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STRATEGIC DEVELOPMENT PLAN FOR GREEN HYDROGEN AND DERIVATIVES PROJECTS AT THE PORT OF ITAGUAÍ, IN RIO DE JANEIRO

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ABSTRACT

This thesis is dedicated to exploring the development of green hydrogen industrial clusters, with a specific focus on the possible creation of a cluster near the Port of Itaguaí in Brazil. The central objectives of this study cover several critical facets of this venture. Initially, a comprehensive assessment of the green hydrogen market is sought, including a detailed mapping of available opportunities and the identification of potential buyers. The strategic location of Itaguaí and the dynamics of the market are taken into account in this analysis.

In addition, this study outlines a comprehensive model that covers all stages of the development of a green hydrogen cluster, from initial conception to expansion, with a special focus on the need for flexibility and scalability in response to changing market conditions and technological advances. It also highlights the crucial importance of cluster efficiency and proper stakeholder management as pillars for the success and sustainability of these ventures, including strategies to promote collaboration between government entities, private companies, research institutions and local communities.

The research also investigates the essential infrastructure requirements needed to enable the production and distribution of green hydrogen, covering everything from state-of-the-art electrolysis facilities to transportation networks and storage solutions. Finally, it analyzes the possible integration of green hydrogen into the chemical industry and its synergistic alignment with Petrobras' development plans and the renewable energy projects underway in the region.

By addressing these key components, this thesis seeks to provide a comprehensive roadmap for establishing green hydrogen clusters, ultimately contributing to the advancement of sustainable energy practices in Brazil's industrial landscape.

Keywords: Itaguaí Port Complex, Energy Transition, Renewable Energy, Decarbonization and Port Infrastructure.

SUMMARY

1. INTRODUCTION

This study focuses on a strategic exploration of the development potential of green hydrogen and its derivatives in the dynamic context of the Port of Itaguaí, in Rio de Janeiro, Brazil. The Port of Itaguaí, situated along the northern coast of Sepetiba Bay, covers approximately 7.2 million square meters and is located on a strategic logistical axis, approximately 90 kilometers west of Rio de Janeiro (or 60 nautical miles southwest of the Port of Rio de Janeiro, in the case of water transport). This busy maritime hub comprises the organized port of Itaguaí, overseen by Portos Rio, formerly Companhia Docas do Rio de Janeiro (CDRJ), as well as Private Use Terminals (TUPs) authorized by the National Waterway Transport Agency (ANTAQ), which share land and waterway access with the organized port.

The Port of Itaguaí is known for its handling of solid mineral bulk, mainly iron ore from Vale S.A. or destined for Companhia Siderúrgica Nacional (CSN), as well as containers and steel products. The Nuclep TUP, in turn, was built to streamline the flow of products from the Nuclep heavy boiler company. Currently, Porto Sudeste specializes exclusively in handling iron ore, as does TIG, a private terminal operated by Vale S.A. The Ternium Brasil Terminal, on the other hand, mainly handles steel products and coal flows, serving the adjacent production unit.

Efficient transportation and accessibility are the lifeblood of this port complex. This ecosystem is interconnected by an extensive network of highways, including federal highways BR-116, BR-465, BR-101 and BR-493, and state highways RJ-105 and RJ-099. Rail access is facilitated by the MRS Logística S.A. rail concession, which serves the Organized Port of Itaguaí, Porto Sudeste and the TIG TUPs. Waterway access is defined by dedicated channels for each port facility, comprising the access channel to TIG, the access channel to the Port of Itaguaí, the access channel to Porto Sudeste, the access channel to the Ternium Brasil Terminal and the access channel to the Nuclep TUP.

The importance of the Port Complex goes far beyond its role as a maritime gateway; it is a fulcrum in the broader energy transition scenario. It is strategically positioned between Brazil's largest cities: Rio de Janeiro and São Paulo, and has great potential to be a player in the hydrogen sector, especially given the synergy with Vale's mining operations and Ternium's pioneering decarbonization initiatives (which have already begun at its industrial plants in Mexico).

This study details the potential for hydrogen adoption in the oil refining and fertilizer sectors, with green hydrogen being adopted as the main decarbonization strategy for European industry, with wider applicability in sectors such as steel, metallurgy, ceramics, glass production and cement. It is important to note that, although the main focus of this document is on future green hydrogen projects (produced using renewable energy sources), it is imperative to recognize that, in 2023, a substantial part, approximately 74%, of the hydrogen consumed in Brazilian industry will come from refineries, and will not have a renewable origin. According to the National Confederation of Industry, the predicted growth in hydrogen demand in Brazil will be predominantly driven by the hydrotreatment of oil derivatives and the production of advanced fuels to meet increasingly stringent environmental regulations.

In addition, the development rekindled by the Itaboraí GasLub Hub, originally conceived as the Rio de Janeiro Petrochemical Complex (COMPERJ) by Petrobras, creates potential synergies with a future green hydrogen HUB near the Port of Itaguaí. The GasLub Hub will have a Natural Gas Processing Unit (UPGN) prepared to receive natural gas from the Santos Basin, reinforcing domestic gas supplies and reducing dependence on LNG imports. At the same time, Petrobras is resuming investments in petrochemicals with a renewed focus on the energy transition, including the production of biofuels.

Together with government initiatives to provide tax incentives for gas-intensive projects, such as nitrogen fertilizer projects, these initiatives could come into line with future green hydrogen projects.

In this sense, ammonia production represents a robust market for hydrogen projects. Brazil's strong dependence on imported ammonia, an essential input for nitrogen fertilizers, strategically positions this type of venture near the port. Ammonia is also currently gaining prominence as a marine fuel, thus offering additional opportunities for the Port of Itaguaí. This synergy extends to the possibility of structuring methanol *bunker* facilities, meeting the evolving needs of the maritime sector.

The production of green methanol, in particular, is immensely promising, not only for maritime transportation, but also for domestic industries, given the current dependence on methanol imports, mainly to serve the biodiesel and plastics sectors. To unlock these opportunities, this study presents a comprehensive strategy, driven by a large-scale ethanol plant, to be coupled with a reformer (to produce hydrogen from the ethanol to be produced) and a green methanol production unit in the port's retro area, optimizing its rail and waterway logistics. The high economic viability of this venture could sustain the production of green hydrogen and methanol (by reforming ethanol and capturing the carbon generated by the fermentation activity carried out in the plant itself), creating a model for similar initiatives not only in Brazil, but throughout the world.

This study also carries out an in-depth exploration of the energy sector, highlighting the use of green hydrogen, produced through the electrolysis of water powered by renewable energy sources. Unlike gray hydrogen, which comes from fossil fuels and releases CO2 emissions, green hydrogen represents a sustainable and environmentally friendly energy alternative. Its potential to decarbonize various energy-intensive sectors and, at the same time, mitigate greenhouse gas emissions, positions the use of green hydrogen as a relevant strategy in the transition of global energy systems and also in clean industrial production.

The applications of green hydrogen are wide-ranging, with this molecule serving as an essential component in industrial processes such as oil refining, the production of ammonia, methanol and a whole range of synthetic fuels. Hydrogen could also support energy generation, in a whole new range of technologies applied to turbines, engines, fuel cells and heat pumps. In the field of mobility and logistics, green hydrogen is emerging as a clean and sustainable fuel for air, sea, road and rail transport, with the increasing use of fuel cells in energy and transport solutions.

As the world turns more and more towards decarbonization and renewable energies, the demand for green hydrogen is set to grow in various sectors.

This introduction lays the foundation for a comprehensive exploration of the potential of green hydrogen in the Port of Itaguaí, with impacts for the whole of Brazil, given the ramifications of this proposal for sustainability and the national energy transition.

2. THE ITAGUAÍ PORT COMPLEX IN THE CONTEXT OF THE ENERGY TRANSITION

The Port of Itaguaí is located on the north coast of Sepetiba Bay, in the municipality of Itaguaí, state of Rio de Janeiro, to the south and east of Madeira Island, occupying an area of approximately 7.2 million m². It is approximately 90 km west of the municipality of Rio de Janeiro and about 60 nautical miles southwest of the Port of Rio de Janeiro.

The Itaguaí Port Complex is made up of the organized port of Itaguaí, managed by Portos Rio, formerly Companhia Docas do Rio de Janeiro (CDRJ), and by Private Use Terminals (TUP) that are authorized by the National Waterway Transport Agency (ANTAQ) and share land and waterway access with the organized port.

In all, four Private Use Terminals (TUP) make up the Port Complex:

1. TUP Nuclebrás Equipamentos Pesados S.A. (Nuclep);

2. Southeast Port;
3. Guaíba Island Terminal (TIG); and
4. Terminal Ternium Brasil.

According to the Itaguaí Port Complex Master Plan (Ministry of Infrastructure, 2019), each port facility in operation has the following cargo handling:

- The Port of Itaguaí stands out for its handling of solid mineral bulk, especially iron ore from Vale S.A. and Companhia Siderúrgica Nacional (CSN), as well as containers and steel products;
- The Nuclep TUP was built to optimize the flow of products from the Nuclep heavy boiler company, the industrial plant where the company's equipment and parts are manufactured;
- Porto Sudeste, which currently handles iron ore exclusively;
- TIG, Vale S.A.'s private terminal, which is also dedicated to iron ore operations;
- The Ternium Brasil Terminal mainly handles steel products and coal originating from or destined for the company's production unit, located in the port's back area.

The accesses to the Itaguaí Port Complex include:

1. **Road access:** access to the hinterland of the Itaguaí Port Complex is via federal highways BR-116, BR-465, BR-101 and BR-493, the last of which is known as the Arco Metropolitano, and state highways RJ-105 and RJ-099, through which cargo to and from the Port Complex is transported.
2. **Rail access:** the rail network associated with the Itaguaí Port Complex is made up of the rail concession under the responsibility of MRS Logística S.A. Among the Complex's port facilities, both the Organized Port of Itaguaí and the Porto Sudeste and TIG TUPs have rail dispatch and reception.
3. **Waterway access:** waterway access to each port facility is analyzed based on the following distinction: TIG access channel, Itaguaí Port access channel, Porto Sudeste access channel, Ternium Brasil Terminal access channel and TUP Nuclep access channel.

As for the performance of its primary functions of cargo storage and transhipment, the figure below shows the projected expansion of the port's cargo handling by 2060:

Figure 1 -Projected cargo demand (in thousand tons) at the Itaguaí Port Complex between 2017 (observed) and 2060 (projected).

Natureza de carga	Carga	Tipo de navegação	Sentido	2017 (t)	2020 (t)	2025 (t)	2030 (t)	2035 (t)	2040 (t)	2045 (t)	2050 (t)	2055 (t)	2060 (t)
Granel sólido mineral	Minério de ferro	Longo curso	Embarque	98.871	101.843	110.431	117.281	121.854	124.521	126.257	128.580	131.665	134.284
	Carvão mineral	Longo curso	Desembarque	5.288	5.554	5.688	5.796	5.955	6.155	6.378	6.604	6.830	7.053
	Coque de petróleo	Longo curso	Desembarque	1.108	1.139	1.169	1.196	1.222	1.246	1.268	1.293	1.317	1.339
	Outros minérios, metais e pedras	Longo curso	Desembarque	717	745	823	911	982	1.030	1.064	1.098	1.132	1.165
	Barrilha	Longo curso	Desembarque	45	46	50	55	62	71	83	94	106	118
Carga geral	Produtos siderúrgicos	Longo curso	Embarque	3.707	4.056	4.419	4.896	5.381	5.808	6.220	6.638	7.057	7.476
	Produtos siderúrgicos	Longo curso	Desembarque	117	126	134	143	154	163	172	181	190	198
Contêineres	Contêineres	Longo curso	Desembarque	836	925	1.044	1.152	1.270	1.459	1.695	1.942	2.190	2.437
	Contêineres	Longo curso	Embarque	647	695	776	877	977	1.061	1.144	1.228	1.312	1.396
	Contêineres	Cabotagem	Embarque	774	881	999	1.150	1.315	1.478	1.639	1.798	1.958	2.117
	Contêineres	Cabotagem	Desembarque	549	579	625	689	758	825	889	952	1.015	1.079
Outros				73	77	82	88	94	100	106	112	118	123
Total				112.752	116.623	126.240	134.234	140.024	143.917	146.914	150.520	154.838	158.787

Source: ANTAQ (2017). Elaboration: LabTrans/UFSC (2019)

Located in a strategic position between the country's largest cities (Rio de Janeiro and São Paulo), the activities carried out at the Itaguaí Port Complex are highly connected to the hydrogen industry, especially with regard to Vale's mining activities and the steel production carried out by Ternium, which is already implementing a decarbonization program at its industrial plants in Mexico, as we will detail later.

This study will also detail that the oil refining and fertilizer sectors have the potential to use hydrogen immediately to implement their decarbonization strategies. In the medium term (the next five years), the steel, metallurgy, ceramics, glass and cement industries are also potential consumers of hydrogen in the country.

Although the focus of this paper is to detail routes for making hydrogen projects feasible at the port, with a focus on hydrogen produced from renewable energy sources, we should clarify that today (2023) around 74% of the hydrogen consumed in Brazilian industry comes from refineries, and is therefore not hydrogen produced from renewable sources.

According to the National Confederation of Industry (in "Sustainable hydrogen: perspectives and potential for Brazilian industry", 2022), the growth in demand for hydrogen in Brazil will come **primarily for the hydrotreatment of oil derivatives** and the production of advanced fuels to meet increasingly demanding environmental regulations, while the growth in the application of hydrogen in vegetable oils as a raw material in refining also stands out.

Still on the subject of the petrochemical sector, the Rio de Janeiro Petrochemical Complex (COMPERJ) was a project designed by Petrobras to be set up in the municipality of Itaboraí, in the state of Rio de Janeiro, in a region that is part of the Itaguaí port hinterland.

The project was modified and is now called the Itaboraí GasLub Hub, where a Natural Gas Processing Unit (UPGN) is being built to receive natural gas from the Santos Basin via the Rota 3 pipeline. When completed, the unit will have the capacity to process 21 million cubic meters of pre-salt gas daily.

The Gaslub Hub, which is currently under construction, will house the Natural Gas Processing Unit (UPGN), which will receive gas from the Santos Basin's pre-salt polygon via a 355-kilometer gas pipeline ("Route 3"). The unit will have the capacity to transport and process an additional 21 million cubic meters of natural gas per day, increasing the supply of gas to the Brazilian market and reducing dependence on LNG imports.

Work was halted in June 2022 by the company contracted to carry out the project. In March 2023, Petrobras signed a contract with Toyo Setal Empreendimentos to complete the work on the Natural Gas Processing Unit (UPGN), with completion scheduled for 2024.

In December 2022, Petrobras approved the engineering project for the fuel and lubricant production units at the Gaslub Hub, integrated with the Reduc refinery in Duque de Caxias (RJ). The feasibility of building a thermoelectric plant is also being analyzed. The company also announced the resumption of investments in petrochemicals, now also with a focus on the energy transition. It intends to invest again in refining, but this time for the production of biofuels, especially green diesel.

The Rio de Janeiro government, for its part, is studying reducing the ICMS tax rate for gas-intensive industries interested in setting up in Gaslub, with a view to attracting fertilizer projects and small-scale natural gas distribution to the hub, for example.

So both the planning of new advanced fuels projects by Petrobras and the resumption of COMPERJ (now the "Gaslub Hub") could create synergy with the development of a green hydrogen hub near the Port of Itaguaí.

Ammonia production is the second potential market for the development of hydrogen projects. As is well known, ammonia is the basic input in the production of nitrogen fertilizers, and this is a strategic market for the country, given the high scale of imports of this input, especially for grain production.

However, as the price of Brazilian natural gas - used as an input in hydrogen production - is historically high compared to international prices, agribusiness currently imports the equivalent of 85% of the volumes of nitrogen fertilizers it uses.

Ammonia is also emerging as a fuel for the energy transition in maritime transport, and this could be another opportunity for the port. In this regard, *Yara International and Azane Fuel*

Solutions recently signed a commercial agreement to establish a network of green ammonia-based ship fuel *bunkers* in Scandinavia by 2024. This comes at the same time as *Maersk, Keppel Offshore & Marine and Sumitomo Corporation* are studying the feasibility of using green ammonia to establish a supply chain with the Port of Singapore in Asia, among other ports.

Similarly, the opportunity to develop an ammonia and methanol bunker to service vessels are opportunities to be considered for the development of a fuel *bunker* near the port of Itaguaí.

In fact, the production of green methanol would open up a number of potential business opportunities at the port, not only for shipping companies but also for the domestic industry, which currently imports practically 100% of the methanol it uses, mainly to supply the biodiesel and plastics industries.

In view of the above, as will be detailed in this study, **the production of green hydrogen to supply domestic industry, the production of ammonia to supply agribusiness and the production of methanol are great opportunities for the Port of Itaguaí** and for Brazilian ports in general.

We will also present a strategy for generating immediate economic viability for the production of renewable hydrogen and green methanol near the port, by structuring a large-scale ethanol plant in its retro area, optimizing its rail and waterway logistics flows.

The high rates of return generated by this type of private venture could fund both the production of green hydrogen (via ethanol reforming, not electrolysis) and green methanol, from the carbon capture generated by the corn fermentation activity carried out in the plant itself, without the need for government subsidies in this business model.

Therefore, as it is an autonomous, self-financed venture to be run on a private basis, a pilot project of this type could later serve as a business model for renewable hydrogen production elsewhere in the world.

3. THE HYDROGEN INDUSTRY

Green hydrogen, also known as renewable hydrogen, is a key molecule for the future of energy systems and industrial development. It is produced through the electrolysis of water using electricity from renewable sources (solar, wind, hydro, etc.).

Unlike gray hydrogen, which is produced from fossil fuels (emitting CO2), green hydrogen is a clean and sustainable alternative energy source for industry. It has the potential to decarbonize the energy-intensive industrial sector and contribute to reducing greenhouse gas emissions. Green hydrogen can be used as a chemical feedstock, fuel and energy source in various industries, including steel production, transportation and heating applications. With the increasing focus on decarbonization and the advancement of renewable energy technologies, the demand for green hydrogen is expected to grow significantly in the coming decades.

Green hydrogen has a wide range of applications in various sectors. The main uses of green hydrogen today are:

- **Industrial processes:** Green hydrogen can be used in industrial processes such as oil refining, ammonia and methanol production. It can also be used in steel production, glass manufacturing and the production of bricks and building materials.
- **Power generation:** Green hydrogen can be used as a non-carbon emitting source of electricity. It can be converted into other green fuels, such as methanol, methane and ammonia, which can be used to generate energy in gas turbines, engines, fuel cells and heat pumps (after green ammonia *cracking* activities, for example).
- **Mobility and Transport:** Green hydrogen can be used as a fuel for transportation, including aviation and maritime, road and rail transport. It can be used in fuel cells to power vehicles and provide clean and sustainable mobility solutions.

The first step to be taken before defining an exploitation model or specific project to develop a green hydrogen *cluster* near the port of Itaguaí is to map *out* opportunities in the sector, especially in terms of the existence of potential buyers (*offtakers*) for the future hydrogen to be produced, thus allowing the scale of the new venture to be estimated, products to be developed, designing a market access strategy, attracting investors or financing lines (in other words, structuring the *funding for* the venture, according to its attractiveness demonstrated by the estimated rate of return), as well as defining technical details such as the technological standard to be adopted, defining the *EPC contractor*, the scale of the project, logistics to be used, etc.

As for mapping opportunities, according to a survey carried out by the German-Brazilian Chamber of Industry and Commerce of Rio de Janeiro (AHK Rio de Janeiro), the table below shows the existing (E) and potential (P) markets for hydrogen consumption in Brazil:

Figure 2 - Brazilian hydrogen market (see Mapping the Brazilian Hydrogen Sector, AHK Rio 2021)

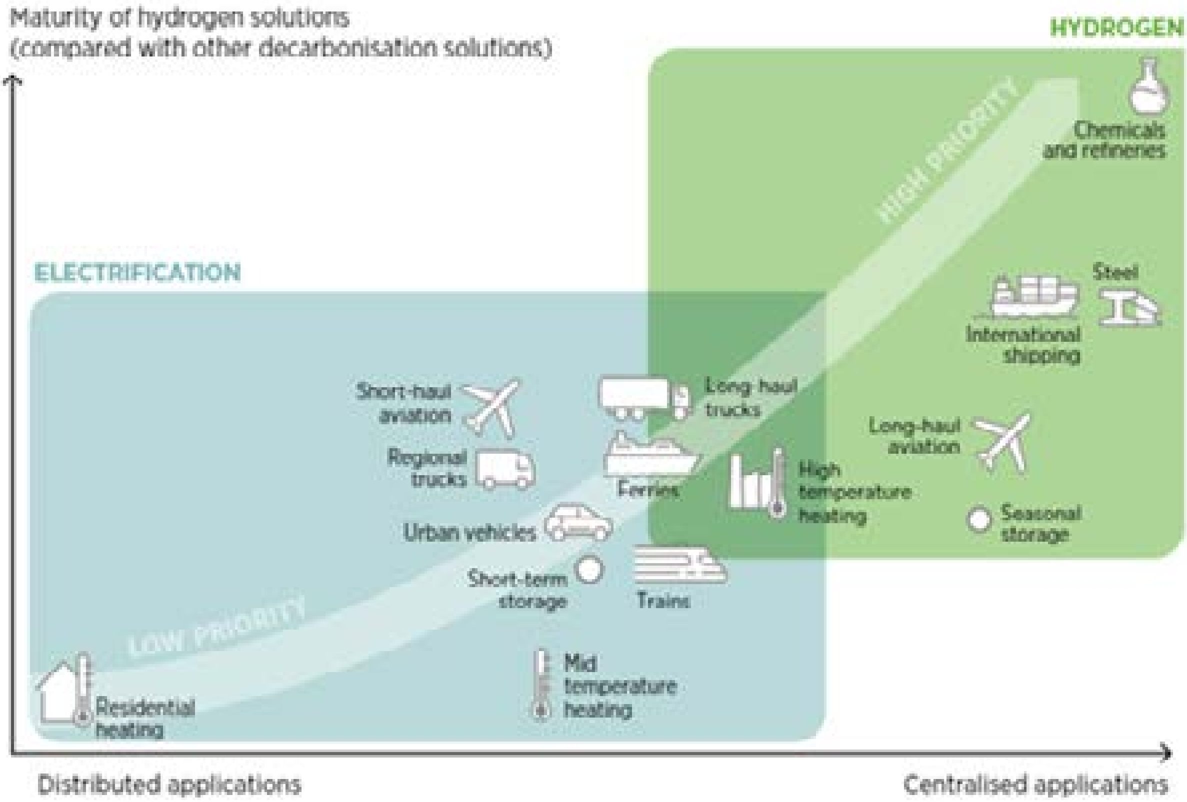
	Empresa	Setor	(E)xistente / (P)otencial	Site
1	Crista Margarina	Alimentação	E	http://cristamargarina.com.br
2	BRF	Alimentação	E	https://www.brf-global.com
3	Cimento ITAMBE	Cimento	P	www.cimentoitambe.com.br
4	Ciplan	Cimento	P	www.ciplan.com.br
5	Crh	Cimento	P	www.crhbrazil.com
6	Intercement	Cimento	P	www.intercement.com
7	Lafargeholcim	Cimento	P	www.lafargeholcim.com
8	Mizu	Cimento	P	www.mizu.com.br
9	Tupi	Cimento	P	www.cimentotupi.com.br
10	Votorantim	Cimento	P	www.votorantimcimentos.com.br
11	Eletronuclear	Energia	E	https://www.eletronuclear.gov.br
12	Bahiagás	Energia	P	http://www.bahiagas.com.br
13	Cegás	Energia	P	http://www.cegas.com.br
14	Sheligas	Energia	P	http://www.sheligas.com.br
15	Naturgy	Energia	P	https://www.naturgy.com.br
16	Comgas	Energia	P	https://www.comgas.com.br
17	Bunge	Fertilizante	P	http://www.bunge.com.br
18	Cmoc Brasil Mineração, Indústria e Participações Ltda	Fertilizante	P	https://cmocbrasil.com/br
19	Vale Fertilizante	Fertilizante	P	http://www.vale.com/brasil
20	Heringer	Fertilizante	P	http://www.heringer.com.br
21	Iharabrás	Fertilizante	P	http://www.ihara.com.br
22	Mosaic Fertilizantes	Fertilizante	P	http://www.mosaicco.com.br
23	Fertipar	Fertilizante	P	https://www.fertipar.com.br
24	Yara Brasil	Fertilizante	P	https://www.yarabrasil.com.br
25	Galvani	Fertilizante	P	http://www.galvani.ind.br
26	Anglo American	Mineração	P	https://brasil.angloamerican.com
27	Mitsui & Co	Mineração	P	https://www.mitsui.com/br/pt
28	Vale	Mineração	P	www.vale.com
29	Braskem	Químico	E	https://www.braskem.com.br
30	Clariant	Químico	E	https://www.clariant.com/pt/Company
31	Oxiteno	Químico	E	http://www.oxiteno.com
32	Evonik Brasil Ltda.	Químico	E	https://central-south-america.evonik.com/pt
33	LANXESS	Químico	E	http://lanxess.com.br/pt/home
34	CSN	Siderurgia	E	www.csn.com.br
35	ArcelorMittal	Siderurgia	E	https://brasil.arcelormittal.com
36	Gerdau	Siderurgia	E	www.gerdau.com.br
37	Ternium	Siderurgia	E	https://br.ternium.com/pt
38	Nicrosol	Siderurgia	E	http://www.nicrosol.com.br
39	CMA CGM	Transporte	P	https://www.cma-cgm.com/local/brasil

Source: Green Hydrogen for Industry.

4. THE INTERNATIONAL EXPERIENCE: UNIDO'S GLOBAL HYDROGEN PROGRAM

UNIDO, the United Nations Industrial Development Organization, has launched its Global Programme for Hydrogen in Industry (GPHI) to support developing countries in their transition to a just and sustainable hydrogen economy. The program aims to influence and guide the development of market policies, standards, financing instruments and coordination between key stakeholders. It also promotes tangible projects to accelerate the adoption of green hydrogen in industries in developing countries and economies undergoing energy transition.

Figure 3 - Priority of green hydrogen policies



Source: IRENA (2020).

UNIDO has developed a model for green hydrogen industrial clusters (GHIC). These clusters are defined as industrial regions or clusters that share green hydrogen and renewable energy electricity for various purposes, such as materials production, heating and cooling, local mobility and industrial feedstock.

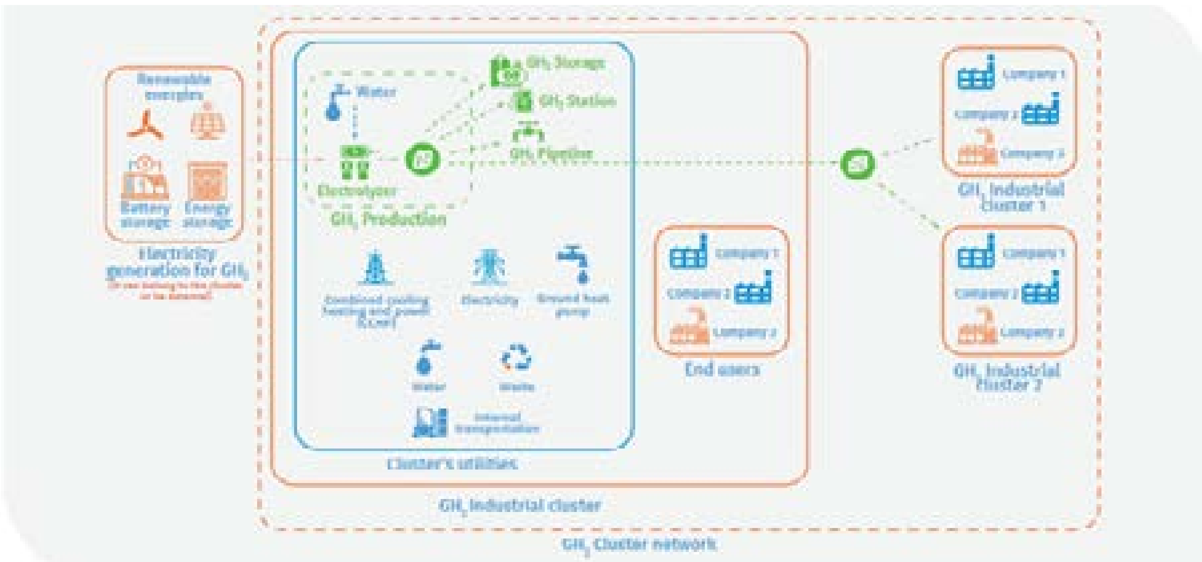
The model aims to accelerate the application of locally produced green hydrogen in industrial zones, clusters and parks. It provides guidance for governments and industries in the preparation, implementation and expansion of green hydrogen industrial clusters. The model consists of three phases: preparation, development of pilot projects and expansion of green hydrogen production within the cluster.

Table 1 - Phases of the model for green hydrogen industrial clusters (GHIC)

PHASES	ACTIVITIES
Phase 1: Preparation of Green Hydrogen Clusters	• Awareness; • Stakeholder involvement; • Preparation of the objective, strategy and work plan for a green hydrogen cluster; • Feasibility studies; • Financial mobilization.
Phase 2: Deployment of Green Hydrogen technologies	• Commissioning pilot projects; • Production, process adaptation and use of green hydrogen in industrial processes; • Testing pilot projects; • Commercial operation.
Phase 3: Scaling up the use of Green Hydrogen in industry	• Fundraising programs and challenges; • Development of green hydrogen networks.

Source: UNIDO (2023).

Figure 4 - General outline of a green hydrogen industrial cluster



Source: UNIDO (2023).

5. CHARACTERISTICS OF GREEN HYDROGEN INDUSTRIAL CLUSTERS

Green hydrogen industrial clusters can be categorized into two types: *greenfield sites and brownfield sites.*

Greenfield Sites: *Greenfield sites* refer to new production clusters that are built from scratch. These clusters are developed in areas where there is potential for renewable energy sources and the production of green hydrogen. *Greenfield sites* offer the opportunity to establish new industrial clusters that can contribute to sustainable projects, create jobs and boost renewable energy developments.

Brownfield Sites: *Brownfield sites*, on the other hand, involve the transformation of existing industrial clusters using green hydrogen. These clusters use and adapt existing infrastructure to produce and supply green hydrogen. *Brownfield* projects are particularly beneficial for energy-intensive industries, such as steel and ammonia production, as green hydrogen can help decarbonize their processes.

Greenfield and brownfield projects have the potential to contribute to the growth of the green hydrogen industry and support the transition to a more sustainable, low-carbon economy.

5.1 Availability of renewable sources of electricity

The availability of renewable electricity is crucial for a green hydrogen industrial cluster. The abundance and accessibility of renewable energy sources such as hydroelectric, wind and solar power is recommended. A combination of these sources can ensure stability of supply. Direct connection between Power-to-X (PtX) installations and renewable energy sources is also encouraged.

The proximity of renewable energy sources to the industrial cluster is preferred to avoid efficiency losses and allow for documentation of origin. Ideally, renewable energy should be directly connected to the industrial cluster and vertically integrated into the cluster to increase delivery efficiency and economic viability.

5.2 Location and access to utilities and auxiliary installations

To ensure the successful production and use of green hydrogen, certain infrastructure requirements need to be met, including:

Internal electricity distribution: The cluster must have a well-established electricity distribution system, including energy storage and transformer stations, if directly connected to renewable energy sources.

Heat production, distribution and storage: The infrastructure for heat management is crucial, including systems for heat production, distribution and storage at high and low temperatures.

Process water and wastewater treatment: Adequate facilities for the treatment and distribution of process water and wastewater management are needed to support the production of green hydrogen.

Carbon capture and utilization (CCU): The infrastructure for capturing, supplying, transporting and distributing CO2 is essential for carbon capture and utilization processes in the production of green hydrogen.

Distribution areas, storage and hydrogen tanks: The cluster must have a well-developed infrastructure for distributing, storing and managing the use of hydrogen or other gases used in industrial processes.

Infrastructure for storing and transporting oxygen: If oxygen is used in other processes or sold to other companies, the cluster must have the necessary infrastructure for its storage and transportation.

These infrastructure requirements are vital for linking the production and end use of green hydrogen within the industrial cluster. They ensure the efficient and effective use of resources and support the overall sustainability of the cluster.

5.3 Composition, scale and synergies

Utilizing synergies in energy-intensive industrial environments can help reduce the costs of green hydrogen production and make the price of green hydrogen and other fuels competitive. These synergies can be achieved by taking advantage of existing industrial parks with high energy demands or excess energy, optimizing existing energy infrastructure, such as combined heat and power plants, in circular economy arrangements.

Converting or integrating these enterprises into green hydrogen industrial clusters can be a strategic measure, especially for entities that currently rely on hydrogen or fossil-based energy for their activities. In the case of GreenLab, this infrastructure is part of the "*Facility as a Service*" concept, which reduces capital and operating expenses for industrial groups with this profile. Effective customer and *stakeholder* management is crucial to the success of these ventures and must be prioritized.

5.4 Case study: GreenLab Skive (Greenfield site)

GreenLab Skive is located in a rural area of Denmark. The location is ideal for testing energy conversion and system integration, as it is close to the national 150 kV electricity grid and the 40 bar gas pipeline that serves the region. A 60-hectare industry is being built in this area as a greenfield project, integrating carefully selected companies with the aim of contributing to the green transition.

The GreenLab model seeks to convert natural resources into value chains - internally, using energy flows (thanks to the co-location of enterprises with hydrogen production and consumption), and externally, through the production of green fuels, allowing the decarbonization of different sectors through different routes.

Figure 5 - Overview of the GreenLab Skive Industrial Cluster

Source: UNIDO (2023).

The GreenLab Skive Industrial Cluster is made up of:

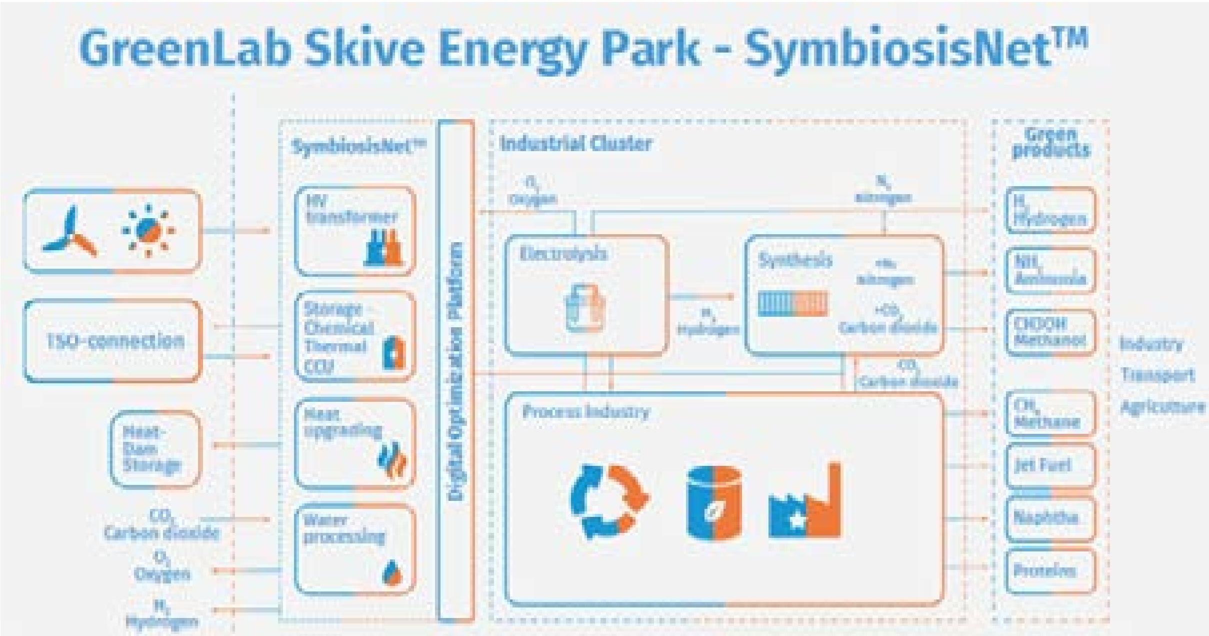
- A renewable energy supplier that provides 80 MW of wind and solar energy, with these sources connected directly.
- A large plant that produces biogas/biomethane from manure and waste from different

production units.

- Two pyrolysis process companies that use green hydrogen.
- Synthesis gas from end-of-life plastics and other agricultural biological waste products to produce biocarbon.
- A company that produces protein-rich feed obtained from local sources of marine waste.
- A municipal waste treatment plant.
- A mill that produces high-density paper and cardboard without glues or chip resins.
- Two pioneering green hydrogen and Power-to-X projects will start operating in the next few years with an electrolyzer capacity of 112 MW; the potential electrolyzer capacity could reach 400 MW with more projects in the pipeline.

GreenLab sets up and manages the cluster infrastructure and utilities for its customers through SymbiosisNet™.

Figure 6 - GreenLab Skive Energy Park diagram



Source: UNIDO (2023).

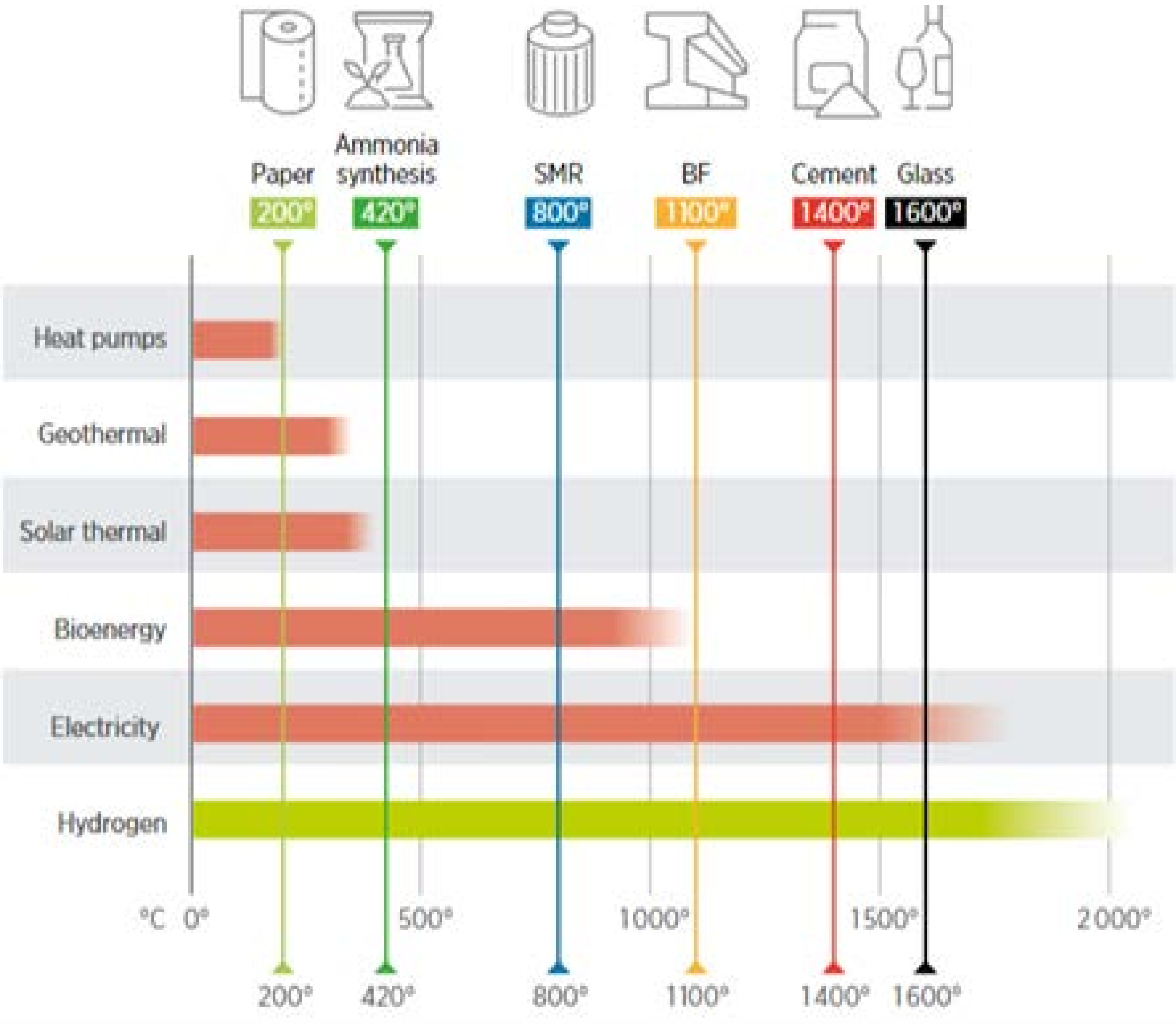
6. OVERVIEW OF THE USES OF GREEN HYDROGEN

Green hydrogen can be used in a variety of applications, replacing gray hydrogen and even natural gas. It has the potential to be used in industries such as chemistry, energy, mobility and transportation.

Current uses for hydrogen include refining, ammonia and methanol production, and it could be used in steel production, transportation and heat generation in the future. Research is underway to explore the use of hydrogen in other sectors, such as glassmaking, brick production and building materials.

The main applications for hydrogen are in industrial production, as some processes cannot be electrified directly with current technologies. Therefore, industrial clusters can move to areas with abundant renewable resources.

Figure 7 - Working temperatures for selected renewable heat technologies

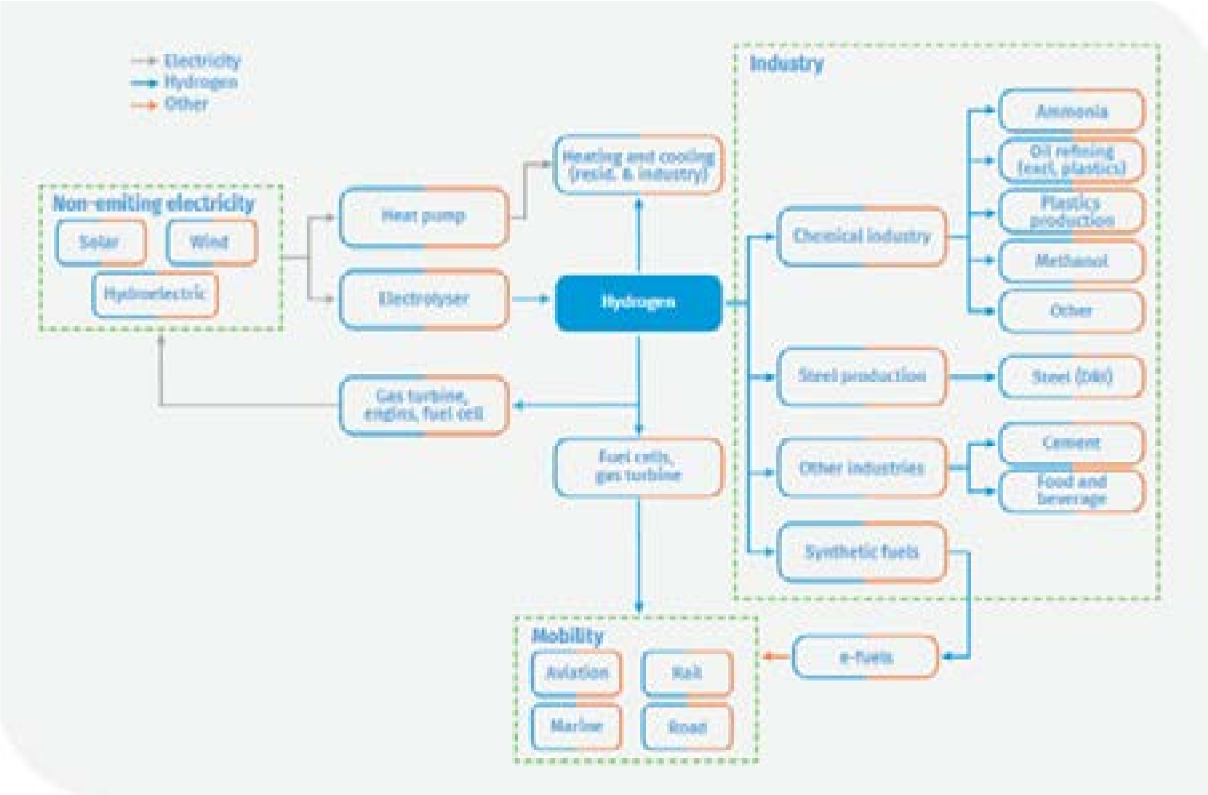


Source: IRENA (2022).

As already mentioned, green hydrogen has a wide range of applications in various sectors. It can be used as a raw material for the production of chemical products, as a source for high-temperature processes and as a fuel for transportation.

In the industrial sector, green hydrogen is already being used in oil refining, ammonia production and methanol production. It also has the potential to be used in steel production, heat generation and other industrial processes. The use of green hydrogen in industry is expected to increase in the future as countries begin to decarbonize their economies and reduce greenhouse gas emissions.

Figure 8 - Overview of possible use cases for green hydrogen



Source: UNIDO (2023).

6.1 Hydrogen in the industrial sector

Hydrogen-based green steel production is considered a key technology for achieving a carbon-neutral steel industry. It is technically feasible and seen as a long-term solution for decarbonizing the steel industry on a large scale .

Primary iron production can take place via two routes: Blast Furnace (BF) (1291 Mt) and Direct Reduced Iron (DRI) (1.8 Mt). In both cases, the iron ore is chemically reduced. This means removing the oxygen, CO2 or water present in the metal. Large amounts of energy are required for this, but more importantly, an energy carrier is needed to chemically react with the oxygen. The BF route uses treated coal (coke) stacked together with the ore in the furnace. It can therefore only use limited amounts of added hydrogen (10-20%), with the coal also fulfilling a structural purpose in the process. This means that the BF route cannot be fully decarbonized with green hydrogen. The DRI route uses a reducing gas (for example, carbon monoxide derived from natural gas to reduce iron ore agglomerates). Green hydrogen can replace these fossil reducing gasses relatively easily.

Hydrogen can be used as a reductant substitute to produce DRI, which can then be turned into steel in an electric arc furnace (EAF). Natural gas is currently used as a reductant in this DRI or EAF route by industries in the Middle East that have access to a cheap supply of natural gas . However, although injecting green hydrogen into blast furnaces can reduce carbon emissions by up to 20%, this does not offer carbon neutral steel production because regular coking coal is still a necessary reducing agent in the blast furnace .

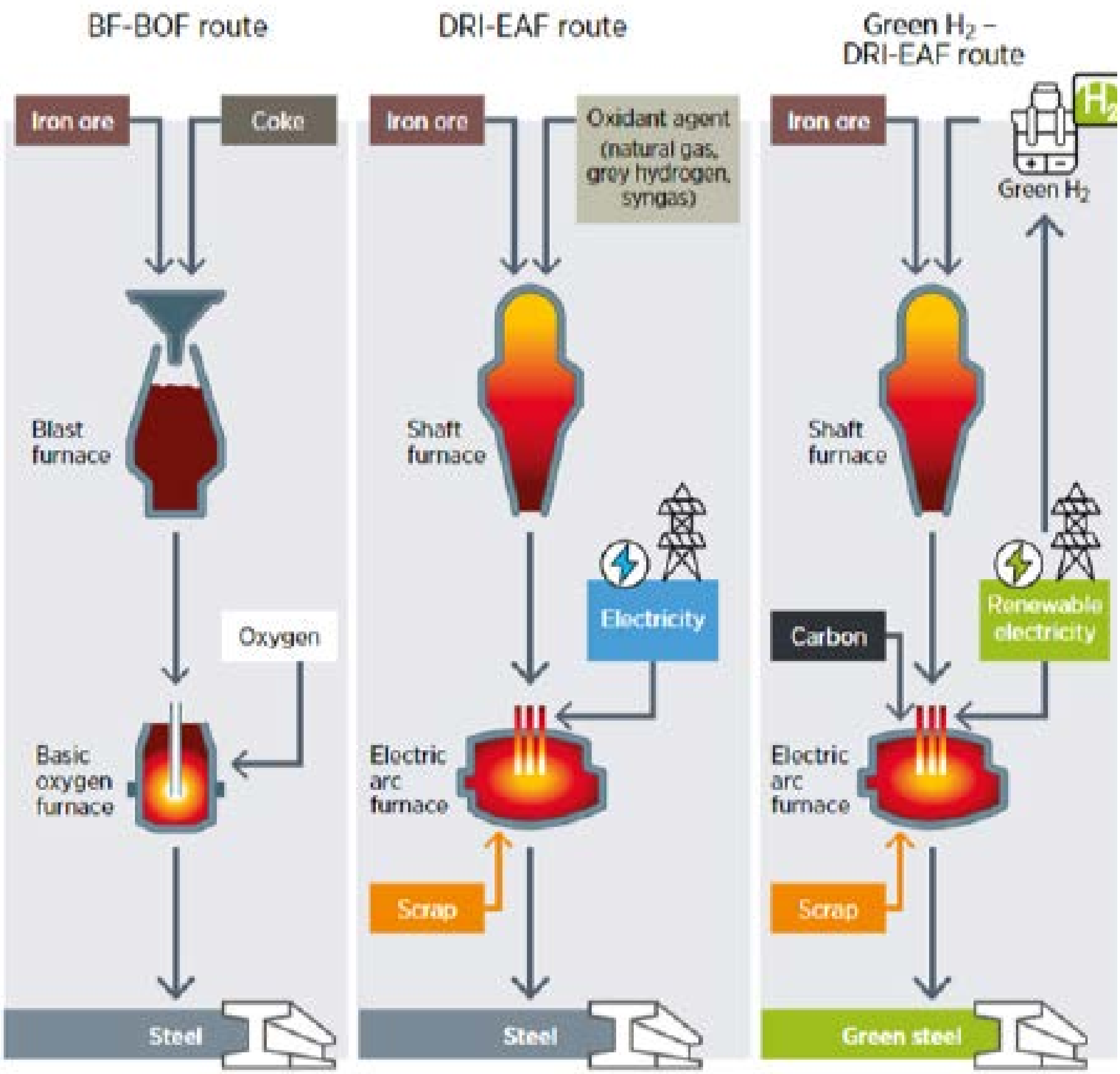
DRI *Smelting Furnace* technology will replace blast furnaces with 80-90% CO2 emissions avoided when green hydrogen and renewable energy are used . This is an ideal solution for the treatment of iron ore in blast furnaces due to the high volume of slag derived from the process.

The steel industry in Europe faces a challenge of decarbonization due to pressure to reduce its carbon footprint. To secure future steel production in Europe, the adoption of hydrogen-based steelmaking is likely to be a key technology. This could involve optimizing BF/BOF processes, switching to EAF using scrap and DRI fueled by natural gas or imported HBI, and finally carbon-neutral EAF production using a hydrogen-based mix of scrap and DRI. The mix of scrap *versus* DRI-based production using EAFs will depend on future product portfolios.

The use of hydrogen in the DRI method will enable the production of high-purity steels without emitting carbon dioxide. The implementation of decarbonization measures, such as the production of hydrogen-based steel, can be done in new and existing facilities, with modernization or complete reconstruction as options. The optimal steps for decarbonization vary depending on factors such as technical feasibility, existing infrastructure, market demands, operating costs and the regulatory environment. Overall, the potential path for steel players in Europe will involve a gradual shift towards decarbonization through the adoption of green hydrogen-based steel production.

This transformation to hydrogen-based steel has its challenges, such as energy supply, security of hydrogen supply, willingness to pay and regulation of the process. The availability of cheap energy from renewable sources and favorable regulations will be crucial factors for the adoption of hydrogen-based steel. The switch to hydrogen-based steel production is expected to take place gradually between 2030 and 2040 in Europe, replacing the current integrated BOF route with DRI and EAF configurations.

Figure 9 - Main steel production routes



Source: IRENA (2022).

6.2 A Case Study: Development of green steel projects: lessons learned from H2 Green Steel (H2GS)

During the summer of 2022, H2GS began preparing the ground for its first project in Boden, Sweden, where it intends to build a large-scale green hydrogen production unit to support an integrated green steel plant.

Production is scheduled to begin in 2025. By 2030, H2GS aims to reach a production capacity of five million tons of high-quality steel. The focus of H2GS's use of green hydrogen will be to reduce iron ore to directly reduced iron (DRI). The use of hydrogen instead of coking coal reduces CO2 emissions from the reduction process by more than 90% compared to the traditional ironmaking process. In the traditional steelmaking process, the reduction of iron ore takes place in a blast furnace by combining the ore with coking coal at high temperatures. This triggers a chemical reaction that separates the oxygen from the iron, forming and emitting large quantities of CO2. In the H2GS production process, green hydrogen is used as a reducing agent, resulting in emissions of water vapor instead of CO2.

The DRI is then fed into the Electric Arc Furnace (EAF), where renewable electricity heats a combination of DRI and steel scrap. During the continuous casting and rolling process, the liquid steel is converted into solid products.

The plant is fully integrated into every reaction in the production chain, limiting the amount of energy used in the processing, storage and handling of materials.

H2GS follows a 5-step process to achieve green steel production :

Stage 1: Giga-scale electrolysis - Using fossil-free electricity to break down water into hydrogen with a focus on producing enough hydrogen to produce 5 million tons of high-quality steel annually by 2030.

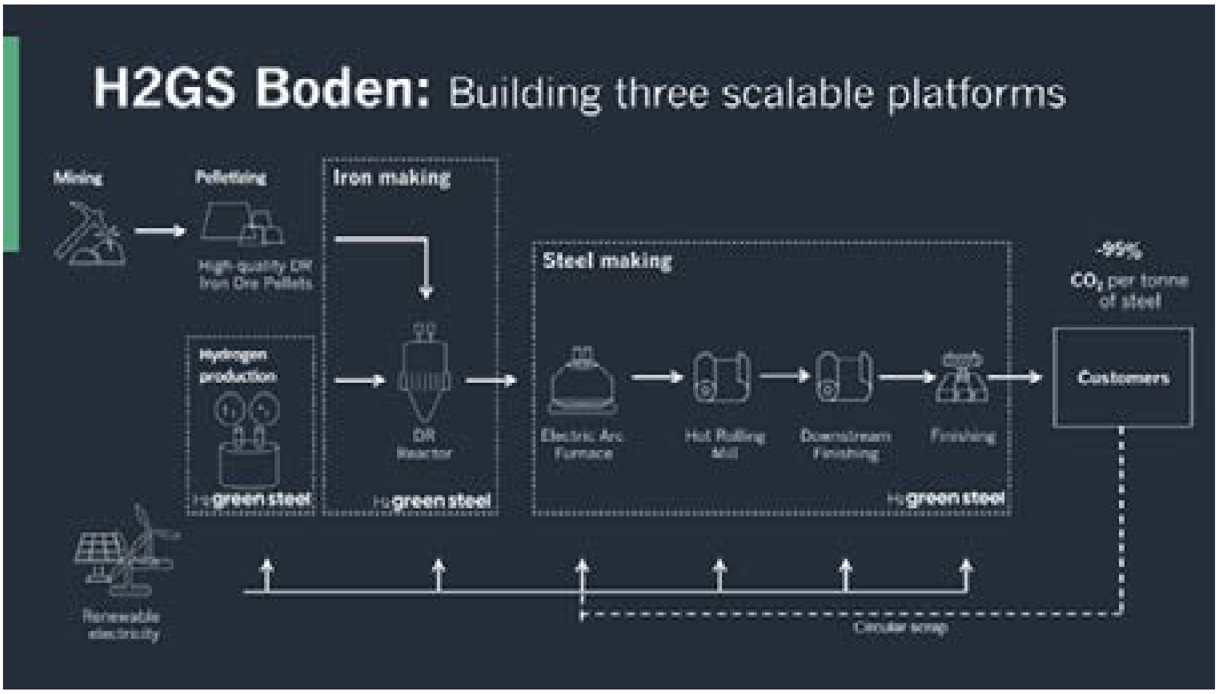
Stage 2: Hydrogen-Based Direct Reduction - Using green hydrogen instead of coal or natural gas to react with oxygen in iron oxide pellets to produce highly metallized direct reduced iron (DRI) for steelmaking with steam as the residue, thus reducing CO2 emissions by more than 95%.

Step 3: Electric arc furnace (EAF) in steelmaking - Using fossil-free electricity to heat DRI and steel scrap to create liquid steel, with the carbon contained in the slag playing an important role in reducing electricity consumption, enabling the transformation of iron into steel.

Stage 4: Continuous Casting and Rolling - Reducing energy consumption by 70% and replacing natural gas in the traditional process.

Stage 5: Downstream finishing lines - Cold rolling, annealing and hot-dip galvanizing processes to adjust the thickness of the steel, creating the desired mechanical properties and protecting against corrosion.

Figure 10 - Overview of steel production using green hydrogen



Source: H2GS Boden

One of the most crucial challenges for decarbonizing hard-to-reduce industries is access to electricity and the related infrastructure. The most electricity-intensive steps in green steel production are hydrogen production and the DRI reactor.

Therefore, the most electricity-intensive part of industrial green steel can be advantageously located in regions with high levels of renewable electricity production, or with the potential to develop even more low-cost renewable energy assets.

Another challenge is the difference in cost and price between traditional steel production and the cost of green steel.

Many customers in the automotive, construction and other sectors are willing to pay a premium for a green product. In order to accelerate and increase the demand for green steel, there are a number of political issues that need to be considered globally:

- A price for greenhouse gas emissions needs to be introduced worldwide.
- Markets with higher prices for GHG emissions can support a border adjustment mechanism to level out costs.
- Pioneer countries can act as facilitators and play an important role in the introduction of an ambitious harmonized standard for net zero carbon steel and its respective premiums.

6.3 Hydrogen in the chemical industry

In the chemical industry, hydrogen is already used as a crucial component in the production of ammonia, methanol and other chemical products. Therefore, integrating green hydrogen into these processes requires minimal modifications.

The only change needed is to switch from obtaining hydrogen by reforming fossil fuels or gasification to electrolysis of water. This means that instead of using fossil fuels, the process would use renewable energy sources to produce hydrogen, making it a more sustainable and environmentally friendly option.

As already mentioned, with regard to **the development of business opportunities for the new hydrogen cluster to be developed near the port in the petrochemical sector, it is important to have access to Petrobras' development plans in the sector, including with regard to the former COMPERJ, currently renamed the Gaslub pole, which could generate synergies with the companies and terminals installed near the Itaguaí Port Complex, especially with regard to the development of the advanced fuels and synthetic fuels market in Brazil.**

Importance should also be given to the potential development of new solar energy projects and *offshore* or *onshore* wind farms in the port's area of influence, which could generate economic viability for new projects near the port.

6.4 Ammonia

Ammonia is produced from hydrogen and nitrogen and is the second most produced chemical commodity globally. In 2020, global ammonia production exceeded 183 Mt. Fertilizer manufacturers are the largest consumers of ammonia, accounting for more than 85% of global production. The agricultural sector is the main consumer of ammonia (Brightling, 2018). For every 1 kg of ammonia, approximately 0.18 kg of hydrogen is required.

In the synthesis of ammonia, the hydrogen used is currently based on fossil fuels, generally using steam methane reforming.

The demand for ammonia is expected to increase due to global population growth, as well as its potential use in international maritime transportation and energy generation.

By 2050, the demand for ammonia is projected to reach almost 600 Mt. Around 55% of this demand could be met with green hydrogen, which is produced by electrolysis of water instead of fossil fuel reforming or gasification (IRENA, 2021b; Saygin and Gielen, 2021).

As already reported, current ammonia production plants normally use hydrogen obtained from steam methane reforming (SMR), which is responsible for 90% of the CO2 emissions associated with ammonia production. To achieve deep decarbonization, ammonia production needs to make the transition to green hydrogen.

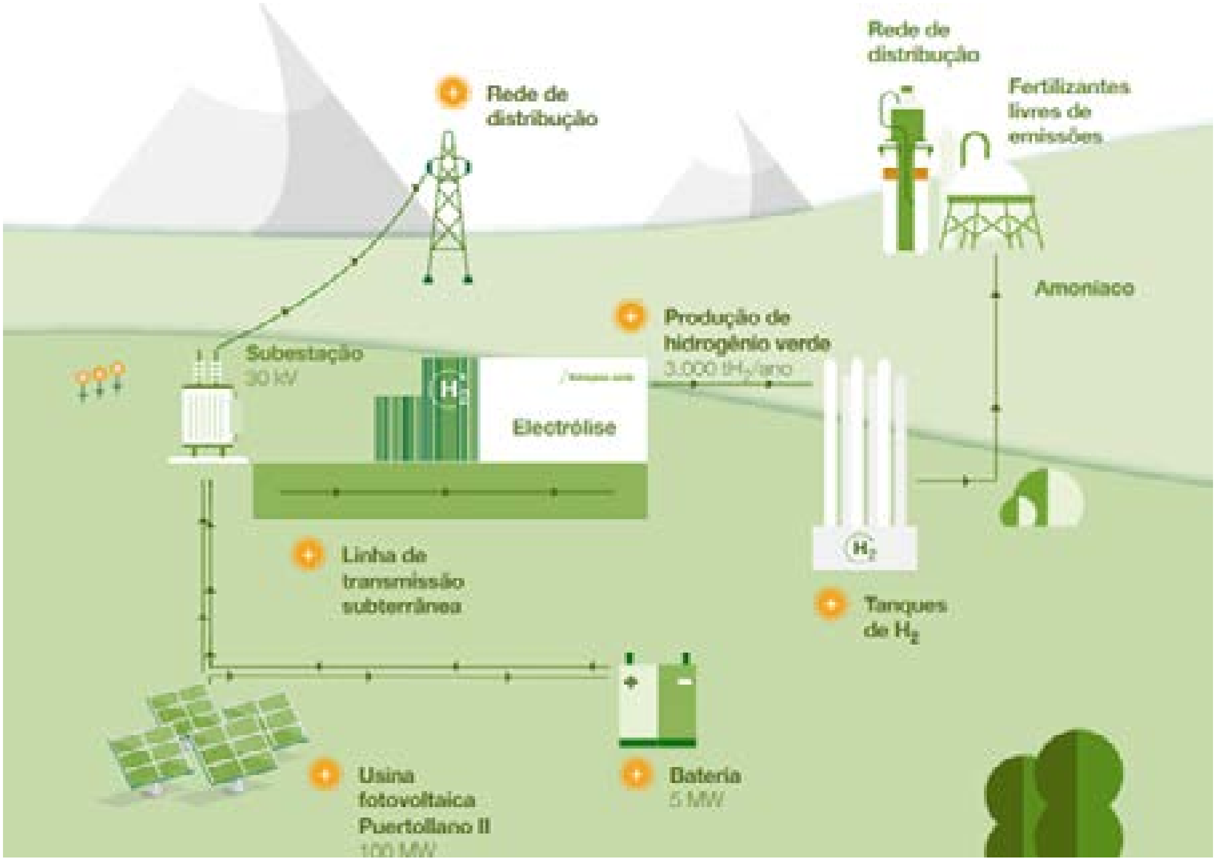
However, it is important to note that renewable energy is also needed to power the other processes required to produce ammonia so that it is truly zero carbon (The Royal Society, 2020).

6.4.1 Green hydrogen and ammonia production projects: lessons learned from the Ammonia Association

The *Ammonia Association* highlights the importance of low-carbon ammonia production in order to decarbonize current markets and meet future demand. There are currently a number of projects under development around the world. One example is the partial decarbonization of Fertiberia's fertilizer plant in Puertollano, Spain, which aims to produce renewable hydrogen and ammonia.

Another significant project is the *ammonia* plant being developed by *Ammonia Energy*, NEOM, Yara and Fertiberia in Saudi Arabia, which plans to produce renewable ammonia using wind and solar energy. These projects demonstrate the potential of using green hydrogen on a large scale to produce green ammonia.

Figure 11 - Green ammonia plant infographic



Source: IBERDROLA.

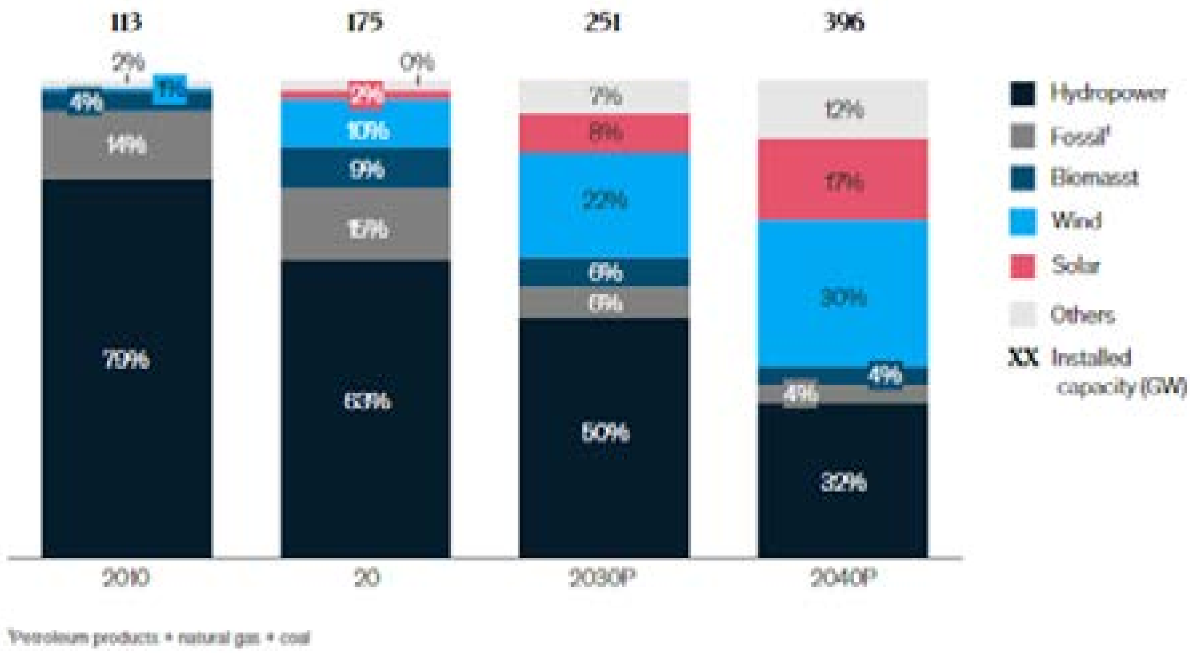
6.4.2 National opportunity in the ammonia market

According to McKinsey, Brazil has the potential to become a global leader in green hydrogen production due to its abundant wind and solar energy resources, integrated low-carbon electricity grid and favorable geographical location for export to Europe and North America. It is estimated that Brazil could generate between US$ 4 and US$ 6 billion from the export of green hydrogen derivatives to the USA and Europe .

According to the consulting agency, the characteristics that qualify Brazil as a possible global leader in the export of green ammonia are:

Abundant renewable energy sources: Brazil has a significant advantage in exporting green ammonia due to its abundance of renewable energy sources, including wind and solar power. With 85% of its energy coming from renewable sources, Brazil can produce green ammonia using clean energy, making it an attractive option for countries looking to reduce their carbon footprint by cracking ammonia for energy production.

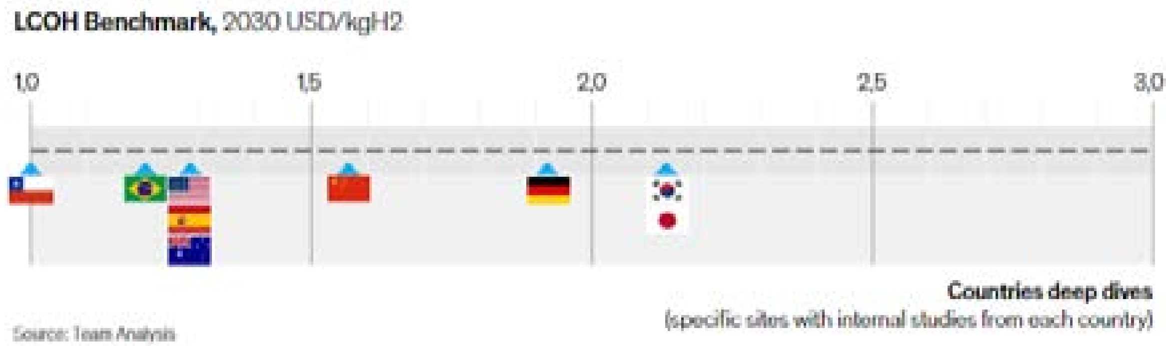
Figure 12 - Brazil's installed electricity capacity by type of source (%)



Source: McKinsey & Company (2021).

Competitive import costs: Import costs for Brazilian green ammonia are expected to be competitive compared to exports from other countries. This cost competitiveness is key to attracting international markets and consolidating Brazil as one of the main exporters of green ammonia.

Figure 13 - Projection of Brazil's competitive advantage in green hydrogen exports in 2030



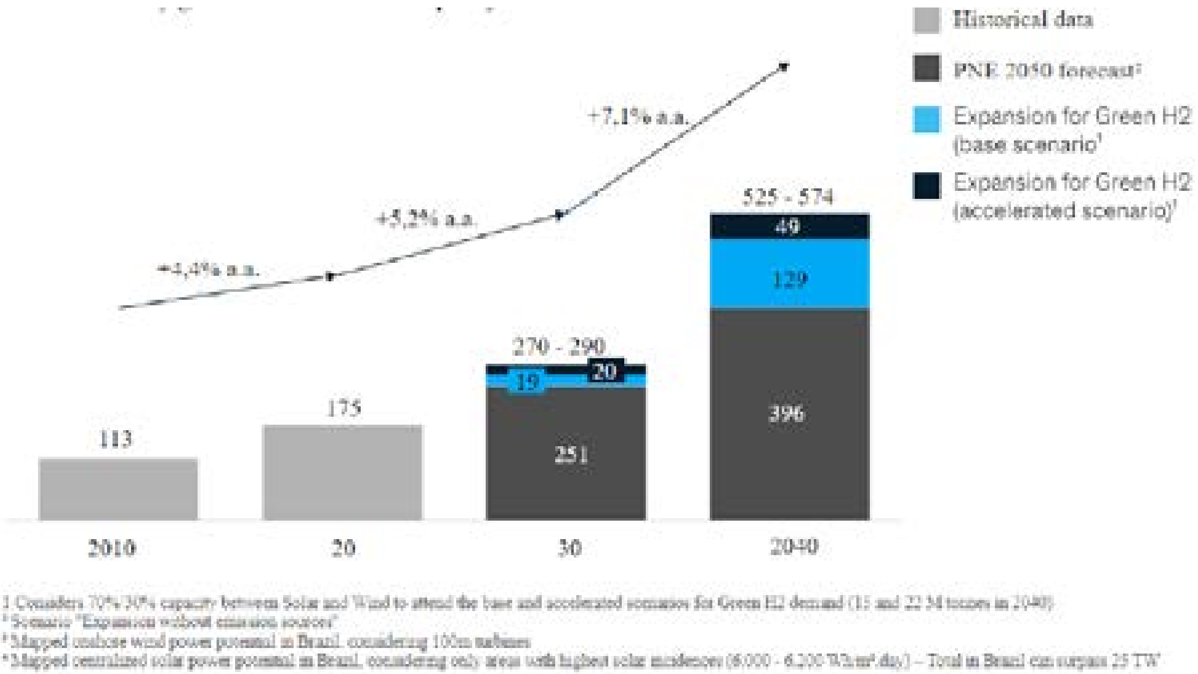
Source: McKinsey & Company (2021).

Geographical advantage: Brazil's geographical location offers an advantage for exporting green ammonia to other countries. With its proximity to Europe and the east coast of North America, Brazil will be able to transport green ammonia efficiently to these major markets, reducing transportation costs and increasing its export potential.

Opportunity for decarbonization: Green ammonia is a low-carbon alternative to grey ammonia, which is traditionally produced from fossil fuels. As countries strive to decarbonize their industries, green ammonia becomes a valuable option for sectors such as fertilizers and chemicals. Brazil's ability to produce green ammonia positions it as a key player in meeting the global demand for sustainable low-carbon solutions.

Investment in Green Hydrogen: To fully unlock the export potential of green ammonia, Brazil needs to invest in the production of green hydrogen. This investment includes additional renewable energy generation, which will further increase Brazil's capacity to produce green ammonia and meet the growing demand from international markets.

Figure 14 - Installed electricity generation capacity in Brazil GW



Source: McKinsey & Company (2021).

6.5 Methanol

Methanol is currently an important component in the chemical industry and is mainly produced from fossil fuels. However, the European market has begun to move towards the consumption of renewable methanol, which can be derived from biomass or synthesized using green hydrogen and carbon dioxide (CO2).

This transition has expanded the use of methanol as a chemical raw material and fuel, while helping to achieve net carbon neutral targets in the industrial and transportation sectors.

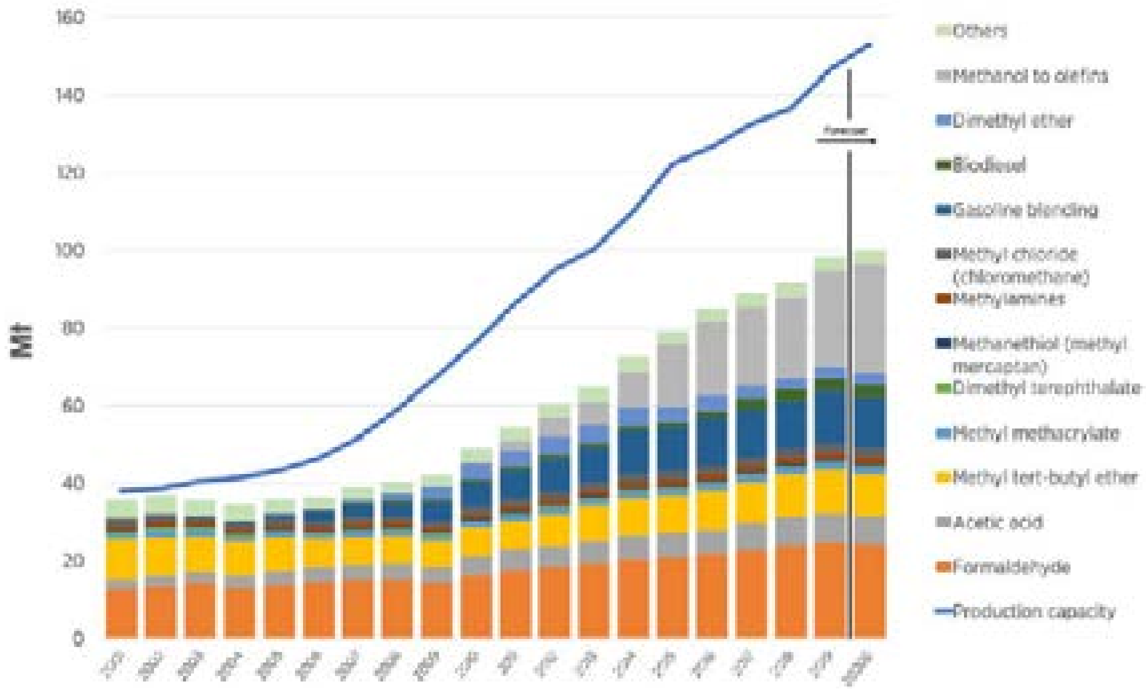
In this sense, although the cost of producing renewable methanol is currently very high and production volumes are low, it is hoped that, with the right policies in place, renewable methanol can become cost-competitive by 2040.

The methanol industry spans the globe, with production in Asia, North and South America, Europe, Africa and the Middle East. Worldwide, more than 90 methanol plants have a combined production capacity of around 110 million metric tons (almost 36.6 billion gallons or 138 billion liters).

In 2021, the global methanol market was valued at more than 37.4 billion US dollars and is projected to reach almost 61.7 billion US dollars by 2030. This industry generates $55 billion in economic activity each year, creating more than 90,000 jobs worldwide .

Life cycle emissions from the current production and use of methanol amount to approximately 0.3 gigatonnes (Gt) of CO2 per year, which represents around 10% of the chemical sector’s total emissions. Methanol production has almost doubled in the last decade, with significant growth observed in China. If current trends continue, production could reach 500 million tons per year by 2050, resulting in the release of 1.5 Gt of CO2 annually, coming exclusively from fossil fuels .

Figure 15 - Global methanol demand and production capacity (2001-2019)



Source: MMSA

6.5.1 Renewable Methanol Production

Methanol is mainly produced from fossil fuels, but it can also be produced from other carbon-containing raw materials such as biomass, biogas, waste streams and CO2 captured from flue gases or through direct air capture (DAC).

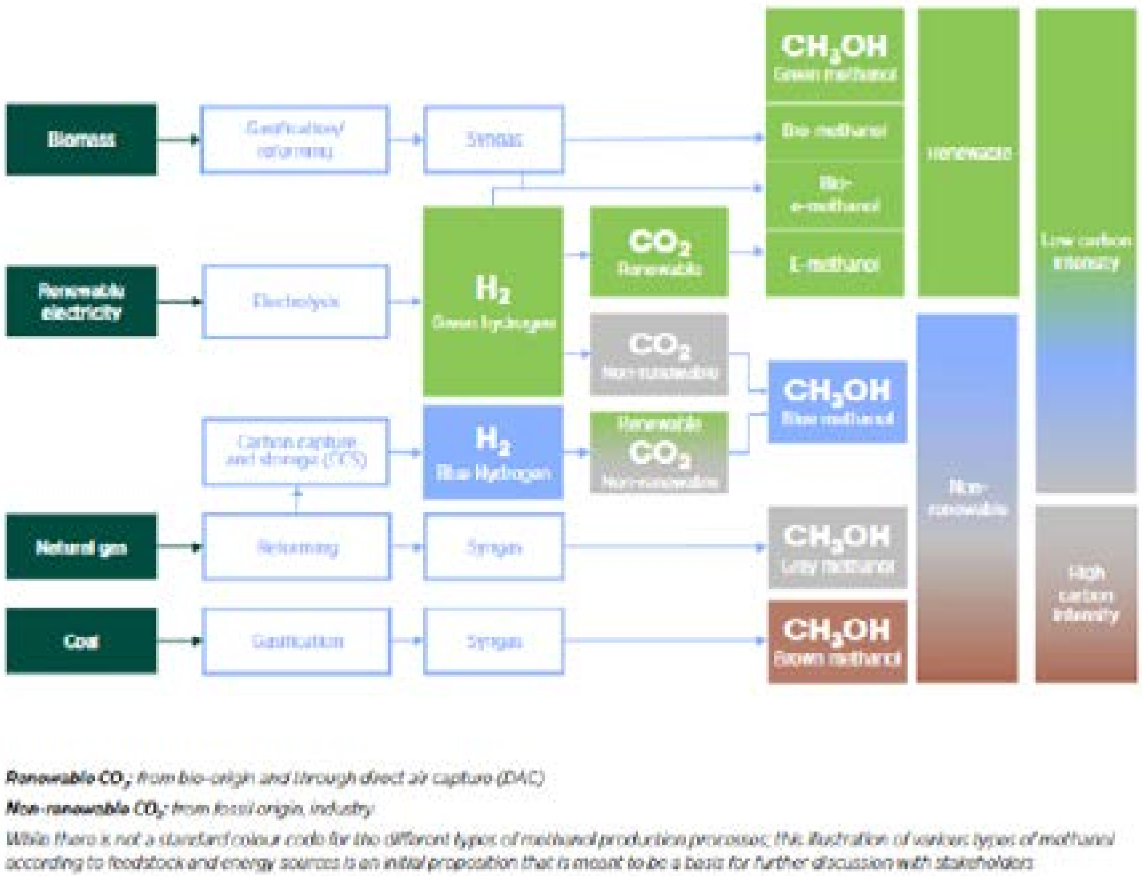
There are two routes to producing renewable methanol:

- **Biomethanol:** produced from sustainable biomass raw materials such as forestry and agricultural waste, landfill biogas, sewage, municipal solid waste (MSW) and black liquor from the pulp and paper industry.
- **Green ethanol:** obtained from CO2 captured from renewable sources (e.g. via BECCS or DAC) and green hydrogen produced with renewable electricity.

To be considered renewable, all the raw materials and energy used in methanol production must come from renewable sources. The methanol produced by these routes is chemically identical to the methanol produced from fossil fuel sources.

Renewable methanol is a sustainable alternative to hydrocarbons and petrochemicals derived from oil. It has the potential to replace these products directly or through methanol derivatives, leading to a market demand of billions of tons of methanol per year. Renewable methanol can be used in the production of plastics, aromatics and other chemicals, supporting the transition to a circular green economy. Although the higher production cost of renewable methanol is currently a barrier, it is considered one of the easiest sustainable alternatives to implement, especially in the chemical and transportation sectors.

Figure 16 - Main methanol production routes



Source: IRENA (2021).

6.5.2 Current progress in the production of renewable methanol

Less than 0.2 Mt of renewable methanol is produced per year worldwide, from just a few production plants. These plants mainly focus on using waste and by-product streams from other industrial processes, such as MSW and low-cost biomass, biogas, waste streams and black liquor from the pulp and paper industry. Some examples of commercial-scale plants include a biomethanol plant in the Netherlands that produces biomethanol from biomethane, a plant in Canada that produces biomethanol from MSW and a plant in Iceland that produces e-methanol by combining renewable hydrogen and CO2 from a geothermal power plant.

These projects benefit from favorable conditions, such as low raw material costs, strong integration with conventional industrial processes or very cheap renewable electricity. There are also other initial or niche opportunities for the production of biomethanol and e-methanol, such as integrated production with sugarcane bioethanol or coalification of biomass feedstock and fossil fuels.

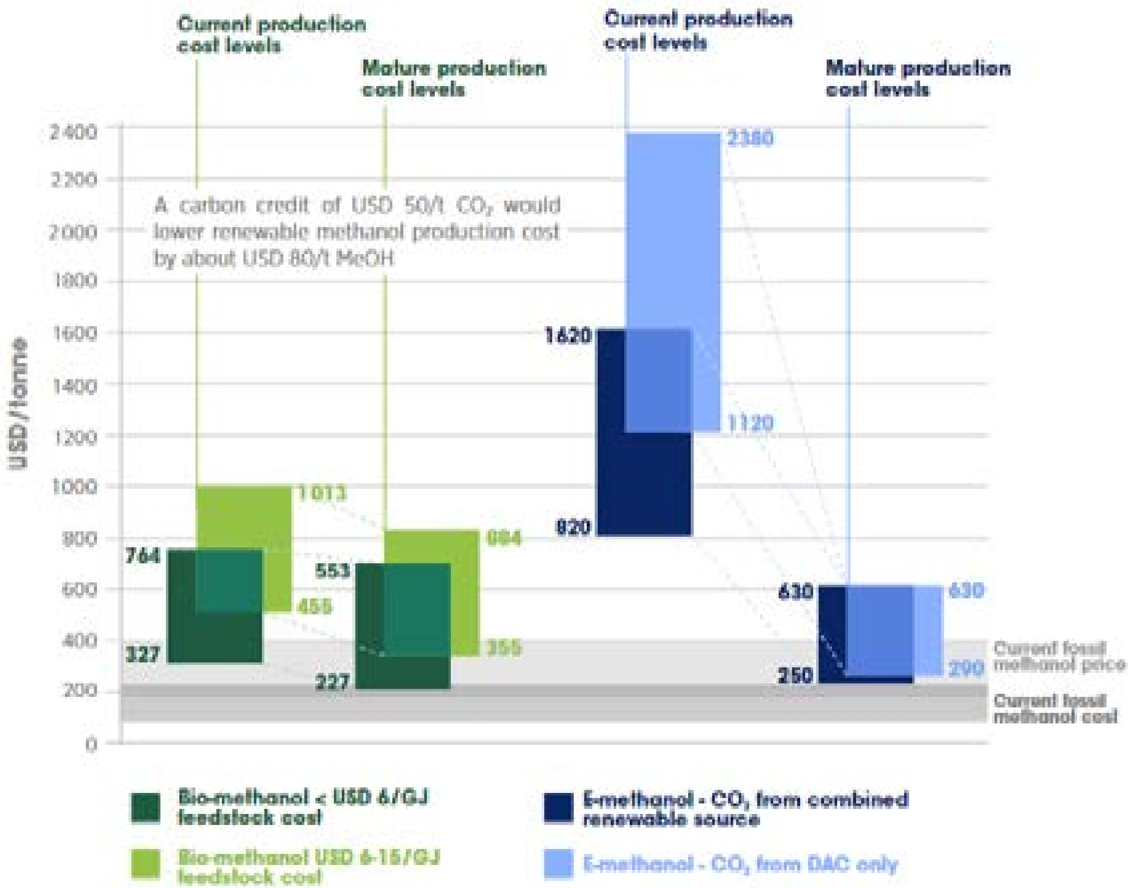
The coalification of renewable feedstock in methanol production facilities based on natural gas or coal can be a strategy to gradually introduce renewable methanol production and reduce the environmental impact and carbon intensity of conventional methanol production.

6.5.3 Cost competitiveness of renewable methanol

Production costs for renewable methanol are currently higher than those for methanol based on natural gas and coal. However, with improvements in production processes and the use of low-cost raw materials, the cost of producing renewable methanol could come closer to that of fossil fuel methanol.

Cost savings will mainly come from reducing production costs through economies of scale, learning curve mechanisms and improved plant configurations. The availability of sustainable, low-cost biomass raw materials also plays a crucial role in expanding biomethanol production.

Figure 17 - Current and future production costs of bio and e-methanol



Source: IRENA (2021)

- **Improving the competitiveness of Biomethanol**

The competitiveness of biomethanol can be improved through technological maturity and cost reduction. Although oil and coal gasification is a proven technology, the application of gasification technologies for biomass and MSW is still in the early stages of commercialization and requires further development.

Reducing capital expenditure (CAPEX) will be crucial in reducing production costs, achieved through economies of scale, learning curve mechanisms and process improvements. In addition, the availability of sustainable, low-cost biomass raw materials is essential for increasing biomethanol production.

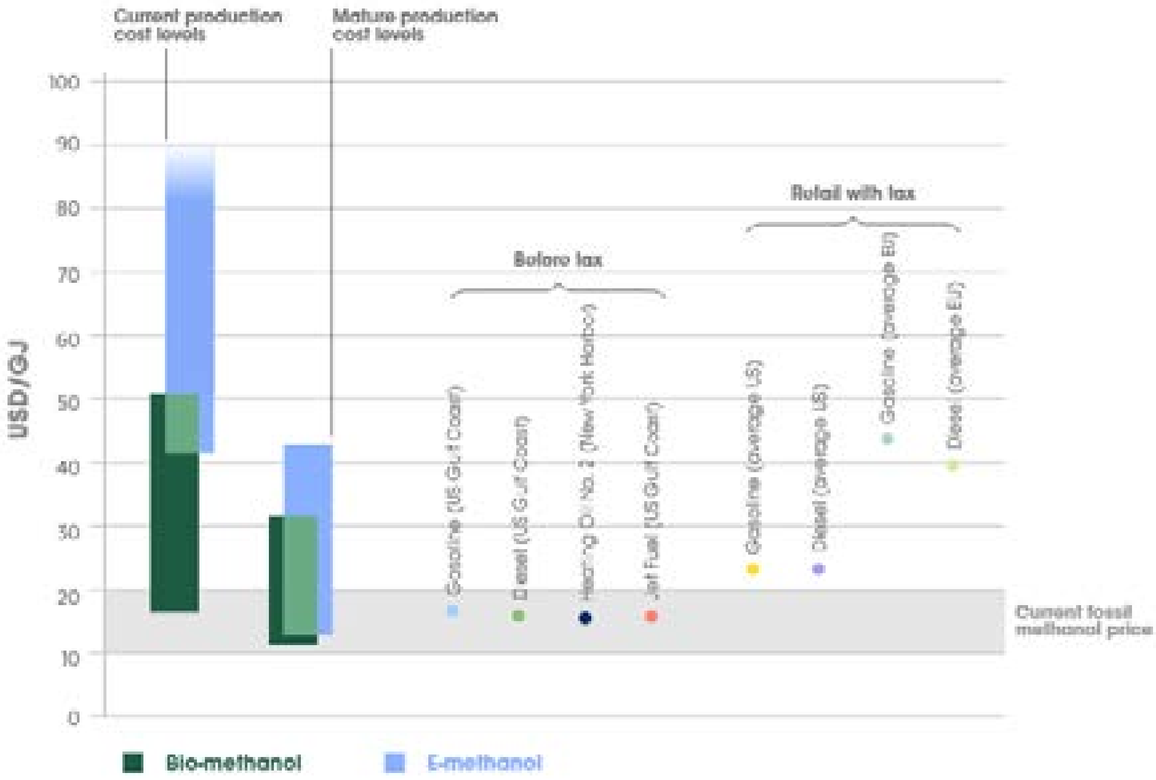
- **Improving the Competitiveness of E-Methanol**

Large-scale production of e-methanol depends on the abundant and low-cost availability of green hydrogen and CO2, as well as the capital cost of the plant. The main cost factors for e-methanol production are the cost of the renewable energy needed to generate hydrogen and the plant utilization rates. Currently, e-methanol production remains expensive, but the cost of renewable electricity from wind and solar power is expected to fall in the coming decades. Economies of scale and innovation in electrolyzers will also contribute to cost reductions.

- **Sustainable and affordable carbon source**

To be renewable and sustainable, the CO2 needed to produce e-methanol can be captured from various sources, such as power plants and industrial exhaust streams. However, the cost of CO2 capture needs to decrease substantially. Combining bio- and e-methanol production in a single facility can be beneficial, where the excess CO2 generated in bio-methanol production can serve as a source of CO2 for e-methanol production using green hydrogen.

Figure 18 - Comparison of renewable methanol with other fuels based on price per unit of energy Current and future production costs of bio and e-methanol



Source: IRENA (2021)

6.5.4 National opportunity in the methanol market

Brazil can benefit from the production of green methanol in several ways. Green methanol is produced using green hydrogen, obtained from renewable sources such as wind, solar and hydroelectric power through the electrolysis of water. This hydrogen can then be combined with CO2 captured from renewable sources to produce green methanol.

Offshore wind energy is one of the routes to the use of hydrogen, ammonia and green methanol in Brazil. Offshore energy generation will enable the development of new electro-intensive markets and attract industries to consume this new renewable source alternative. The production of hydrogen for industrial consumption and power generation, including for export, in the form of ammonia and green methanol is emerging as the future of *offshore* wind energy.

Sugarcane can be used to produce bio-methanol through the biomass conversion process. Converting biomass into energy and chemical carriers represents an interesting direction for reducing dependence on fossil fuels and protecting the environment. Methanol is one of these vectors that is widely used as an energy source and raw material for various value-added products.

Methanol synthesized from fossil fuels such as natural gas and coal as a feedstock is not sustainable and therefore much interest has been diverted to the use of biomass for biomethanol synthesis. Thermochemical conversion, biological routes and other new strategies demonstrate an effective route to biomethanol production. Biomass-based raw materials appear to be an ideal substrate for such pathways .

In Brazil, the basic sugar source is sugar cane - whose yeast can ferment directly into ethanol . Ethanol can then be converted into methanol through a process called dehydration. This process involves removing water from ethanol to produce methanol.

The use of green methanol as a fuel could help reduce greenhouse gas emissions and contribute to global efforts to mitigate climate change. In addition, the development of a green methanol industry in Brazil could create jobs and stimulate economic growth.

Another route to producing biomethanol could be through the production of corn bioethanol, a highly profitable project in economic and financial terms.

In this plant model, which uses corn as an input for example, a basket of co-products is generated after fermentation, such as bioethanol, corn oil, DDGS or WDG (animal feed), electricity (usually generated by steam created in boilers) and carbon dioxide.

These last two outputs (electricity and carbon dioxide) could be used in another industrial plant, attached to the ethanol plant, but to generate biomethanol.

In fact, if part of the ethanol produced is applied to a reformer, we could generate a simplified model of sustainable hydrogen production, which the literature already calls “biohydrogen”.

If this biohydrogen is combined with the carbon dioxide generated in the bioethanol production process, we will have biomethanol, produced in a more economically viable way than using an electrolyzer.

In fact, in addition to the fact that hydrogen production from ethanol reforming is cheaper than using an electrolyzer, the high internal rate of return of a bioethanol production venture could make a biomethanol project viable.

Among other strategies, Chapter 6 will go into greater detail about the feasibility of producing biohydrogen and biomethanol from a bioethanol plant to be set up next to the port of Itaguaí, using the port’s rail infrastructure to transport the inputs (biomass and corn) to the plant.

6.6 Synthetic fuels

E-fuels originate from the industrial process of electrolysis that separates hydrogen from oxygen in water. Subsequently, the hydrogen is mixed with carbon dioxide to create, together with plant or animal sources, fuels that don't use oil or natural gas.

Expanding the production of green hydrogen, which is necessary for the production of synthetic fuels, requires a reduction in the production costs of solar and wind energy, as well as advances in electrolysis and *e-fuel* transformation technologies.

These are fundamental elements of the energy transition in the transportation of people and cargo. In air transport, for example, the use of sustainable aviation fuel (SAF) and technological innovations that increase the efficiency of aircraft turbines still have a long way to go to increase the competitiveness of synthetic fuels.

In Punta Arenas, in the far south of Chile, for example, the Haru Oni project is already in operation, a pioneering experiment to create a green fuel complex led by *Highly Innovative Fuels* (HIF).

With broad support from the German government and in association with Exxon, Siemens Energy, Porsche, among other companies, the initial investment was US$74 million. The project aims to produce 130,000 liters of *e-fuels* initially and reach 550 million liters by 2027. This project alone would be able to increase the current global production of green hydrogen by 13.75 times (2021).

Another project, even more ambitious, is being developed in the south of Texas, in Matagorda County. Coordinated by the same HIF and focused on the production of methanol for the chemical industry, this project is scheduled to start production in 2024 and plans to produce 750 million tons of *e-fuels* by 2027, using 300 million tons of green hydrogen and 2 million tons of recycled CO2 annually (as available at www.epbr.com.br , accessed on 23.08.23).

Due to the low production costs of clean energies (such as solar and wind), Brazil has enormous potential for the production of synthetic fuels in the future, by groups such as Petrobras and Vibra.

Leader in the Brazilian fuel and lubricant distribution market, Vibra holds the license to use the Petrobras brand, forming a network of 8,300 gas stations throughout the country. Vibra Energia's franchises for the segment are the BR Mania convenience stores and the Lubrax+ automotive lubrication centers. With a logistics structure that guarantees its presence in all regions of the country, the company has a portfolio of more than 18,000 major corporate clients in segments such as aviation, transportation, industry, mining, chemicals and agribusiness.

With the BR Aviation brand, for example, Vibra has around 57% of the aviation market, supplying aircraft at more than 90 Brazilian airports. In lubricants, it is the market leader with the Lubrax brand and has the largest industrial plant for producing lubricants in Latin America (as reported at www.vibraenergia.com.br, accessed on 23.08.23).

As it is investing heavily in fuel distribution along the Brazilian coast via cabotage, Vibra is a potential strategic partner for the Port of Itaguaí in a future project to produce and distribute synthetic fuels in the country.

6.7 Advantages of structuring green hydrogen clusters

Investing in green hydrogen offers several benefits for both the environment and society. Firstly, the production of green hydrogen can replace fossil fuels, leading to a decrease in fossil fuel consumption and an improvement in air, soil and water quality.

This transition to green hydrogen could help reduce greenhouse gas emissions and help combat global warming.

Secondly, the development of green hydrogen industrial clusters can create new opportunities for economic growth and job creation. These clusters can serve as hubs for the production, storage, distribution and consumption of green hydrogen, attracting investment and fostering innovation in the renewable energy sector.

In addition, the establishment of green hydrogen networks and collaborations between clusters could promote the sharing of knowledge, best practices and the replication of successful projects. This could accelerate the deployment of green hydrogen technologies and make it easier to scale up production to meet the growing demand for clean energy.

7. STRATEGIES FOR MAKING PROJECTS VIABLE IN A FUTURE GREEN HYDROGEN CLUSTER NEAR THE PORT OF ITAGUAÍ

Being physically located between the two most important metropolises in Brazil (São Paulo and Rio de Janeiro), in a highly industrialized region and with good access infrastructure (road, rail and waterway), the Itaguaí Port Complex is suitable for large-scale infrastructure projects, of which a green hydrogen cluster could be an example.

Leaving aside the issue of the petrochemical industry (specifically with regard to the future production of synthetic fuels), which has already been addressed in the topic of the Gaslub Pole (formerly COMPERJ) and also the possibility of producing green ammonia, to be used by the fertilizer industry or to be exported to the international market, (The terminals most strongly connected with the issue of green hydrogen production and/or consumption are the Ternium Brasil Terminal and the operations of mining company VALE, which operates the Guaíba Island Terminal (TIG) in Itaguaí.)

Ternium is a leading steel company in Latin America. Ternium's facilities are located in Mexico, Brazil, Argentina, Colombia, the southern United States and Central America. The company also participates in the controlling group of Usiminas, the leading flat steel company in the Brazilian market.

According to its 2021 Sustainability Report, Ternium plays an active role in global efforts to tackle climate change. As a steel company, it is looking for ways to reduce the carbon footprint of its operations and the steel value chain. To this end, the company has partnered with suppliers and other companies and associations to promote the development of low carbon dioxide emission systems. In order to decarbonize its operations in the long term, Ternium intends to develop steelmaking technologies, make raw materials, renewable energy and infrastructure available, and edit government regulations to promote fair trade.

In August 2021, the company signed a memorandum of understanding (MoU) with Vale, its main iron ore supplier, to jointly study the use of iron ore briquettes in its blast furnaces and the economic viability of investing in an iron ore briquetting plant using Vale's technology.

The company is also developing partnerships for the use of biomass, a substitute for metallurgical coal for its steel units in Brazil and Argentina. To improve these sustainable purchasing and procurement practices, Ternium has entered into a partnership with Exiros, a company specializing in purchasing, which is 50% owned by Ternium and 50% by Tenaris.

At the *Green Hydrogen Application Summit* held by the German-Brazilian Chamber of Commerce and Industry in Rio de Janeiro (AHK Rio) in October 2022, Titus Schaar, Vice President of Operations at Ternium Brasil, said that the company was interested in talking to potential partners to make further progress in low-carbon industrial production, for example, using CO2 to be made available by the company together with H2V from a partner and producing blue methanol on a small scale. On a large scale, the company would need to rely on the supply of green hydrogen at a competitive price.

He also said that neither natural gas nor H2V are competitively priced in Brazil. "If someone offers green hydrogen at US$ 2 to 3 a kilo, we will invest," said Schaar, who was quite clear about how to make Ternium's business plan in Brazil viable in a low-carbon context.

In view of the lack of subsidies for the development of the green hydrogen market along the lines currently practiced in the USA and Europe, hydrogen projects in Brazil are only likely to become viable by lowering production costs or by identifying *offtakers* on the international market, especially in countries such as Germany, Belgium and the Netherlands.

In this sense, in a practical way, we present below 5 options for feasibility studies for projects that could be developed in the port of Itaguaí:

a) structuring a large-scale plant (over 50 MW) to **produce green ammonia to** be exported for energy production in Europe (for example, in the auctions held by **HINT.CO** in Germany). It should be noted that, in this case, the *offtaker* would have to be international, given the lower cost of ammonia imported by Brazil for the manufacture of fertilizers. The renewable energy for this venture could come from one or more of the solar or wind power projects currently being planned in the region;

b) installation of a large corn ethanol plant next to the port, to be integrated with a plant for **reforming ethanol and producing green hydrogen** (with **NEA/Hytron** technology, for example), with the high rate of return of an ethanol plant used to compensate and reduce the costs of producing green hydrogen to a minimum (even if cross-subsidized), if possible to a value of USD 3 per kilo, thus enabling a partnership and attracting investment from **Ternium** for the production of **blue methanol**, from the supply of carbon dioxide by this company, as proposed by its Vice President of Operations;

c) in another format, the **reforming of ethanol to produce hydrogen** would be coupled with the **carbon dioxide produced by the ethanol plant itself** (as a result of fermentation), thus generating **green methanol to** be sold to potential buyers in Brazil. In both cases, the necessary inputs (corn for fermentation and biomass for energy generation in the boiler) would arrive at the port by rail, from the origins of both inputs in the state of Minas Gerais, and would be packed in large silos to be installed at the port;

d) a partnership with GIZ or another international support organization for the installation of an **electrolyzer unit next to the port**, which could supply **green hydrogen on** a small or medium scale (5 to 10 MW, for example) for industrial applications, mobility, etc. in Brazil. As it is a modular project, **VALE**, for example, could become a partner in this project if it is interested in this hydrogen for the decarbonization projects it is currently studying and intends to implement soon, and the increased supply of H2 from the new plant could be combined with the expansion of green hydrogen application projects in the company's activities. Several ports around the world are currently installing small electrolyzer units for use in the port's own logistics activities (in cranes, forklifts and containers, for example, which are already starting to operate with **hydrogen fuel cells**).

e) structuring a green hydrogen plant (to be coupled with a carbon dioxide supplier, such as Ternium) for the production of synthetic fuels (SAF or e-gasoline, for example) to supply the Brazilian aviation market, urban transportation or even for export to Europe, to meet the demand of various countries, such as Germany, which has sought to stimulate these fuels.

A more in-depth quantitative study, with entry and exit numbers, could be carried out once the routes have been defined.

Other business models could emerge from an increase in demand **for methanol for ships (in a future bunker** next to the port, for example), or even when Petrobras' hydrogen projects are officially announced, and we could then try to connect them to the port.

8. CONCLUSION

The Port of Itaguaí, located on the north coast of Sepetiba Bay in Rio de Janeiro, is emerging as a key player in the global energy transition. This large maritime complex, which includes the organized port managed by Companhia Docas do Rio de Janeiro (CDRJ) and several Private Use Terminals (TUPs) authorized by the National Waterway Transport Agency (ANTAQ), has firmly established itself as one of the pillars of industrial activity, with a special focus on the handling of solid mineral bulk, steel production and port logistics.

As we look to the future, the strategic location of the Port of Itaguaí, between Brazil's main urban centers, Rio de Janeiro and São Paulo, takes on even greater significance. This bustling center is in a unique position at the confluence of several industries, with notable links to the hydrogen sector. These connections include Vale's mining operations and Ternium's pioneering decarbonization efforts in its Mexican and North American industrial plants.

Our analysis also covered the immediate potential for using hydrogen in the refining and fertilizer sectors as decarbonization strategies. Indeed, the steel, metallurgy, ceramics, glass and cement sectors are set to join the ranks of the new consumers of green hydrogen over the next five years.

In the *oil & gas* sector, the development of the Itaboraí GasLub Hub promises to be a watershed in Brazil's energy scenario. This complex, initially conceived as the Rio de Janeiro Petrochemical Complex (COMPERJ) by Petrobras, is strategically positioned to receive natural gas from the Santos Basin, reinforcing domestic gas supplies and reducing dependence on LNG imports. In addition, Petrobras' renewed focus on energy transition, biofuel production and the possible reduction of ICMS rates for gas-intensive industries in the GasLub region offers promising avenues for synergy for a future hydrogen venture in the port's hinterland.

The production of ammonia, especially for the production of nitrogen fertilizers, also aligns strategically with the Port of Itaguaí's ambitions in the area of hydrogen. The potential for ammonia and methanol bunkering facilities opens new doors for maritime transportation, with green ammonia emerging as a transformative fuel. Meanwhile, the production of green methanol holds significant promise for both shipping companies and domestic sectors, reducing import dependency and advancing sustainability goals.

In light of these opportunities, our study outlines a strategy for generating immediate economic viability for a hydrogen production project. In this sense, a large-scale ethanol plant, strategically located in the port's back area, would optimize rail and waterway logistics, paving the way for the production of green hydrogen and methanol through ethanol reforming. This self-sustainable venture, driven by the capture of carbon generated by corn fermentation, would highlight the potential for private sector initiatives to finance the production of green hydrogen and methanol without the need for government subsidies.

In conclusion, the Port of Itaguaí is emerging as a dynamic catalyst in the global energy transition, offering strategic advantages for the production of green hydrogen, ammonia and methanol. Its logistical connections with several large companies on the Rio-São Paulo-Belo Horizonte axis and the infrastructure already in place position this port as strategic for future hydrogen projects in Brazil.

As we venture into this transformative era of energy transition, the Port of Itaguaí's journey towards social, financial and environmental sustainability is promising and exemplifies the power of innovation and collaboration in shaping a greener future.

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