the worldwide hydrogen market with their strategy. Regarding these features, Brazil may follow these lessons to be on the path of hydrogen development. The main conclusion and policy implications present in this paper are summarized below:

(i) Brazil must establish a regulatory framework providing legal and regulatory security to investors. The country is being prospected by national and international companies to develop hydrogen projects, but to provide their solid establishment, the government should fast-track its hydrogen regulatory framework, even if it must go through a transition period until the implementation of the final rule;

(ii) The Brazilian government should promote strong public policies related to the development of the entire hydrogen chain, making the most of its existing competitive advantages;

(iii) Brazil shall make concrete alliances with front-runners countries that can boost research and development, pilot projects and scale projects, making room for them through supporting policy. In the case of developing countries, such as Brazil, alliances are essential for the deployment of new technologies;

4. CONCLUSIONS

Clean Hydrogen is at a time of unprecedented political and commercial momentum, with policies and projects worldwide expanding rapidly. The acceleration of these efforts is crucial to guarantee a significant portion of Hydrogen in the energy system in the coming decades. (IRENA, 2019b). The recent global energy crisis, mainly attributed to the invasion of Ukraine by Russia in February 2022, underscores the need for policy to align energy security needs with climate goals. Renewable hydrogen can contribute to energy security by decreasing dependency on fossil fuels. Furthermore, developing an international hydrogen market can increase the diversity of potential energy suppliers, increasing energy security mainly for energy importing countries (IEA, 2022).

Aiming to identify the possibilities and challenges for Brazil to engage in a hydrogen market of scale, this study addressed steps that the country should take in other to thrive in this field. From the first paper it is concluded that producing and storing hydrogen from renewable hybrid systems with wind or solar PV power plants is not viable, once the CAPEX of the whole value chain is considerably high. The economy of the process is only achieved when considering projects exclusively dedicated to hydrogen production with high-capacity factor, additionally electrolysers prices must be reduced from the current levels by half at list. Furthermore, the hydrogen produced must be traded with end users or exported, because when considering the addition of fuel cells to the project, to transform hydrogen back into power, the project becomes completely unfeasible.

This vision brings some insights as:

(i) the viability of green hydrogen production in Brazil does not only relay on abundant renewable resources with low costs of electricity;

(ii) the cost reduction of the hydrogen chain will only happen when the components start to be produced in scale worldwide;

(iii) both demand side and production side must be incentivised, because the tradeoff production versus demand must be equalized in order to grow a sustainable market.

To face these challenges, the second paper came to analyze in depth what actions the country should take to accelerate its hydrogen market by scrutinizing hydrogen front-runners countries. The development of this second paper led to lessons to be learned for Brazil to get on track with hydrogen market development.

The main concern that emerged from this study is that Brazil is still very incipient in the development of a hydrogen economy. The country has not even published its hydrogen strategy so far, unlike neighboring countries such as Chile which has announced its green hydrogen strategy in November 2020 (GOVERNMENT OF CHILE, 2020), and Colombia that launched its strategy in September 2021 and a roadmap in October 2021 (HYDROGEN CENTRAL, 2021).

From the research it is clear the linkage:

(i) If Brazil wants to guarantee its space and accelerate its hydrogen market, the country must stablish a legal and regulatory framework; even if it must go through a transition period until the final rule's implementation, it is essential for investors engagement.

(ii) Furthermore, Brazil needs to boost public policies to support the deployment of projects from pilot to industrial scale, making robust bonds with international hydrogen leaders from the public and private sectors.

(iii) Hydrogens hubs are seen internationally as key for the establishment of a hydrogen market, once it concentrates hydrogen production, storage, usage and export, saving on transport costs, that are considered high within the hydrogen chain.

(iv) Brazil is already emerging with potential hydrogen hubs, but it is still incipient, because the existing infrastructure is still insufficient and is not yet able to run on hydrogen.

(v) Thus, funds for research and development are necessary to ensure that existing infrastructure, e.g. natural gas network, can run with (blend) hydrogen. In parallel investments and financial lines must be available for adapting infrastructure and even building new facilities.

Hence, the renewable potential is not the only factor that determine high-potential hydrogen producers. Many other factors came into play, such as existing infrastructure, soft factors (e.g. government support, business friendliness, political stability) and potential demand for hydrogen. Brazil has a long run to become a reference in the hydrogen issue, the government and business leaders must cooperate and start acting now to influence the pace of the renewable energy transition, the pace of which must be accelerated.

Al last, iIt is hoped that the discussions and results presented here can support regulatory formulation, public policies, strategies for the public and private sectors, and actions to improve international and mainly the national hydrogen market towards a sustainable future.

5. REFERENCES

ABDIN, Z.; MÉRIDA, W. Hybrid energy systems for off-grid power supply and hydrogen production based on renewable energy: A techno-economic analysis. **Energy Conversion and Management**, v. 196, p. 1068–1079, 15 set. 2019.

ACUÑA, L. G.; PADILLA, R. V.; MERCADO, A. S. Measuring reliability of hybrid photovoltaic-wind energy systems: A new indicator. **Renewable Energy**, v. 106, p. 68–77, 2017a.

ACUÑA, L. G.; PADILLA, R. V.; MERCADO, A. S. Measuring reliability of hybrid photovoltaic-wind energy systems: A new indicator. **Renewable Energy**, v. 106, p. 68–77, 2017b.

AGUILERA, R. F.; INCHAUSPE, J. An overview of hydrogen prospects: Economic, technical and policy considerations. 2021.

AKEYO, O. M.; PATRICK, A.; IONEL, D. M. Study of Renewable Energy Penetration on a Benchmark Generation and Transmission System. **Energies**, v. 14, n. 1, p. 169, 31 dez. 2020.

AL-GHUSSAIN, L.; AHMED, H.; HANEEF, F. Optimization of hybrid PV-wind system: Case study Al-Tafilah cement factory, Jordan. **Suatainable Energy Technologies and Assessments**, v. 30, p. 24–36, 2018a.

AL-GHUSSAIN, L.; AHMED, H.; HANEEF, F. Optimization of hybrid PV-wind system: Case study Al-Tafilah cement factory, Jordan. **Suatainable Energy Technologies and Assessments**, v. 30, p. 24–36, 2018b.

ALSTOM. **World premiere: 14 Coradia iLint to start passenger service on first 100% hydrogen operated rout**. Disponível em: <https://www.alstom.com/press-releases-news/2022/8/world-premiere-14-coradia-ilint-start-passenger-service-first-100>. Acesso em: 8 out. 2022.

ALVES, B. **Power mix in Germany 2021**. Disponível em: <https://www.statista.com/statistics/736640/energy-mix-germany/>. Acesso em: 29 jul. 2022.

ANEEL. Tratamento regulatório à situação de Constrained-off de usinas eólicas Relatório de Análise de Impacto Regulatório. p. 1–10, 2019a.

ANEEL. Tender Document for Auction No . 01 / 2019-Aneel 2019 Auction for Electricity Supply. n. 01, p. 1–38, 2019b.

ANEEL. **Resultados dos Leilões de Geração no Ambiente Regulado**. [s.l: s.n.]. Disponível em: <https://app.powerbi.com/view?r=eyJrIjoiYmMzN2Y0NGMtYjEyNy00OTNlLWI1YzctZjI0ZTUwMDg5ODE3IiwidCI6IjQwZDZmOWI4LWVjYTctNDZhMi05MmQ0LWVhNGU5YzAxNzBlMSIsImMiOjR9>.

ANTUNES CAMPOS, R.; RAFAEL DO NASCIMENTO, L.; RÜTHER, R. The complementary nature between wind and photovoltaic generation in Brazil and the role of energy storage in utility-scale hybrid power plants. **Energy Conversion and Management**, v. 221, p. 113160, 1 out. 2020.

APPUNN, K.; ERIKSEN, F.; WETTENGEL, J. **Germany's greenhouse gas emissions and energy transition targets**. Disponível em: <https://www.cleanenergywire.org/factsheets/germanys-greenhouse-gas-emissions-and-climate-targets#:~:text=The%202050%20net%2Dzero%20target,net%20zero'%20within%20three%20decades.>. Acesso em: 20 jul. 2022.

AQUILA, G. et al. An overview of incentive policies for the expansion of renewable energy generation in electricity power systems and the Brazilian experience. . 1 abr. 2017, p. 1090–1098.

ARENA. **High Efficiency Silicon Solar Cell Technology**. Disponível em: <https://arena.gov.au/projects/development-and-commercialisation-of-high-efficiency-silicon-solar-cell-technology/>. Acesso em: 22 set. 2022.

ARNOLD, C. H2 Hub, Total Eren's new Australian Project. **Energy News**, 18 ago. 2022.

ASKARZADEH, A.; COELHO, L. DOS S. A novel framework for optimization of a grid independent hybrid renewable energy system: A case study of Iran. **Solar Energy**, v. 112, p. 383–396, 2015.

AUSTOM. **Alstom Coradina iLint - the world´s 1st hydrogen poered train**. Disponível em: <https://www.alstom.com/solutions/rolling-stock/alstom-coradia-ilint-worlds-1st-hydrogen-powered-train>. Acesso em: 8 out. 2022.

AUSTRALIA GAS INFRASTRUCTURE GROUP (AGIG). **Australia's first whole of network decarbonisation project**. Disponível em: <https://www.agig.com.au/hydrogen-park-gladstone>. Acesso em: 2 set. 2022.

AUSTRALIAN GOVENMENT. **Technology Investment Roadmap: First Low Emissions Technology Statement – 2020**. [s.l: s.n.]. Disponível em: <https://www.dcceew.gov.au/sites/default/files/documents/first-low-emissions-technology-statement-2020.pdf>. Acesso em: 19 ago. 2022.

AUSTRALIAN GOVENMENT. **Low Emissions Technology Statement 2021**. [s.l: s.n.]. Disponível em: <https://www.dcceew.gov.au/sites/default/files/documents/low-emissions-technology-statement-2021.pdf>. Acesso em: 22 set. 2022.

AUSTRALIAN GOVERNMENT. **Australia's Intended Nationally Determined Contribution to a new Climate Change Agreement | August 2015**. [s.l: s.n.]. Disponível em: <https://unfccc.int/sites/default/files/NDC/2022-06/Australias%20Intended%20Nationally%20Determined%20Contribution%20to%20a%20new%20Climate%20Change%20Agreement%20-%20August%202015.pdf>. Acesso em: 22 jul. 2022.

AUSTRALIAN GOVERNMENT. **State of Hydrogen**. [s.l: s.n.]. Disponível em: <https://www.dcceew.gov.au/sites/default/files/documents/state-of-hydrogen-2021.pdf>. Acesso em: 29 ago. 2022a.

AUSTRALIAN GOVERNMENT. **International partnerships to accelerate low emissions technology**. Disponível em: <https://www.dcceew.gov.au/about/news/international-partnerships-to-accelerate-low-emissions-technology>. Acesso em: 22 set. 2022b.

AUSTRALIAN GOVERNMENT. **Australia Nationally Determined Contribution - Communication 2021**. [s.l: s.n.]. Disponível em: <https://unfccc.int/sites/default/files/NDC/2022-06/Australia%20Nationally%20Determined%20Contribution%20Update%20October%202021%20WEB.pdf>. Acesso em: 22 jul. 2022c.

AUSTRALIAN GOVERNMENT. **Growing Australia's hydrogen industry**. Disponível em: <https://www.dcceew.gov.au/energy/hydrogen#toc_6>. Acesso em: 18 set. 2022.

BARRETO, L.; MAKIHIRA, A.; RIAHI, K. The hydrogen economy in the 21st century: a sustainable development scenario. **International Journal of Hydrogen Energy**, v. 28, n. 3, p. 267–284, 2003.

BAYER, B.; BERTHOLD, L.; MORENO RODRIGO DE FREITAS, B. The Brazilian experience with auctions for wind power: An assessment of project delays and potential mitigation measures. **Energy Policy**, v. 122, n. July, p. 97–117, 2018.

BELANÇON, M. P. Brazil electricity needs in 2030: Trends and challenges. **Renewable Energy Focus**, v. 36, p. 89–95, 1 mar. 2021.

BHUYAN, S. K.; HOTA, P. K.; PANDA, B. Power quality analysis of a grid-connected solar/wind/hydrogen energy hybrid generation system. **International Journal of Power Electronics and Drive Systems**, v. 9, n. 1, p. 377–389, 2018a.

BHUYAN, S. K.; HOTA, P. K.; PANDA, B. Power quality analysis of a grid-connected solar/wind/hydrogen energy hybrid generation system. **International Journal of Power Electronics and Drive Systems**, v. 9, n. 1, p. 377–389, 2018b.

BØDAL, E. F.; KORPÅS, M. Value of hydro power flexibility for hydrogen production in constrained transmission grids. **International Journal of Hydrogen Energy**, v. 45, n. 2, p. 1255–1266, 6 jan. 2020.

BOECHEM, F. **Proposta para Lei do Hidrogênio no Senado traz desenvolvimento para a indústria**. Disponível em: <https://epbr.com.br/proposta-para-lei-do-hidrogenio-no-senado-traz-desenvolvimento-para-a-industria/>. Acesso em: 24 set. 2022.

BORNAPOUR, M. et al. Probabilistic optimal coordinated planning of molten carbonate fuel cell-CHP and renewable energy sources in microgrids considering hydrogen storage with point estimate method. **Energy Conversion and Management**, v. 206, n. January, p. 112495, 2020.

BP. **BP to lead and operate one of the world's largest renewables and green hydrogen energy hubs based in western Australia**. Disponível em: <https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-to-lead-and-operate-one-of-the-worlds-largest-renewables-and-green-hydrogen-energy-hubs-based-in-western-australia.html>. Acesso em: 3 set. 2022.

BRASIL. **Decreto nº 5.163 de 30 de Julho de 2004**. [s.l: s.n.]. Disponível em: <www.planalto.gov.br/ccivil_03/_ato2004-2006/2004/decreto/D5163compilado.htm>.

BRASIL. Projeto de Lei do Senado n° 232, de 2016. . 2016, p. 1–19.

BRASIL. Resolução Normativa ANEEL nº 954, de 30 de Novembro de 2021. . 30 nov. 2021.

BRASILALEMANHA. **Aliança Brasil-Alemanha para o Hidrogênio Verde aposta no potencial brasileiro como fornecedor internacional**. Disponível em: <https://brasilalemanhanews.com.br/destaque/alianca-brasil-alemanha-para-o-hidrogenio-verde-aposta-no-potencial-brasileiro-como-fornecedor-internacional/>.

BRAZIL. **Resolução Normativa nº 927, de 22 de março de 2021**. [s.l: s.n.]. Disponível em: <https://www.in.gov.br/web/dou/-/resolucao-normativa-n-927-de-22-de-marco-de-2021-310000413>.

BRUCE S et al. **National Hydrogen Roadmap Pathways to an economically sustainable hydrogen industry in Australia**. [s.l: s.n.]. Disponível em: <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/energy-and-resources/national-hydrogen-roadmap>. Acesso em: 20 ago. 2022.

BURGER, L. **BASF readies more ammonia production cuts in gas supply crunch**. Disponível em: <https://www.reuters.com/business/energy/basf-considers-more-ammonia-production-cuts-gas-supply-crunch-sources-2022-07-27/#:~:text=During%20normal%20times%2C%20ammonia%20production,a%20surge%20in%20gas%20prices.>. Acesso em: 8 out. 2022.

CALDERÓN, M. et al. Evaluation of a hybrid photovoltaic-wind system with hydrogen storage performance using exergy analysis. **International Journal of Hydrogen Energy**, v. 36, n. 10, p. 5751–5762, maio 2011a.

CALDERÓN, M. et al. Evaluation of a hybrid photovoltaic-wind system with hydrogen storage performance using exergy analysis. **International Journal of Hydrogen Energy**, v. 36, n. 10, p. 5751–5762, 1 maio 2011b.

CAMELO, H. DO N. et al. A hybrid model based on time series models and neural network for forecasting wind speed in the Brazilian northeast region. **Sustainable Energy Technologies and Assessments**, v. 28, p. 65–72, 1 ago. 2018.

CCEE. **Tipos de Leilões**. Disponível em: <https://www.ccee.org.br/web/guest/mercado/leilao-mercado>.

CCEE. **Comercialização**. Disponível em: <https://www.ccee.org.br/web/guest/perfil-segmentado/comercializacao>.

CCEE. **InfoLeilão Dinâmico, 045, janeiro/2021**. Disponível em: <https://www.ccee.org.br/web/guest/mensal>.

CCEE. **Entenda o mercado e a CCEE**. [s.l: s.n.].

CCEE. **Tipos de Leilões**. Disponível em: <https://www.ccee.org.br/portal/faces/pages_publico/o-que-fazemos/como_ccee_atua/tipos_leiloes_n_logado?_afrLoop=103613785101374&_adf.ctrl-state=5j7uq622f_1#!%40%40%3F_afrLoop%3D103613785101374%26_adf.ctrl-state%3D5j7uq622f_5>.

CCEE. **InfoLeilão Dinâmico, 045, janeiro/2021**. [s.l: s.n.]. Disponível em: <https://www.ccee.org.br/portal/faces/pages_publico/o-que-fazemos/infomercado/info_leilao_dinamico?contentId=CCEE_661116&_afrLoop=850247264690122&_adf.ctrl-state=10vh3z1hmj_111#!%40%40%3F_afrLoop%3D850247264690122%26contentId%3DCCEE_661116%26_adf.ctrl-stat>. Acesso em: 10 mar. 2021f.

CCEE. **Brasil vai liderar grupo de trabalho internacional sobre certificação de energia para produzir hidrogênio**. Disponível em: <https://www.ccee.org.br/pt/web/guest/-/brasil-vai-liderar-grupo-de-trabalho-internacional-sobre-certificacao-de-energia-para-produzir-hidrogenio>. Acesso em: 24 set. 2022.

CEYLAN, C.; DEVRIM, Y. Design and simulation of the PV/PEM fuel cell based hybrid energy system using MATLAB/Simulink for greenhouse application. **International Journal of Hydrogen Energy**, v. 46, n. 42, p. 22092–22106, jun. 2021a.

CEYLAN, C.; DEVRIM, Y. Design and simulation of the PV/PEM fuel cell based hybrid energy system using MATLAB/Simulink for greenhouse application. **International Journal of Hydrogen Energy**, v. 46, n. 42, p. 22092–22106, 18 jun. 2021b.

CHANDRASEKAR, A.; FLYNN, D.; SYRON, E. Operational challenges for low and high temperature electrolyzers exploiting curtailed wind energy for hydrogen production. **International Journal of Hydrogen Energy**, jan. 2021a.

CHANDRASEKAR, A.; FLYNN, D.; SYRON, E. Operational challenges for low and high temperature electrolyzers exploiting curtailed wind energy for hydrogen production. **International Journal of Hydrogen Energy**, v. 46, n. xxxx, p. 28900–28911, 30 jan. 2021b.

CHAVES, A. C.; DORES, A. B.; DE CASTRO, N. O Brasil na Transição Energética para o Hidrogênio Verde. **Valor Econômico**, p. 1–3, 2021.

CHEN, C.; LU, Y.; XINGA, L. Levelling renewable power output using hydrogen-based storage systems: A techno-economic analysis. **Journal of Energy Storage**, v. 37, p. 1002413, 2021.

CHEN, C.; YANG, Z.; HU, G. Signalling the cost of intermittency: What is the value of curtailed renewable power? **Journal of Cleaner Production**, v. 302, p. 126998, 2021.

CHIAPPINI, G. **Portos com eólicas offshore são modelos preferidos para hidrogênio verde no Brasil**. Disponível em: <https://epbr.com.br/portos-e-eolicas-offshore-sao-modelos-preferidos-preferidos-para-hidrogenio-verde-no-brasil/>. Acesso em: 24 set. 2022.

CLEAN ENERGY COUNCIL. **Clean Energy Australia Report 2022**. Australia: [s.n.]. Disponível em: <https://assets.cleanenergycouncil.org.au/documents/resources/reports/clean-energy-australia/clean-energy-australia-report-2022.pdf>. Acesso em: 19 ago. 2022.

CLIFFORD CHANCE. **Focus On Hydrogen: Germany Implements First Pure Hydrogen Midstream Regulation And Introduces Definition For Green Hydrogen**. Düsseldorf: [s.n.]. Disponível em: <https://www.cliffordchance.com/content/dam/cliffordchance/briefings/2021/06/focus-on-hydrogen-germany-implements-first-pure-hydrogen-midstream-regulation.pdf>. Acesso em: 5 ago. 2022.

CMS. The Promise of Hydrogen : An International Guide. n. October, 2020.

COAG. **Australia's National Hydrogen Strategy**. [s.l: s.n.]. Disponível em: <https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf>. Acesso em: 16 fev. 2021.

COAG ENERGY COUNCIL HYDROGEN WORKING GROUP. **Australia's National Hydrogen Strategy**. [s.l: s.n.]. Disponível em: <https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf>. Acesso em: 19 ago. 2022.

CRANMORE PARTNERS AND ENERGY ESTATE. **Hydrogen Investability Index**. [s.l: s.n.]. Disponível em: <https://www.h2-index.com/>. Acesso em: 9 jul. 2022.

CSIRO. **Tallawarra B Dual Fuel Capable Gas/Hydrogen Power Plant**. Disponível em: <https://research.csiro.au/hyresource/tallawarra-b-dual-fuel-capable-gas-hydrogen-power-plant/>. Acesso em: 17 set. 2022a.

CSIRO. **Publications - Australia**. Disponível em: <https://research.csiro.au/hyresearch/resources/key-publications/>. Acesso em: 15 set. 2022b.

CSIRO. **Port Kembla Hydrogen Hub**. Disponível em: <https://research.csiro.au/hyresource/port-kembla-hydrogen-hub/>. Acesso em: 17 set. 2022a.

CSIRO. **Hydrogen Park Gladstone**. Disponível em: <https://research.csiro.au/hyresource/hydrogen-park-gladstone/>. Acesso em: 2 set. 2022b.

CSIRO. **Australian Government – Hydrogen Industry Policy Initiatives**. Disponível em: <https://research.csiro.au/hyresource/policy/australia-and-new-zealand/australia/>. Acesso em: 20 ago. 2022c.

DA SILVA CÉSAR, A. et al. Hydrogen productive chain in Brazil: An analysis of the competitiveness' drivers. **Journal of Cleaner Production**, v. 207, p. 751–763, 2019.

DANTAS, M. C.; SILVA, K.; THOMAS, A. Novas perspectivas para o mercado de hidrogênio com o novo mercado de gás 1. p. 1–7, 2020.

DE LAAT, P. **Overview of Hydrogen Projects in the Netherlands**. [s.l: s.n.]. Disponível em: <https://www.topsectorenergie.nl/sites/default/files/uploads/TKI Gas/publicaties/Overview Hydrogen projects in the Netherlands versie 1mei2020.pdf>.

DE LAAT, P. **Overview of Hydrogen Projects in the Netherlands**. Netherlands: [s.n.]. Disponível em: <https://energycentral.com/c/og/overview-hydrogen-projects-netherlands>. Acesso em: 16 jul. 2022.

DE LIMA, M. M. **Sistemas de Armazenamento em Parques Eólicos Considerando PLD Horario e Situações de Constrained-off**. [s.l.] Universidade Tecnológica Federal do Paraná, 2021.

DELPIERRE, M. et al. Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis. **Journal of Cleaner Production**, v. 299, p. 126866, 2021.

DENHOLM, P.; HAND, M. Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. **Energy Policy**, v. 39, n. 3, p. 1817–1830, 1 mar. 2011.

DINCER, I.; ACAR, C. Smart energy solutions with hydrogen options. **International Journal of Hydrogen Energy**, v. 43, n. 18, p. 8579–8599, 2018.

DINH, V. N. et al. Development of a viability assessment model for hydrogen production from dedicated offshore wind farms. **International Journal of Hydrogen Energy**, 16 jun. 2020.

DO NASCIMENTO CAMELO, H. et al. A hybrid model based on time series models and neural network for forecasting wind speed in the Brazilian northeast region. **Sustainable Energy Technologies and Assessments**, v. 28, p. 65–72, ago. 2018.

DO SACRAMENTO, E. M. et al. Feasibility study for the transition towards a hydrogen economy: A case study in Brazil. **Energy Policy**, v. 62, p. 3–9, 1 nov. 2013.

DOKSO, A. **German authorities boost hydrogen projects in Lower Saxony**. Disponível em: <https://energynews.biz/german-authorities-boost-hydrogen-projects-in-lower-saxony/#:~:text=Twelve%20hydrogen%2Drelated%20initiatives%20are,federal%20government’s%201.6%20billion%20euros.>. Acesso em: 8 out. 2022.

DUTRA, R. M.; SZKLO, A. S. Incentive policies for promoting wind power production in Brazil: Scenarios for the Alternative Energy Sources Incentive Program (PROINFA) under the New Brazilian electric power sector regulation. **Renewable Energy**, v. 33, n. 1, p. 65–76, 2008.

ENERGY NETWORK AUSTRALIA. **Gas Vision 2050 - Delivering the pathway to net zero for Australia - 2022 outlook**. [s.l: s.n.]. Disponível em: <https://www.energynetworks.com.au/resources/reports/2022-reports-and-publications/delivering-the-pathway-to-net-zero-for-australia-2022-outlook/>. Acesso em: 3 set. 2022.

ENERGYPARTNERSCHAFT DEUTSCHLAND-CHINAR. **The Role of Hydrogen in Germany’s Energy Transition**. Disponível em: <https://www.energypartnership.cn/home/the-role-of-hydrogen-in-germanys-energy-transition/>. Acesso em: 29 jul. 2022.

EPE. **Energia Renovável**. [s.l: s.n.].

EPE. National Energy Plan 2050. p. 1–232, 2020a.

EPE. **Plano Nacional de Energia 2030**. Brasília: [s.n.].

EPE. Bases para a consolidação da Estratégia Brasileira do Hidrogênio. p. 36, 2021a.

EPE. **Relatório Síntese Balanço Energético Nacional Relatório Síntese - BEN 2021**. [s.l: s.n.]. Disponível em: <https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-2021>.

EPE. **Anuário Estatistico de Energia Elétrica 2021**. [s.l: s.n.]. Disponível em: <https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-160/topico-168/EPEFactSheetAnuario2021.pdf>.

EPE. **Anuário Estatistico de Energia Elétrica 2021**. Disponível em: <https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-160/topico-168/Anuário_2021.pdf>.

EPE. **MME apresenta ao CNPE proposta de diretrizes para o Programa Nacional do hidrogenio (PNH2)**. Disponível em: <https://www.epe.gov.br/pt/imprensa/noticias/mme-apresenta-ao-cnpe-proposta-de-diretrizes-para-o-programa-nacional-do-hidrogenio-pnh2->.

EPE; MME. **Plano Decenal de Expansão de Energia 2030**. [s.l: s.n.]. Disponível em: <https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/plano-decenal-de-expansao-de-energia-2030>. Acesso em: 4 out. 2022.

EUROPEAN COMISSION. **The North Seas Energy Cooperation**. Disponível em: <https://energy.ec.europa.eu/topics/infrastructure/high-level-groups/north-seas-energy-cooperation_en>. Acesso em: 17 jul. 2022.

EUROPEAN COMMISSION. **Summary of the Commission assessment of the draft National Energy and Climate Plan 2021-2030**. [s.l: s.n.]. Disponível em:

<https://energy.ec.europa.eu/system/files/2019-06/necp_factsheet_nl_final_0.pdf>. Acesso em: 4 jul. 2022.

EUROPEAN COMMISSION. **Communication from the Commission to the Europian Parliament, th European Council, the Council, The European Economic and Social Commitee and the Commitee of the Regions - REPowerEU Plan**. Brussels: [s.n.]. Disponível em: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483>. Acesso em: 7 out. 2022a.

EUROPEAN COMMISSION. **Communication from The Commission to The European Parliament, The European Council, The Council, The European Economic and Social Committee and The Committee of The Regions - REPowerEU Plan**. Brussels: [s.n.]. Disponível em: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483>. Acesso em: 8 out. 2022b.

EUROPEAN COUNCIL. **Update of the NDC of the European Union and its Member States**. Berlin: [s.n.]. Disponível em: <https://unfccc.int/sites/default/files/NDC/2022-06/EU_NDC_Submission_December%202020.pdf>. Acesso em: 19 jul. 2022.

EUROPEAN PARLIAMENTARY RESEARCH SERVICE. **Important projects of common European interest**. [s.l: s.n.]. Disponível em: <https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/659341/EPRS_BRI(2020)659341_EN.pdf>. Acesso em: 12 out. 2022.

EZAR NADALETI, W. C.; ALVES LOURENÇO, V.; AMERICO, G. Green hydrogen-based pathways and alternatives: Towards the renewable energy transition in South America's regions e Part A. 2021.

FAERMAN, H. **Hydrogen advances and players wait for regulation in Brazil**. Disponível em: <https://www.h2verdebrasil.com.br/en/noticia/hydrogen-advances-and-players-wait-for-regulation-in-brazil/>. Acesso em: 5 out. 2022.

FALCÃO, D. S.; PINTO, A. M. F. R. **A review on PEM electrolyzer modelling: Guidelines for beginners**. **Journal of Cleaner Production**Elsevier Ltd, , 10 jul. 2020a. . Acesso em: 18 mar. 2021

FALCÃO, D. S.; PINTO, A. M. F. R. **A review on PEM electrolyzer modelling: Guidelines for beginners**. **Journal of Cleaner Production**Elsevier Ltd, , 10 jul. 2020b.

FEDERAL MINISTRY FOR DIGITAL AND TRANSPORT. **European Commission approves 41 large-scale hydrogen projects**. Disponível em: <https://www.bmvi.de/SharedDocs/EN/PressRelease/2022/052-41-large-scale-hydrogen-projects.html>. Acesso em: 30 jul. 2022.

FEDERAL MINISTRY FOR ECONOMIC AFFAIRS AND CLIMATE CHANGE. **Northen Germany Regulatory Sandbox**. Disponível em: <https://www.bmwk.de/Redaktion/EN/Pressemitteilungen/2021/04/210414-Launch-of-the-Northern-Germany-Regulatory-Sandbox.html>. Acesso em: 5 ago. 2022.

FEDERAL MINISTRY FOR ECONOMIC AFFAIRS AND ENERGY. **The National Hydrogen Strategy**. Berlin: [s.n.]. Disponível em:

<https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6>. Acesso em: 22 jul. 2022.

FEDERAL MINISTRY OF FINANCE. **Immediate climate action programme for 2022**. Disponível em: <https://www.bundesfinanzministerium.de/Content/EN/Standardartikel/Topics/Priority-Issues/Climate-Action/immediate-climate-action-programme-for-2022.html#>. Acesso em: 20 jul. 2022.

FEHLING, M. **Energy Transition in Germany: What Role For Green Hydrogen?** Disponível em: <https://www.ippi.org.il/promotion-of-green-hydrogen-in-the-context-of-the-energiewende/>. Acesso em: 6 ago. 2022.

FEITZ, A.; TENTHOREY, E.; COGHLAN, R. **Prospective hydrogen production regions of Australia**. [s.l: s.n.]. Disponível em: <http://pid.geoscience.gov.au/dataset/ga/130930>.

FUEL CELLS AND HYDROGEN 2 JOINT UNDERTAKING (FCH 2 JU). **Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans**. [s.l: s.n.]. Disponível em: <https://www.fch.europa.eu/sites/default/files/file_attach/Brochure%20FCH%20Netherlands%20%28ID%209474122%29.pdf>. Acesso em: 16 jul. 2022.

FUHRMANN, M.; EMEA & RUSSIA DEPT. GLOBAL ECONOMIC & POLITICAL STUDIES DIV.; MITSUI & CO. GLOBAL STRATEGIC STUDIES INSTITUTE. **Germany's National Hydrogen Strategy-Serious Efforts to Realize a Decarbonized Society; Development of Green Hydrogen Supply Infrastructure is the Challenge**. [s.l: s.n.]. Disponível em: <https://www.mitsui.com/mgssi/en/report/detail/__icsFiles/afieldfile/2021/02/19/2012_fuhrmann_e.pdf>. Acesso em: 29 jul. 2022.

GASUNIE. **Gasunie 2020 annual report**. [s.l: s.n.]. Disponível em: <https://www.gasuniereport2020.nl/en/download-as-pdf>. Acesso em: 13 jul. 2022.

GASUNIE. **Gasunie Annual report 2021**. Netherlands: [s.n.]. Disponível em: <https://www.gasuniereport2021.nl/en>. Acesso em: 16 jul. 2022.

GERMANY TRADE & INVEST. **Green hydrogen is set to play a decisive role in Germany's energy transition. Carbon-neutral energy provision will also help the country realize its climate protection goals.** Disponível em: <https://www.gtai.de/en/invest/industries/energy/green-hydrogen#524570>. Acesso em: 29 jul. 2022.

GERMANY WORKS. **Hydrogen technologies**. Disponível em: <https://germanyworks.com/branch/hydrogen/#summary>. Acesso em: 29 jul. 2022.

GLORIA, L.; LEITES, T. N. **Regulatory advances and improvements in Latin America : Case study of VPP markets in Brazil**. 2nd European GRID SERVICE MARKETS Symposium P. **Anais**...Lucerne: 2nd European GRID SERVICE MARKETS Symposium, 2018. Disponível em: <https://www.researchgate.net/publication/332082475_Regulatory_advances_and_improvements_in_Latin_America_a_Case_study_of_VPP_markets_in_Brazil>

GOVENMENT OF SOUTH AUSTRALIA. **South Australia - Port Of Rotterdam Hydrogen Supply Chain Pre-Feasibility Study**. [s.l: s.n.]. Disponível em: <https://www.energymining.sa.gov.au/__data/assets/pdf_file/0007/733237/RELEASE_FINAL_

SA_-_Rotterdam_H2_Supplychain_pre-FS_report_-_exec_summary_presentation.pdf>. Acesso em: 27 ago. 2022.

GOVERNMENT OF CHILE. **Chile, a clean energy provider for a carbon neutral planet GREEN HYDROGEN STRATEGY**. Santiago: [s.n.]. Disponível em: <https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf>. Acesso em: 11 out. 2022.

GOVERNMENT OF SOUTH AUSTRALIA. **Hydrogen in South Australia**. Disponível em: <https://www.energymining.sa.gov.au/industry/modern-energy/hydrogen-in-south-australia>. Acesso em: 20 ago. 2022.

GOVERNMENT OF THE NETHERLANDS. **Government Strategy on Hydrogen**. [s.l: s.n.]. Disponível em: <https://www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen>. Acesso em: 9 jul. 2022.

GRANGE RESOURCES. **ESG Report - Baseline**. [s.l: s.n.]. Disponível em: <https://grange.blob.core.windows.net/public/c964126b-9133-47ec-a15f-c951a686e643.pdf>. Acesso em: 17 set. 2022.

GUTIÉRREZ-MARTÍN, F.; AMODIO, L.; PAGANO, M. Hydrogen production by water electrolysis and off-grid solar PV. **International Journal of Hydrogen Energy**, v. 46, n. 57, p. 29038–29048, 2021.

HANCOCK, L.; WOLLERSHEIM, L. Eu carbon diplomacy: Assessing hydrogen security and policy impact in australia and germany. **Energies**, v. 14, n. 23, 1 dez. 2021.

HASSANZADEHFARD, H. et al. Design and optimum energy management of a hybrid renewable energy system based on efficient various hydrogen production. **International Journal of Hydrogen Energy**, v. 45, n. 55, p. 30113–30128, nov. 2020a.

HASSANZADEHFARD, H. et al. Design and optimum energy management of a hybrid renewable energy system based on efficient various hydrogen production. **International Journal of Hydrogen Energy**, v. 45, n. 55, p. 30113–30128, 6 nov. 2020b.

HERNÁNDEZ-GÓMEZ, Á.; RAMIREZ, V.; GUILBERT, D. **Investigation of PEM electrolyzer modeling: Electrical domain, efficiency, and specific energy consumption**. **International Journal of Hydrogen Energy**Elsevier Ltd, , maio 2020a.

HERNÁNDEZ-GÓMEZ, Á.; RAMIREZ, V.; GUILBERT, D. **Investigation of PEM electrolyzer modeling: Electrical domain, efficiency, and specific energy consumption**. **International Journal of Hydrogen Energy**Elsevier Ltd, , 26 maio 2020b.

HEUSER, P. M. et al. Techno-economic analysis of a potential energy trading link between Patagonia and Japan based on CO2 free hydrogen. **International Journal of Hydrogen Energy**, v. 44, n. 25, p. 12733–12747, 2019.

HODGES, A. et al. A high-performance capillary-fed electrolysis cell promises more cost-competitive renewable hydrogen. [s.d.].

HRITSYSHYNA, M.; HUTAREVYCH, N. Legal regulation of hydrogen in germany and ukraine as a precondition for energy partnership and energy transition. **Energies**, v. 14, n. 24, 1 dez. 2021.

HUBER, I. **Germany's Hydrogen Industrial Strategy**. Disponível em: <https://www.csis.org/analysis/germanys-hydrogen-industrial-strategy>. Acesso em: 21 jul. 2022.

HUNTER HYDROGEN TASKFORCE. **Hunter Hydrogen Roadmap (2021-2040)**. [s.l: s.n.]. Disponível em: <https://hunter.org.au/wp-content/uploads/2021/11/20211117-Hunter-Hydrogen-Roadmap.pdf>. Acesso em: 3 set. 2022.

H-VISION. **Using hydrogen to make large and fast cuts in carbon emissions**. Disponível em: <https://www.h-vision.nl/en>. Acesso em: 28 jul. 2022a.

H-VISION. **Blue hydrogen as accelerator and pioneer for energy transition in the industry Feasibility study report**. [s.l: s.n.]. Disponível em: <https://www.h-vision.nl/application/files/7316/0726/0879/H-vision_Eindrapport_Blue_hydrogen_as_accelerator.pdf>. Acesso em: 28 jul. 2022b.

HYDROGEN CENTRAL. **The Colombian Hydrogen Strategy**. Disponível em: <https://hydrogen-central.com/colombian-hydrogen-strategy-targets/>. Acesso em: 11 out. 2022.

HYDROGEN COUNCIL. **Path to hydrogen competitiveness - A cost perspective**. [s.l: s.n.]. Disponível em: <https://www.h2knowledgecentre.com/content/policypaper1202?crawler=redirect&mimetype=application/pdf>. Acesso em: 24 set. 2022.

HYDROGEN ENERGY SUPPLY CHAIN PROJECT. **Latrobe Valley Hydrogen Production**. Disponível em: <https://www.hydrogenenergysupplychain.com/supply-chain/latrobe-valley/>. Acesso em: 2 set. 2022.

HYSATA. **Hysata's electrolyser breaks efficiency records**. Disponível em: <https://hysata.com/news/hysatas-electrolyser-breaks-efficiency-records-enabling-world-beating-green-hydrogen-cost/>. Acesso em: 19 ago. 2022.

IBGE. **Brazil map - Municipalities locations**.

IEA. **The Future of Hydrogen**. [s.l: s.n.].

IEA. **The Future of HydrogenThe Future of Hydrogen**. [s.l: s.n.].

IEA. **The Future of Hydrogen**. [s.l: s.n.].

IEA. **Hydrogen**. Paris: [s.n.].

IEA. **Hydrogen in Latin America**. [s.l: s.n.].

IEA. **Global Hydrogen Review 2022**. [s.l: s.n.]. Disponível em: <https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf>. Acesso em: 24 set. 2022.

IHS MARKIT - S&P GLOBAL. **Germany leads pack of countries pouring finance into hydrogen**. Disponível em: <https://cleanenergynews.ihsmarkit.com/research-analysis/germany-tops-table-of-states-pouring-finance-into-hydrogen.html#:~:text=Germany%20not%20only%20has%20a,exports%20abroad%20through%20international%20partnerships.>. Acesso em: 29 jul. 2022.

INTERNATIONAL ENERGY AGENCY. **The Netherlands 2020 - Energy Policy ReviewInternational Energy Agency**. [s.l: s.n.]. Disponível em: <https://www.connaissancedesenergies.org/sites/default/files/pdf-actualites/The_Netherlands_2020_Energy_Policy_Review.pdf>.

INTERNATIONAL TRADE ADMINISTRATOR. **Netherlands - Country Commercuial Trade**. Disponível em: <https://www.trade.gov/country-commercial-guides/netherlands-energy>. Acesso em: 23 jul. 2022.

IPHE. **Germany 37th IPHE SC Meeting Country Update Presentation April 2022**. [s.l: s.n.]. Disponível em: <https://www.iphe.net/_files/ugd/45185a_298ef05186e84f85b88ef72cb5f84c29.pdf>. Acesso em: 8 out. 2022.

IRENA. **Green hydrogen: A guide to policy making**. Abu Dhabi: [s.n.]. v. 2

IRENA. Solutions to integrate high shares of renewable energy. n. June, p. 28, 2019a.

IRENA. **Hydrogen: a Renewable Energy Perspective**. [s.l: s.n.].

IRENA. **Solutions for a Renewable-Powered Future - Solution XI: Power-to-X solutions**. [s.l: s.n.]. Disponível em: <https://irena.org/-/media/Files/IRENA/Agency/Topics/Innovation-and-Technology/IRENA_Landscape_Solution_11.pdf?la=en&hash=2BE79AC597ED18A96E5415942E0B93232F82FD85>. Acesso em: 18 fev. 2021c.

IRENA. **Solutions for a Renewable-Powered Future - Solution XI: Power-to-X solutions**. [s.l: s.n.].

IRENA. **Renewable capacity statistics 2020 International Renewable Energy Agency**. [s.l: s.n.].

IRENA. **Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5^{0}C Climate Goal**. [s.l: s.n.]. Disponível em: <https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf>.

IRENA. **Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5^{0}C Climate Goal**. Abu Dhabi: [s.n.].

IRENA. **World Energy Transitions Outlook: 1.5°C Pathway**. Abu Dhabi: [s.n.].

IRENA. **Renewable capacity highlights 2022**. [s.l: s.n.]. Disponível em: <www.irena.org/publications.>.

IRENA. **Geopolitics of the energy transformation : the hydrogen factor.** Abu Dhabi.: [s.n.]. Disponível em: <https://www.irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen>. Acesso em: 23 jul. 2022b.

ISPT. **Hydrohub Innovation Program Public report A One-GigaWatt Green-Hydrogen Plant Advanced Design and Total Installed-Capital Costs**. [s.l: s.n.]. Disponível em: <https://ispt.eu/media/Public-report-gigawatt-advanced-green-electrolyser-design.pdf>. Acesso em: 23 jul. 2022.

JOHNSON, E.; KNOWLMAN, EDWARD. **Hydrogen blends and renewable gases to be included in national gas framework**. Disponível em: <https://www.minterellison.com/articles/national-gas-law-h2-amendment>. Acesso em: 20 ago. 2022.

KAR, S. K. et al. Overview of hydrogen economy in Australia. **Wires Energy and Environment**, 5 ago. 2022.

KELMAN, R. et al. Can Brazil Become a Green Hydrogen Powerhouse? **Journal of Power and Energy Engineering**, v. 08, n. 11, p. 21–32, 2020.

KHOUJA, A. Hydrogen production costs of a polymer electrolyte membrane electrolysis powered by a renewable hybrid system. **International Journal of Hydrogen Energy**, v. 46, n. 27, p. 14005–14023, 2021.

KNOSALA, K. et al. The role of hydrogen in German residential buildings. **Energy and Buildings**, v. 276, p. 112480, 1 dez. 2022.

KUDRIA, S. et al. Resource potential for wind-hydrogen power in Ukraine. **International Journal of Hydrogen Energy**, v. 46, n. 1, p. 157–168, 2021.

KURMAYER, N. J. **Germany to invest €8 bn in large-scale hydrogen projects**. Disponível em: <https://www.euractiv.com/section/energy-environment/news/germany-to-invest-e8-bn-in-large-scale-hydrogen-projects/>. Acesso em: 29 jul. 2022.

KURMAYER, N. J. **German government disavows blue hydrogen**. Disponível em: <https://www.euractiv.com/section/energy/news/german-government-disavows-blue-hydrogen/>. Acesso em: 29 jul. 2022.

KUTA, S. **Hydrogen-Powered Passenger Trains Are Now Running in Germany**. Disponível em: <https://www.smithsonianmag.com/smart-news/hydrogen-powered-passenger-trains-are-now-running-in-germany-180980706/>. Acesso em: 8 out. 2022.

LATROBE CITY. **Hydrogen Industry Commercialisation in Latrobe City**. Latrobe: [s.n.]. Disponível em: <https://www.latrobe.vic.gov.au/sites/default/files/2022-04/LCC%20Hydrogen%20Industry%20Commercialisation.pdf>. Acesso em: 2 set. 2022.

LEEUWEN, C. VAN; ZAUNER, A. **Deliverable 8.3 - Report on the costs involved with PtG technologies and their potentials across the EUStore and GO project**. [s.l: s.n.]. Disponível em: <https://cordis.europa.eu/project/id/691797/reporting>.

LEWIS, J. **Australia remaisn world's top LNG exporter but it could lose its crown this year**. Disponível em: <https://www.upstreamonline.com/lng/australia-remains-worlds-top-lng-exporter-but-it-could-lose-its-crown-this-year/2-1-1147625>. Acesso em: 5 set. 2022.

LIMA, M. A. et al. Renewable energy in reducing greenhouse gas emissions: Reaching the goals of the Paris agreement in Brazil. **Environmental Development**, v. 33, p. 100504, 1 mar. 2020.

LO FARO, M.; CANTANE, D. A.; NARO, F. In the path for creating Research-to-business new opportunities on green hydrogen between Italy and Brazil. **International Journal of Hydrogen Energy**, 2022.

LONGDEN, T. et al. **Green Hydrogen Production Costs in Australia: Implications of Renewable Energy and Electrolyser CostsCCEP Working Paper**: ZCEAP Working Paper ZCWP03-20. [s.l: s.n.]. Disponível em: <https://energy.anu.edu.au/files/2020 09 01 - ZCEAP - CCEP Working Paper - Green hydrogen production costs.pdf>.

LOWER SAXONY STATE CHANCELLERY. **Lower Saxony Sets Corse for Financing large-Scale Hydrogen Progects**. Disponível em: <https://www.wasserstoff-niedersachsen.de/en/finanzierung-wasserstoff/>. Acesso em: 8 out. 2022.

LUND, H. et al. Energy storage and smart energy systems. **International Journal of Sustainable Energy Planning and Management**, v. 11, p. 3–14, 2016a.

LUND, H. et al. Energy storage and smart energy systems. **International Journal of Sustainable Energy Planning and Management**, v. 11, p. 3–14, 2016b.

LUND, H. et al. Smart energy and smart energy systems. **Energy**, v. 137, p. 556–565, 2017.

LUND, H.; SALGI, G. The role of compressed air energy storage (CAES) in future sustainable energy systems. **Energy Conversion and Management**, v. 50, n. 5, p. 1172–1179, 2009a.

LUND, H.; SALGI, G. The role of compressed air energy storage (CAES) in future sustainable energy systems. **Energy Conversion and Management**, v. 50, n. 5, p. 1172–1179, 1 maio 2009b.

LYSENG, B. et al. System-level power-to-gas energy storage for high penetrations of variable renewables. **International Journal of Hydrogen Energy**, v. 43, n. 4, p. 1966–1979, 25 jan. 2018.

MATTOS, M. **Políticas públicas no Brasil associadas ao hidrogênio e suas tecnologias**. Disponível em: <https://editorabrasilenergia.com.br/politicas-publicas-no-brasil-associadas-ao-hidrogenio-e-suas-tecnologias/>. Acesso em: 24 set. 2022.

MAUR, P.; LEITE, A.; SCH, P. **Hidrogênio : usos energéticos , políticas públicas e regulamentação**. Disponível em: <https://www.conjur.com.br/2021-mai-09/opiniao-hidrogenio-usos-politicas-publicas-regulamentacao?imprimir=1>.

MAYYAS, A. et al. **Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers**. [s.l: s.n.]. Disponível em: <https://www.nrel.gov/docs/fy10osti/72740.pdf.>.

MAYYAS, A. et al. **Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers**. [s.l: s.n.].

MAYYAS, A.; WEI, M.; LEVIS, G. Hydrogen as a long-term, large-scale energy storage solution when coupled with renewable energy sources or grids with dynamic electricity pricing schemes. **International Journal of Hydrogen Energy**, v. 45, n. 33, p. 16311–16325, jun. 2020a.

MAYYAS, A.; WEI, M.; LEVIS, G. Hydrogen as a long-term, large-scale energy storage solution when coupled with renewable energy sources or grids with dynamic electricity pricing schemes. **International Journal of Hydrogen Energy**, v. 45, n. 33, p. 16311–16325, 24 jun. 2020b.

MAZZEO, D. et al. A literature review and statistical analysis of photovoltaic-wind hybrid renewable system research by considering the most relevant 550 articles: An upgradable matrix literature database. **Journal of Cleaner Production**, v. 295, p. 126070, 2021a.

MAZZEO, D. et al. A literature review and statistical analysis of photovoltaic-wind hybrid renewable system research by considering the most relevant 550 articles: An upgradable matrix literature database. **Journal of Cleaner Production**, v. 295, p. 126070, 2021b.

MAZZEO, D.; MATERA, N.; OLIVETI, G. **Interaction between a wind-PV-battery-heat pump trigeneration system and office building electric energy demand including vehicle charging**.

IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe). **Anais**...2018a.

MAZZEO, D.; MATERA, N.; OLIVETI, G. **Interaction between a wind-PV-battery-heat pump trigeneration system and office building electric energy demand including vehicle charging**. IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe). **Anais**...2018b.

MCDONAGH, S. et al. Hydrogen from offshore wind: Investor perspective on the profitability of a hybrid system including for curtailment. **Applied Energy**, v. 265, n. February, p. 114732, 1 maio 2020.

MENEZES, R. F. A.; SORIANO, G. D.; DE AQUINO, R. R. B. Locational Marginal Pricing and Daily Operation Scheduling of a Hydro-Thermal-Wind-Photovoltaic Power System Using BESS to Reduce Wind Power Curtailment. **Energies**, v. 14, n. 5, p. 1441, 2021.

MINISTRY OF INDUSTRY ENERGY AND EMISSIONS REDUCTION. **Future hydrogen industry to create jobs, lower emissions and boost regional Australia**. Disponível em: <https://www.minister.industry.gov.au/ministers/taylor/media-releases/future-hydrogen-industry-create-jobs-lower-emissions-and-boost-regional-australia>. Acesso em: 27 ago. 2022.

MME. **Programa Nacional do Hidrogênio - Proposta de Diretrizes**. Brasilia: [s.n.]. Disponível em: <https://www.epe.gov.br/sites-pt/sala-de-imprensa/noticias/PublishingImages/Paginas/MME-apresenta-ao-CNPE-proposta-de-diretrizes-para-o-Programa-Nacional-do-Hidrogenio-PNH2/HidrognioRelatriodiretrizes.pdf>. Acesso em: 30 set. 2022a.

MME. **Baseline to support the Brazilian Hydrogen Strategy**. [s.l: s.n.]. Disponível em: <https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-569/NT_Hidrogênio_EN_revMAE (1).pdf>.

MME; EPE. **Estudos para a expansão da geração**. [s.l: s.n.].

MOHAMMADI, A.; MEHRPOOYA, M. A comprehensive review on coupling different types of electrolyzer to renewable energy sources. **Energy**, v. 158, p. 632–655, 1 set. 2018a.

MOHAMMADI, A.; MEHRPOOYA, M. A comprehensive review on coupling different types of electrolyzer to renewable energy sources. **Energy**, v. 158, p. 632–655, 1 set. 2018b.

MORAIS, G. H. Constrained-off : a formulação da REN nº 927 / 2021 e seus impactos para a energia renovável. p. 1–6, 2021.

MORRISON, K. **Australia's Origin, Orica plan hydrogen hub in NSW**. Disponível em: <https://www.argusmedia.com/en/news/2306710-australias-origin-orica-plan-hydrogen-hub-in-nsw>. Acesso em: 2 set. 2022.

NADALETI, W. C.; BORGES DOS SANTOS, G.; LOURENÇO, V. A. The potential and economic viability of hydrogen production from the use of hydroelectric and wind farms surplus energy in Brazil: A national and pioneering analysis. **International Journal of Hydrogen Energy**, v. 45, n. 3, p. 1373–1384, 13 jan. 2020.

NASCIMENTO, G. et al. The Role of Natural Gas Power Plants in Mitigation of High Variability of Renewable Energy Sources in the North and Northeast of Brazil. 2021.

NETHERLANDS ENTERPRISE AGENCY. **SDE++ 2021 Stimulation of Sustainable Energy Production and Climate Transition**. [s.l: s.n.]. Disponível em: <https://english.rvo.nl/sites/default/files/2021/10/SDEplusplus_oktober_2021_ENG.pdf>. Acesso em: 17 jul. 2022.

NETHERLANDS ENTERPRISE AGENCY (RVO); FME; TKI NEW GAS. **Excelling in Hydrogen Dutch technology for a climate-neutral world**. Netherlands: [s.n.]. Disponível em: <https://www.rvo.nl/sites/default/files/2021/03/Dutch%20solutions%20for%20a%20hydrogen%20economy.pdf>. Acesso em: 9 jul. 2022.

NETHERLANDS ENTERPRISE AGENCY (RVO); FME; TKI NEW GAS (TOP SECTOR ENERGY). **Excelling in Hydrogen Dutch technology for a climate-neutral world**. Netherlands: [s.n.]. Disponível em: <https://english.rvo.nl/sites/default/files/2022/05/NL-Dutch-solutions-for-a-hydrogen-economy-V-April-2022-DIGI_0.pdf>. Acesso em: 14 jul. 2022.

NETHERLANDS MINISTRY OF ECONOMIC AFFAIRS AND CLIMATE POLICY. **National Climate Agreement**. [s.l: s.n.]. Disponível em: <https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/national-climate-agreement-the-netherlands>.

NEW SOUTH WALLES GOVERNMENT. **Port Kembla Hydrogen Hub - Investment Prospectus**. [s.l: s.n.]. Disponível em: <https://portkemblahydrogenhub.com.au/app/uploads/2021/11/Port-Kembla-Hydrogen-Hub-Investment-Prospectus-October-2021.pdf>. Acesso em: 17 set. 2022.

NORTH SEA WIND POWER HUB. Towards the first hub-and-spoke project. p. 59, 2021.

NS ENERGY. RWE , Neptune Energy to develop green hydrogen project in North Sea. 2022.

OKUNDAMIYA, M. S. Size optimization of a hybrid photovoltaic/fuel cell grid connected power system including hydrogen storage. **International Journal of Hydrogen Energy**, v. 46, n. 59, p. 30539–30546, dez. 2020a.

OKUNDAMIYA, M. S. Size optimization of a hybrid photovoltaic/fuel cell grid connected power system including hydrogen storage. **International Journal of Hydrogen Energy**, 11 dez. 2020b.

ONS. **O Sistema Interligado Nacional**. Disponível em: <http://www.ons.org.br/paginas/sobre-o-sin/o-que-e-o-sin>.

ONS. **Boletins da Operação**. [s.l: s.n.]. Disponível em: <http://www.ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/geracao-fator-capacidade-medios-mensais.aspx>.

ONS. **Boletim Mensal de Geração Solar Fotovoltaica**. Disponível em: <http://www.ons.org.br/AcervoDigitalDocumentosEPublicacoes/Boletim Mensal de Geração Solar 2021-02.pdf>.

ONS. Boletim Mensal de Geração Solar Fotovoltaica. 2021c.

ONS. **Indicadores de Desempenho do SIN outubro de 2021**. [s.l: s.n.]. Disponível em: <http://www.ons.org.br/AcervoDigitalDocumentosEPublicacoes/Relatório dos Indicadores 2021_10_Outubro.pdf>.

ONS. **Boletim Mensal de Energia**. [s.l: s.n.]. Disponível em: <https://www.gov.br/mme/pt-br/assuntos/secretarias/spe/publicacoes/boletins-mensais-de-energia/2021/portugues/12-boletim-mensal-de-energia-dezembro-2021/view>. Acesso em: 2 out. 2022.

PARKES, R. Another Aussie green hydrogen hub in the works as Total Eren eyes 1GW Darwin. **Recharge**, 16 ago. 2022.

PEKIC, S. **Australias green hydrogen firm Hysata raises $29,5 mlm**. Disponível em: <https://www.offshore-energy.biz/australias-green-hydrogen-firm-hysata-raises-29-5-mln/>. Acesso em: 19 ago. 2022.

PEPPAS, A. et al. Performance evaluation and life cycle analysis of RES-hydrogen hybrid energy system for office building. **International Journal of Hydrogen Energy**, v. 46, n. 9, p. 6286–6298, fev. 2021a.

PEPPAS, A. et al. Performance evaluation and life cycle analysis of RES-hydrogen hybrid energy system for office building. **International Journal of Hydrogen Energy**, v. 46, n. 9, p. 6286–6298, 3 fev. 2021b.

PETERS, R. **Blue Hydrogen Paves the Way for Green Hydrogen**. Disponível em: <https://www.tno.nl/en/focus-areas/energy-transition/roadmaps/towards-co2-neutral-industry/hydrogen-for-a-sustainable-energy-supply/blue-hydrogen-paves-the-way-for-green-hydrogen/>. Acesso em: 24 jul. 2022.

PEYERL, D. Tecnologias disponíveis para mitigação dos efeitos adversos sobre o meio ambiente: das primeiras renováveis à economia do hidrogênio. Em: PIMENTAL, C.; ROLIM, M. J. C. P. (Eds.). **Caminhos jurídicos e regulatórios para a descarbonização do Brasil**. 2021. ed. Belo Horizonte: Editora Forum: 2021, 2018. p. 119–131.

PFENNINGER, S. Dealing with multiple decades of hourly wind and PV time series in energy models: A comparison of methods to reduce time resolution and the planning implications of inter-annual variability. **Applied Energy**, v. 197, p. 1–13, 1 jul. 2017.

PIERRY, F. **Brazil taps into green hydrogen certification**. Disponível em: <https://www.argusmedia.com/en/news/2365580-brazil-taps-into-green-hydrogen-certification>. Acesso em: 24 set. 2022.

PORTAL SOLAR. **Atlas Renewable Energy inicia operação do Complexo Sertão Solar Barreiras na Bahia**.

PORTHOS. **CO2 reduction through storage beneath the North Sea**. Disponível em: <https://www.porthosco2.nl/en/>. Acesso em: 24 jul. 2022.

POSHYDON. **Poshydon Process**. Disponível em: <https://poshydon.com/en/home-en/process/>.

POWELL, A. **$70 million funding for TAS Green Hydrogen Hub**. Disponível em: <https://www.energymagazine.com.au/70-million-funding-for-tas-green-hydrogen-hub/>. Acesso em: 29 ago. 2022.

PRADO, F. A. DE A. How much is possible? An integrative study of intermittent and renewables sources deployment. A case study in Brazil. **Renewable-Energy-Driven Future**, p. 511–538, 1 jan. 2021.

PRATES, J. P. Projeto de Lei 757/2022. . 29 mar. 2022.

PRICEWATERHOUSECOOPERS ADVISORY N.V. **HyWay 27: hydrogen transmission using the existing natural gas grid? Final report for the Ministry of Economic Affairs and Climate Policy**. Netherlands: [s.n.]. Disponível em: <https://www.hyway27.nl/en/latest-news/hyway-27-realisation-of-a-national-hydrogen-network>. Acesso em: 16 jul. 2022.

RABIEE, A.; KEANE, A.; SOROUDI, A. Green hydrogen: A new flexibility source for security constrained scheduling of power systems with renewable energies. **International Journal of Hydrogen Energy**, v. 46, n. 37, p. 19270–19284, 2021.

RAMOS, C. C. et al. Hydrogen economy development in Brazil: An analysis of stakeholders' perception. **Sustainable Production and Consumption**, v. 34, p. 26–41, 1 nov. 2022.

REN, G. et al. **Overview of wind power intermittency: Impacts, measurements, and mitigation solutions**. **Applied Energy**Elsevier Ltd, , 15 out. 2017. . Acesso em: 2 fev. 2021

REUTERS. **Australian state plans laws to speed up hydrogen production**. Disponível em: <https://www.reuters.com/business/sustainable-business/australian-state-plans-laws-speed-up-hydrogen-production-2022-05-31/>. Acesso em: 20 ago. 2022.

RIBEIRO, V. et al. O Desafio Da Gestão Dos Eventos De Constrained-Off Eólico (Curtailment) No Setor Elétrico Brasileiro Vis A Vis A Experiência Internacional. **XXV SNPTEE, Seminario Nacional de Produção e Transmissão Elétrica**, p. 1–9, 2019.

RINGSGWANDL, L. M. et al. Current Legislative Framework for Green Hydrogen Production by Electrolysis Plants in Germany. 2022.

ROWELL, J. et al. **The down low on hydrogen policy and regulation in Australia**. [s.l: s.n.]. Disponível em: <https://www.allens.com.au/globalassets/pdfs/sectors-services/energy/the-down-low-on-hydrogen-policy-and-regulation-in-australia.pdf>. Acesso em: 20 ago. 2022.

SAEEDMANESH, A.; MAC KINNON, M. A.; BROUWER, J. Hydrogen is essential for sustainability. **Current Opinion in Electrochemistry**, v. 12, p. 166–181, 2018.

SANDRI, O. et al. Hydrogen for all? Household energy vulnerability and the transition to hydrogen in Australia. **Energy Research & Social Science**, v. 79, p. 102179, 1 set. 2021.

SANTOS, S. **Complexo Sertão Solar Barreiras, está completamente operacional**. Disponível em: <https://opetroleo.com.br/complexo-sertao-solar-barreiras-esta-totalmente-operacional/>. Acesso em: 9 out. 2022.

SAWLE, Y.; GUPTA, S. C.; BOHRE, A. K. Review of hybrid renewable energy systems with comparative analysis of off-grid hybrid system. **Renewable & sustainable energy reviews**, v. 81, n. 2, p. 2217–2235, 2018.

SCHALENBACH, M. et al. Pressurized PEM water electrolysis: Efficiency and gas crossover. **International Journal of Hydrogen Energy**, v. 38, n. 35, p. 14921–14933, nov. 2013.

SHELL. **Shell to start building Europe's largest renewable hydrogen plant**. Disponível em: <https://www.shell.com/media/news-and-media-releases/2022/shell-to-start-building-europes-largest-renewable-hydrogen-plant.html>. Acesso em: 8 out. 2022.

SILVA, S. B.; DE OLIVEIRA MARCO, M. A. G.; SEVERINO, M. M. Economic evaluation and optimization of a photovoltaic–fuel cell–batteries hybrid system for use in the Brazilian Amazon. **Energy Policy**, v. 38, n. 11, p. 6713–6723, 1 nov. 2010.

SILVA, S. B.; SEVERINO, M. M.; DE OLIVEIRA, M. A. G. A stand-alone hybrid photovoltaic, fuel cell and battery system: A case study of Tocantins, Brazil. **Renewable Energy**, v. 57, p. 384–389, 1 set. 2013.

SINSEL, S. R.; RIEMKE, R. L.; HOFFMANN, V. H. Challenges and solution technologies for the integration of variable renewable energy sources—a review. **Renewable Energy**, v. 145, p. 2271–2285, 2020.

SNOWY HYDRO. **What is the Hunter Power Project?** Disponível em: <https://www.snowyhydro.com.au/hunter-power-project/about-the-hunter-power-project/>. Acesso em: 17 set. 2022.

SOLIANO PEREIRA, O. L. Renewable energy as a tool to assure continuity of a low emission Brazilian electric power sector - Results of an aggressive renewable energy policy. **2009 IEEE Power and Energy Society General Meeting, PES '09**, p. 1–7, 2009.

STEITZ, C. **E.ON and Australia's FFI to explore green hydrogen shipments to Europe**. Disponível em: <https://www.reuters.com/business/sustainable-business/eon-australias-ffi-explore-green-hydrogen-transport-europe-2022-03-29/>. Acesso em: 8 out. 2022.

THE ENERGY MIX. **Germany's Massive Boost for Hydrogen Leaves Out Fossil-Derived 'Blue' Variety**. Disponível em: <https://www.theenergymix.com/2022/01/19/germanys-massive-boost-for-hydrogen-leaves-out-fossil-derived-blue-variety/>. Acesso em: 29 jul. 2022.

THE WIND POWER. **Baixa do Feijão (Brazil) Brazil**. Disponível em: <https://www.thewindpower.net/windfarm_en_23624_baixa-do-feijao.php>.

THELLUFSEN, J. Z. et al. Smart energy cities in a 100% renewable energy context. **Renewable and Sustainable Energy Reviewse**, v. 129, p. 109922, 2020.

TNO. **FARADAY LAB TNO**. Disponível em: <https://www.tno.nl/en/focus-areas/energy-transition/roadmaps/towards-co2-neutral-industry/hydrogen-for-a-sustainable-energy-supply/faraday-lab-optimising-and-scaling-up-electrolysis/>. Acesso em: 23 jul. 2022.

TOUILI, S. et al. Analysis of the yield and production cost of large-scale electrolytic hydrogen from different solar technologies and under several Moroccan climate zones. **International Journal of Hydrogen Energy**, v. 45, n. 51, p. 26785–26799, 2020.

UNFCCC. The Paris Agreement. p. 1–5, 2015.

VAN DE GRAAF, T. et al. The new oil? The geopolitics and international governance of hydrogen. **Energy Research & Social Science**, v. 70, p. 101667, 1 dez. 2020.

VAN DER MEER, J. P.; PEROTTI, R.; DE JONG, F. **HyLAW - National Policy Paper - Netherlands**. Netherlands: [s.n.]. Disponível em: <https://www.hylaw.eu/sites/default/files/2019-03/HyLAW_National%20Policy%20Paper_Netherlands.pdf>. Acesso em: 2 jul. 2022.

VAN RENSSEN, S. The hydrogen solution? **Nature Climate Change**, v. 10, p. 799–801, 2020.

VIANA, A. G.; RAMOS, D. S. **Outcomes from the first large-scale solar PV auction in Brazil**. **Renewable and Sustainable Energy Reviews**Elsevier Ltd, , 1 ago. 2018. . Acesso em: 9 mar. 2021

VON BURCHARD, F. **Hydrogen Law and Regulation in Germany**. Disponível em: <https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/germany>. Acesso em: 21 jul. 2022.

WANG, D. et al. Quantifying the flexibility of hydrogen production systems to support large-scale renewable energy integration. **Journal of Power Sources**, v. 399, p. 383–391, 30 set. 2018.

WANG-HELMREICH, H.; LOCHNER, S. The potential of natural gas as a bridging technology in low-emission road transportation in Germany. **Thermal Science**, v. 16, n. 3, p. 729–746, 2012.

XIANG, H. et al. Integration and economic viability of fueling the future with green hydrogen: An integration of its determinants from renewable economics. **International Journal of Hydrogen Energy**, v. 46, n. 77, p. 38145–38162, 2021.

YU, D. et al. Risk-averse stochastic operation of a power system integrated with hydrogen storage system and wind generation in the presence of demand response program. **International Journal of Hydrogen Energy**, v. 44, n. 59, p. 31204–31215, 29 nov. 2019.

YUSAF, T. et al. Hydrogen Energy Demand Growth Prediction and Assessment (2021-2050) Using a System Thinking and System Dynamics Approach. 2022.

ZHANG, G.; WAN, X. A wind-hydrogen energy storage system model for massive wind energy curtailment. **International Journal of Hydrogen Energy**, v. 39, n. 3, p. 1243–1252, jan. 2014a.

ZHANG, G.; WAN, X. A wind-hydrogen energy storage system model for massive wind energy curtailment. **International Journal of Hydrogen Energy**, v. 39, n. 3, p. 1243–1252, 16 jan. 2014b.

ZHAO, G. et al. Life cycle cost analysis: A case study of hydrogen energy application on the Orkney Islands. **International Journal of Hydrogen Energy**, v. 44, n. 19, p. 9517–9528, 12 abr. 2019.

ZOULIAS, E. I.; LYMBEROPOULOS, N. Techno-economic analysis of the integration of hydrogen energy technologies in renewable energy-based stand-alone power systems. **Renewable Energy**, v. 32, n. 4, p. 680–696, 1 abr. 2007.

6. APPENDIX I

PUBLISHED SCIENTIFIC ARTICLES

- MACEDO, S. F.; PEYERL, D. Prospects and Economic Feasibility Analysis of Wind and Solar Photovoltaic Hybrid Systems for Hydrogen Production and Storage: A Case Study of the Brazilian Electric Power Sector. **International Journal of Hydrogen Energy**, v. 47, 10 Feb. 2022. https://doi.org/10.1016/j.ijhydene.2022.01.133

- PEYERL, D.; CACHOLA, C. S.; ALVES, V. H.; MONDAGRON, M.; MACEDO, S. F.; GUICHET, X.; MOUTINHO DOS SANTOS, E. Applying Small-Scale Liquefied Natural Gas Supply Chain by Fluvial Transport in the Isolated Systems: The Case of Amazonas, Brazil. **Energy for Sustainable Development**. V. 68, 7 Apr. 2022. https://doi.org/10.1016/j.esd.2022.03.010

BOOK CHAPTERS (Submitted)

1) MACEDO, S.; PEYERL, D.. Hydrogen: A Brazilian outlook. PEYERL, D.; RELVA, S. G.; SILVA, V. O. da (Org.). Energy Transition in Brazil. Springer. 2023
1) ZACHARIAS, L. G.; MACEDO, S. F.; PEYERL, D.. Bio-hidrogênio para veículos no Brasil: uma análise por meio da perspectiva multinível. PEYERL, D.; MASCARENHAS, K. L.; MOUTINHO DOS SANTOS, E. (Org.). Transição energética, Percepção social e Governança. Synergia.

PAPERS PUBLISHED IN SCIENTIFIC EVENTS

- MACEDO, S. F.; PEYERL, D. Hybrid Energy Systems With Hydrogen Storage Systems: The Brazilian Case Study. **Global Renewable Energy Researchers Meet, 2021, Melborne**

- CIOTTA, M.; PEYERL, D.; MACEDO, S. F.; TASSINARI, C. Hydrogen Storage in Depleted Offshore Oil and Gas Fields in Brazil. **8th Symposium on Hydrogen, Fuel Cells and Advanced Batteries**, 2022, Buenos Aires. Hyceltec