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DEVELOPING A SUSTAINABLE HYDROGEN ECONOMY IN BRAZIL: TRACKING SOME LEGAL AND REGULATORY PATHS

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November 2023

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ABSTRACT

The climate crisis is a global challenge that, allied to the increase in world energy demand, requires the urgent finding of technological alternatives that will lead to the decarbonization of the energy sector with a sustainable pattern of development. Low– carbon hydrogen has emerged as one new key technological solution to the energy sector's paramount task ahead. Brazil, as a country endowed with an abundance of renewable energy sources, in particular, solar and wind energy, and also critical natural resources such as rare metals, has seen a rise of low-carbon hydrogen as a strategic path to address the decarbonization target. This paper argues that despite the country's extremely advantageous position in the global scenario, Brazil's strategy along with its institutional, legal and regulatory structures need to keep pace with the ongoing global hydrogen race, transforming a comparative advantage into a feasibly competitive one, able to not only convey social and economic benefits to the country, but also contribute to the world's decarbonization process.

1. INTRODUCTION

The climate crisis is a global challenge that, allied to the increase in world energy demand, requires the urgent finding of technological alternatives compatible with a sustainable pattern of development.

The latest Intergovernmental Panel on Climate Change Report (IPCC, 2023) that focuses the climate crisis points out that even though "climate change has already caused widespread impacts and related losses and damages on human systems and altered terrestrial, freshwater and ocean ecosystems worldwide", we can still secure a livable and sustainable future for all with deep, rapid and sustained reductions in greenhouse-gas (GHG) emissions.

The IPCC Report also states that achieving this reduction will demand a greater focus on adaptation, more emphasis on equitable solutions, scaled up financing, as well as enhanced developments in technology and international cooperation.

In response to this scenario, the world has watched a myriad of emergent technologies aimed at addressing the energy trilemma—the challenge of reconciling energy security with socio-environmental demands and affordability—in a context of climate crisis.

Energy security[1] has always been a key domestic issue for most nations; in recent years, however, the topic has become central to the international agenda in the face of the climate crisis and geopolitical concerns. Currently, the objective of ensuring

[1] The concept of energy security can be approached from various perspectives and it is not a static concept. It is permanently evolving in response to risks and circumstances. Several authors have noted the elusive nature of the concept and that despite the high importance of energy security the term is "not clearly defined", "seems to be rather blurred", "slippery or difficult to define" (See: Checchi, Behrens, & Egenhofer, Long-Term Energy Security Risks for Europe: A sector-specific approach, 2009 and Alhajji, What is Energy Security? Definitions and Concepts, 2008). For the purposes of this article, we will consider a broader concept of energy security, taking into account not only energy reliability (security of supply), but also the energy sector's environmental impact and the notion of sustainability. For more information see: ROLIM, Maria João C. P. *Reconciling Energy, the Environment and Sustainable Development. The Role of Law and Regulation*. p. 35-90. ISBN 978-94-035-1461-1

energy security cannot be dissociated from the need to reduce the negative environmental impacts of the energy sector. This in itself has caused a move towards energy transition all over the world.

Even though it is a global trend, energy transition can be carried out in various ways depending on the particular domestic realities of any country. A recent study by McKinsey & Company (MCKINSEY, 2022) indicates that, in relation to energy transition, countries can be grouped into five main archetypes, with differing prospects:

1. **Affluent, energy-secure countries:** Countries that have abundant domestic production of energy and a high GDP per capita. Such countries have the potential to remain as energy exporters but need to reconsider energy sources in the face of more restrictive emissions targets. The United States is a prominent example of this.

2. **Affluent, energy-exposed countries:** Countries that face energy-security challenges and can take the transition process as an opportunity to reshape their domestic scenario, thus reducing their dependence on fossil fuel imports. German, Italy and Japan are indicated as representative of this category.

3. **Large, emissions-intensive economies:** Countries, including China, India, and South Africa, which need to meet growing energy demands with

cleaner resources while also reducing their reliance on high-emissions fuels, particularly coal.

4. **Developing, naturally endowed economies**: Basically, countries endowed with an abundance of renewable energy sources, in particular, solar and wind energy, and also critical natural resources such as rare metals. This is the case of Brazil and, as the study clearly indicates, the natural path should be to set up a framework to develop these resources and move on to a sustainable mode of production.
5. **Developing, at-risk economies**: Parts of Africa and Southeast Asia, along with several island nations, represent this group. These economies are marked by a strong reliance on agricultural activity and a disproportionate exposure to climate risk. For these countries, the development of renewables is restricted because of either financial constraints or limited natural endowments. Their main challenge, nevertheless, is to overcome their domestic financial limitations and prioritize the establishment of basic infrastructure services and investments in climate adaptation.

The McKinsey study is one way of categorizing countries in the current energy transition trend. Although it is not the only one, this classification illustrates the main aspects different countries will have to consider in order to define their position in a new global order.[2]

Additionally, the study highlights that all countries, irrespective of the classification, will need to take actions to achieve a high level of decarbonization while at the same time ensure energy security and affordability.

The last few years, many policy strategies and technologies have emerged as possible responses to that context. This aspect has prompted an urgent need to revisit and, in many cases, adapt regulations and legal frameworks to follow suit. Low–carbon hydrogen has then emerged as one new key technological solution to the energy sector's paramount task ahead. By presenting itself as a source of energy with low or no GHG emissions, low–carbon hydrogen is being promoted as part of a strategic objective by governments and companies worldwide.

This paper explores some key aspects related to the rise of low-carbon hydrogen as a strategic path to address the decarbonization target with focus on Brazil. It argues that despite the country's extremely advantageous position in the global scenario, Brazil's strategy along with its institutional, legal and regulatory structures all need to keep pace with the ongoing race at the global level in order to transform a comparative advantage into a feasibly competitive one, able to not only convey social and economic benefits to the country, but also contribute to the

[2] For more information see: Yergin, Daniel. The New Map: Energy, Climate, and the Clash of Nations. United States: Penguin Publishing Group, 2020.

world's decarbonization process.

2. LOW-CARBON HYDROGEN: DEFINITIONS AND ECONOMICS

Hydrogen is the lightest chemical element, which under standard conditions is a gas of diatomic molecules having the formula H_2. It is colorless, odorless, tasteless, non-toxic, and highly combustible. Hydrogen is also an energy carrier that can be used to store, move, and deliver energy produced from other sources.

Natural gas is the main source used for hydrogen production today, accounting for approximately 75% of world production, followed by coal, which accounts for a 23% share (EPE, 2021). This process is highly carbon-intensive and responsible for around 800 million tons of CO_2 emissions every year.[3] Currently, hydrogen plays a key role in the production of fertilizers as well as in oil refining, and industrial and hospital gases. (EPE, 2021).

The use of hydrogen in productive processes is not a novelty. It has been used since 1975;[4] what is new is the shift in production towards using renewable energy as an energy source and/or introducing carbon capture methods.[5] In fact, not even these

[3] Data available at: https://www.iea.org/fuels-and-technologies/hydrogen. Visited in March 2023.
[4] Mainly used in markets like fertilizers, oil refining, and industrial and hospital gases.

[5] Apart from fossil fuels, renewable energy sources and low emitting processes are being developed. These different processes have led to a classification of hydrogen by color, with each color based on the carbon intensity of the production process or the amount of greenhouse gas emitted for every kilogram of hydrogen produced. The more commonly accepted colors and their respective process are:

i. gray (or brown/black), produced by steam methane reforming (SMR) or gasification of fossil clean technological routes are exactly innovative. The novelty is in the hydrogen momentum itself, pushed forward by the need for decarbonization, the maturity of the technologies and the anticipated cost reductions. Low-carbon hydrogen has gained predominance by playing an essential role in achieving global net-zero emissions and, thus, limiting climate change.

Hydrogen, both low carbon and renewable, and its derivatives are recognized today as key pillars to replace fossil fuels and help decarbonize sectors that cannot be feasibly electrified yet, such as shipping, aviation and some industrial processes like ammonia and steel production (the "hard-to-decarbonize sectors") (IRENA, 2020).

As a disruptive option for energy transition, low–carbon hydrogen is expected to play a major role in the future energy transition landscape (IEA, 2019). Building upon current early technology deployment, the World Energy Council forecasts that "by 2040 the demand for low-carbon hydrogen may exceed the current demand for fossil-based hydrogen today" (WEC, 2021). The global green hydrogen market size is expected to reach USD 60.56 billion by 2030 (REPORTLINKER, 2022).

The numbers and expectations just quoted above indicate the relevance of

fuels, mostly natural gas;

ii. green, produced by electrolyzers supplied by renewable electricity. In some cases, production is based on bioenergy, such as biomethane or solid biomass gasification.
iii. blue, produced by SMR or gasification with carbon capture of fossil fuels;
iv. turquoise, via pyrolysis of fossil fuels, where the by-product is solid carbon;
v. pink, produced with nuclear energy, using electrolysis; and
vi. white, naturally occurring, geological hydrogen.

hydrogen for both achieving the decarbonization targets as well as unleashing the potential to boost economic growth in a more sustainable way. This is the point to be discussed in more detail in this paper: the potential impact that low-carbon hydrogen might have in Brazil's green reindustrialization and how legal and regulatory tools can contribute to this process.

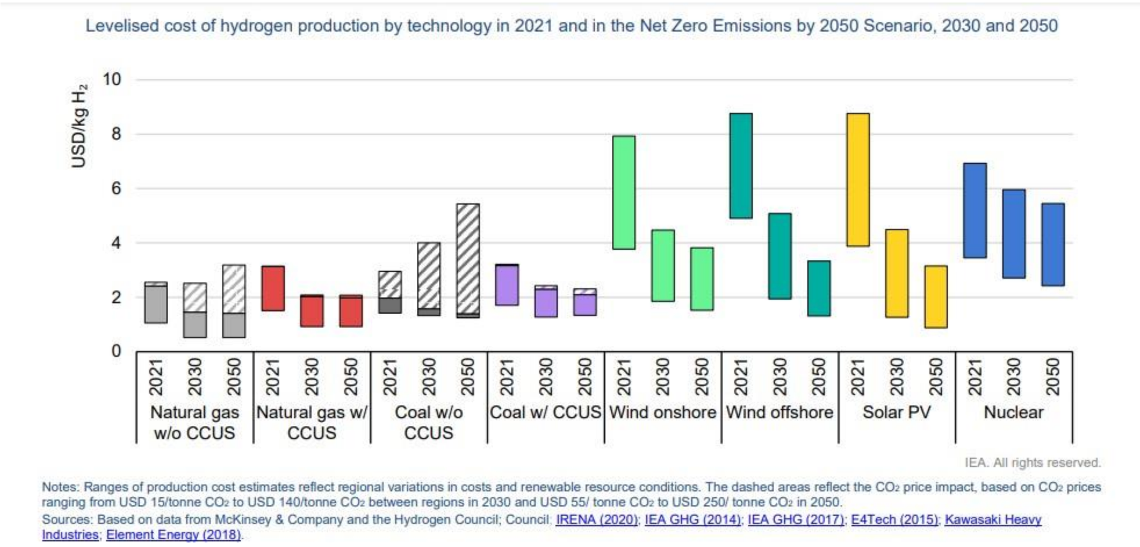
For the production of low-carbon hydrogen, there are currently two main routes: (i) preventing the escape of emissions generated from producing hydrogen with fossil fuels (for example, using carbon capture and storage); and (ii) using electricity generated from renewable energy to split water into hydrogen and oxygen, known as electrolysis (IEA, 2021a), providing in this way "energy storage in chemical bonds" (Luna et al., 2019, p. 2). The electrolysis process has been known for decades, but it is only now that industrial scale-up is becoming viable.

There is also the possibility of converting biomass and biofuels into hydrogen through gasification, gas reforming or biological processes, which are interesting alternatives for Brazil. The synthesis gas resulting from gasification, in addition to hydrogen, is also rich in carbon monoxide, requiring a separation step to obtain pure hydrogen (EPE, 2021).

Currently, the lowest hydrogen production costs are observed in the steam reforming of methane (natural gas) and coal gasification, which consist of technological routes based on fossil energy sources without carbon capture. Water electrolysis is, in general, the most expensive technological route compared to those already available in the market (IEA, 2022).[6]

However, as argued by the International Energy Agency (IEA) in its latest Global Hydrogen Review Report (IEA, 2022), expectations are for significant cost reductions in the longer term. The graphic below compares hydrogen production costs by technology in 2021 and by 2030 and 2050.

Figure 1: Cost Reductions to Produce Low-Emission Hydrogen



Source: IEA (2022)

The graphic shows that by 2030, hydrogen from solar PV may fall below USD 1.5/kg H2 and by 2050 below USD 1/kg H2 (with a reduction in electricity costs, and cost reductions and efficiency improvements for electrolysers). This would make hydrogen from solar PV competitive with hydrogen production from

[6] Pursuant to the IEA, "the average cost comparisons are: USD 1.0-2.5/kg H2 from unabated natural gas; USD 1.5-3.0/kg H2 from natural gas with CCUS; and USD 4.0-9.0/kg H2 for production via electrolysis with renewable electricity".

natural gas with CCUS by 2030 in regions with good resource conditions (i.e., 2,600 full load hours).

Likewise, the Bloomberg New Energy Finance report (BNEF, 2020) projects cost reductions for hydrogen production from renewable sources and estimates competitive costs by 2030, thus extending an advantage over hydrogen from fossil sources by 2050. An additional 20-25% reduction in costs could be added in countries with the best renewable resources and hydrogen storage, such as Brazil—as explored further in this paper. Furthermore, a study made by the Hydrogen Council points to a potential reduction in the cost of green hydrogen production of almost 60% by 2030, indicating that the Capex and Electricity cost components will account for the greatest reduction opportunities (HYDROGEN COUNCIL, 2020).

The current technological and market challenges to scale low-carbon hydrogen worldwide are well known. On the whole, storing high quantities of hydrogen (EFI, 2023), managing expected costs associated with stranded fossil fuel assets, and developing international and national markets condense the main challenges to overcome. Given the different positions and objectives countries may hold, the strategies and legal responses associated with these may also differ. Nevertheless, looking at the big picture, one can foresee a global market transformation with significant domestic impacts. This paper focus on Brazil's position and strategy.

Beginning with a short overview of the existing renewable energy structure in Brazil, the paper will focus on analyzing the ongoing process of developing a national strategy to advance the county's potential in the low-carbon hydrogen market, as well as discussing the current and expected future challenges Brazil may face and how legal and regulatory tools could facilitate the process.

3. BRAZIL'S ENERGY OUTLOOK: THE ENERGY AND ELECTRICITY MATRIX IN BRAZIL

Among the world's regions, Brazil has one of the highest shares of renewables in its power generation, only behind the United States and China;[7] the same may be said of its energy mix, which has a significant portion of renewables.

In 2021, Brazil's share of renewables in the electricity mix amounted to 78.1% (53.4% hydroelectric, 12.8% natural gas, 10.6% wind, 8.2% biomass, 3.4% steam coal and 2.5% solar) (EPE, 2022). As for the energy mix, the renewables accounted for 44.7% (16.4% sugarcane biomass, 11% hydroelectric, 8.7% firewood and charcoal and 8.7% other renewables[8]) (EPE, 2022).

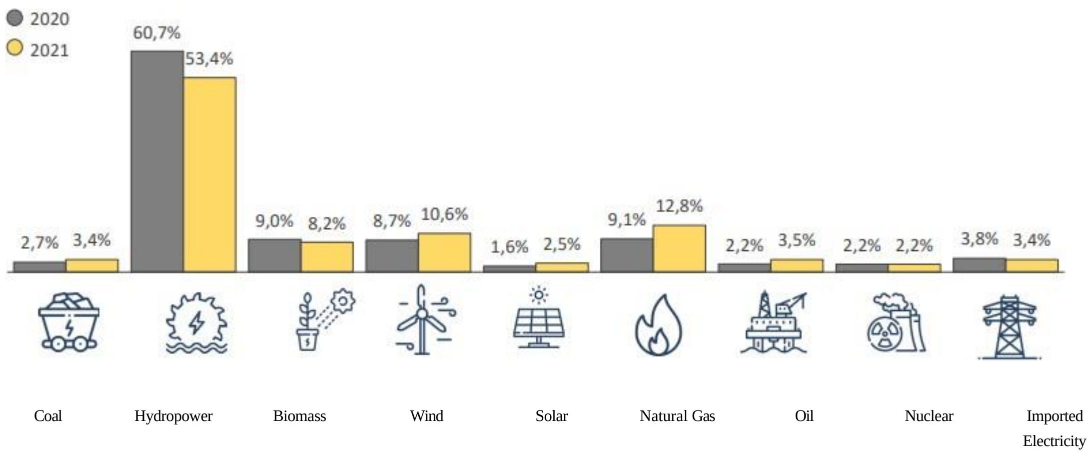
Looking from an evolutionary perspective, Brazil's energy matrix presented

[7] Data available at: https://www.iea.org/countries/brazil. Visited in March 2023.

[8] The supply of "Other Renewables" is distributed among 8 categories of energy sources with the largest share of bleach, wind energy and biodiesel, which together are equivalent to more than 80% of "Other Renewables".

significant drop in hydro source participation still in 2021, which was associated with an unexpectedly long period of water scarcity demanding the use of fossil fuel–powered thermoelectric plants. This led to a 5.7% reduction in the renewable energy matrix compared to 2020, with an increase in the supply of other sources, such as steam coal (+47.2%), natural gas (+46.2%), and also wind (+26 .7%) and photovoltaic solar energy (+55.9%).

Figure 3: Change in the Electricity Matrix: 2020 to 2021



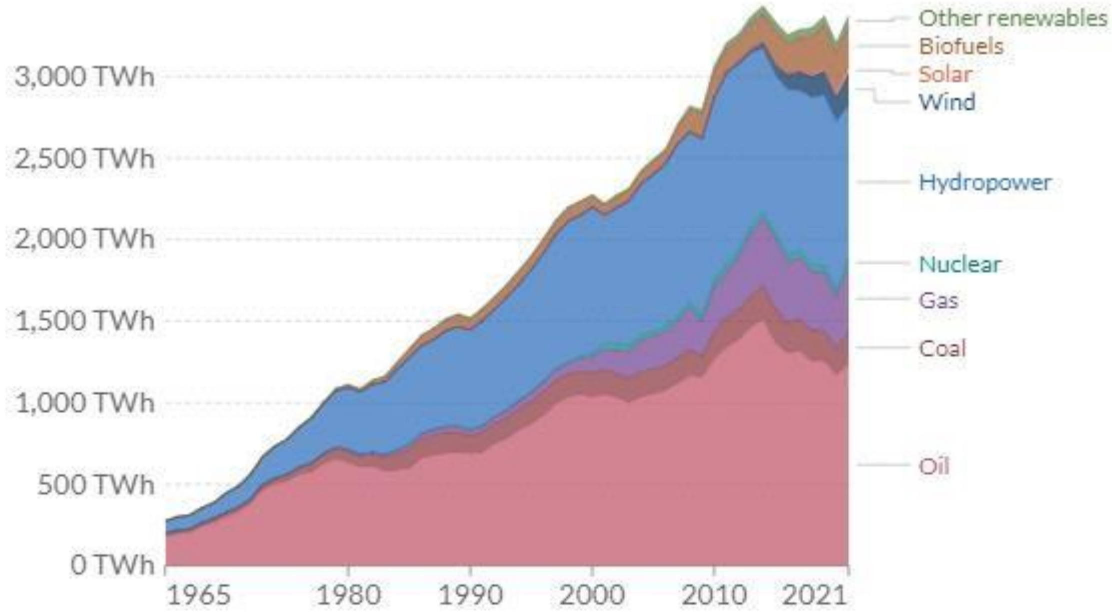
Source: EPE (2022)

From a historical perspective, one can see that both the energy and electricity matrix in Brazil has evolved to encompass more renewable sources,[9] such as

[9] According to the IEA, Brazil has several case studies of clean energy financing such as: (i) boosting the development of clean energy with competitive procurement and public finance (utility-scale solar PV, wind); (ii) setting supportive policies and reducing costs (distributed solar); (iii) developing new business models to attract private investment in transmission; and (iv) attracting private, international investment into liquefied natural gas distribution in importers. In the IEA climate-driven scenarios, around 30% of clean energy investment by 2030 will occur in Brazil, Mexico and India, which is similar to the

wind and solar energy, albeit relying on a significant portion of fossil fuel ones to supply the transportation sector and other industries in general. The charts below show the evolution of the energy and electricity matrix, respectively, in Brazil.

Figure 2: Brazil's Energy Consumption by Source from 1965 to 2021



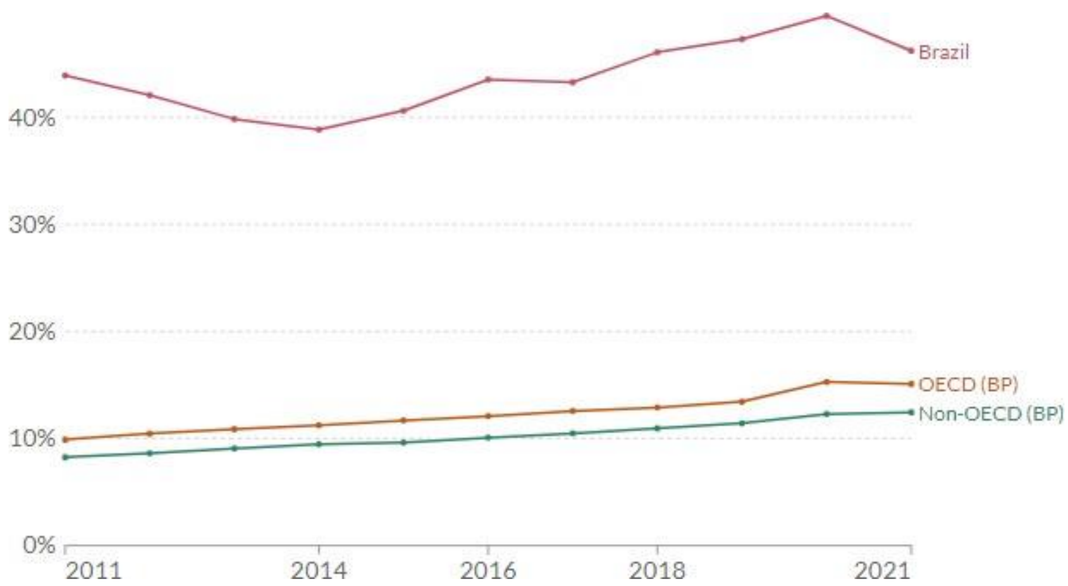
Source: OUR WORLD IN DATA (2022)

That said, it is noteworthy that Brazil has held a quite advantageous position compared to the rest of the world in terms of energy mix sustainability for several years. As seen in the graphic below, Brazil's share of renewables in 2021 was 46.22%, compared to 15.9%, in OECD countries, and 12.45%, in non-OECD

combined share of these countries over the past five years. For more information see: IEA (2021b). Financing Clean Energy Transitions in EMDEs. World Energy Investment 2021 Special Report.

countries.

Figure 3: Share of Primary Energy from Renewable Sources from 2011 to 2021 – Brazil vs. OECD and non-OECD Countries



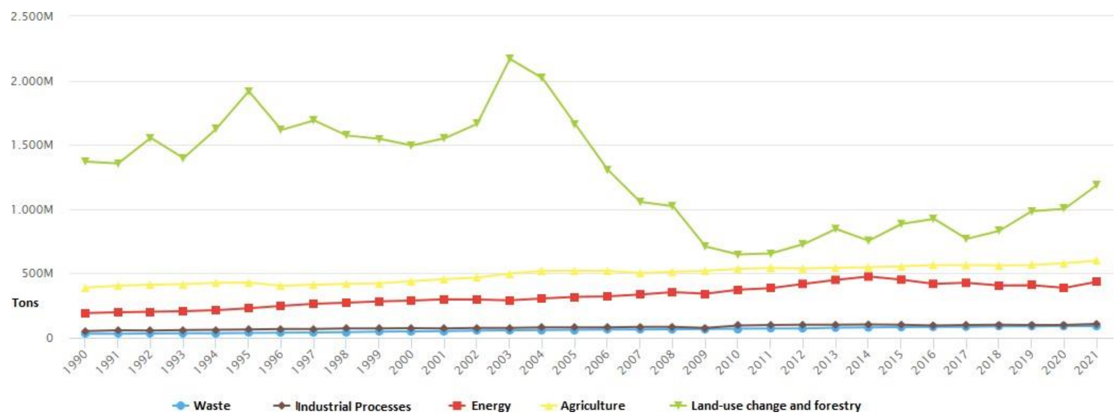
Source: OUR WORLD IN DATA (2022)

As for GHG emissions, pursuant to data from the Climate Observatory's Greenhouse Gas Emissions Estimation System - SEGG[10], Brazil emitted 2.42 billion gross tons of CO2 equivalent in 2021. Unlike the rest of the world, land use changes are largely responsible for the majority of emissions in Brazil, accounting for 49% of such emissions. Deforestation alone in the Amazon accounted for 77% of those emissions. The second most emitting sector is agriculture with 24.7%,

[10] Data available at: https://plataforma.seeg.eco.br/total_emission.

followed by energy 17.9%, industrial processes 4.4% and waste 4%, as seen in the graphic below.

Figure 4: GHG Emissions by Sector from 1990 to 2029



Source: SEGG (2019)[11]

The data shows that even though Brazil enjoys a relatively clean energy and electricity mix, the country's emissions present significant room for improvement.

The overall scenario indicates that the development of a sustainable hydrogen strategy provides an opportunity to advance the country's position in the international scene, given its abundance of clean energy sources, as well as the fact that hydrogen also offers a viable and necessary solution to addressing the domestic need for reducing emissions from hard- to-abate sectors, such as transport, mining and steel, as well as the fertilizer industry.

The following section presents the existing hydrogen market in Brazil, both in

[11] Ibid.

terms of production and investment, and discusses the potential that the current hydrogen strategy under development offers in terms of fulfilling the country's needs and allowing for making the most of its comparative advantages.

4. THE HYDROGEN MARKET IN BRAZIL: AN OVERVIEW

Currently, Brazil produces large volumes of hydrogen from unabated fossil fuels for oil refining, ammonia [12] and methanol production, and iron and steel manufacturing (EPE, 2019). The vast majority of hydrogen production plants are located in coastal regions close to the gas pipeline network in Brazil. This scenario indicates that there already is a significant demand for hydrogen, which, however, needs to migrate to a low carb hydrogen demand due to Brazil's climate change commitments.

In this direction, EPE (EPE, 2020) drafted a study on the possibilities and future of hydrogen from fossil fuels in Brazil, highlighting the importance of minimizing or compensating the consequences of this production process. The study points out that the current high–emitting hydrogen production should shift to new processes, such as gasification with carbon capture or pyrolysis, and start producing low-carbon hydrogen (known as blue or turquoise). The ultimate purpose in this move

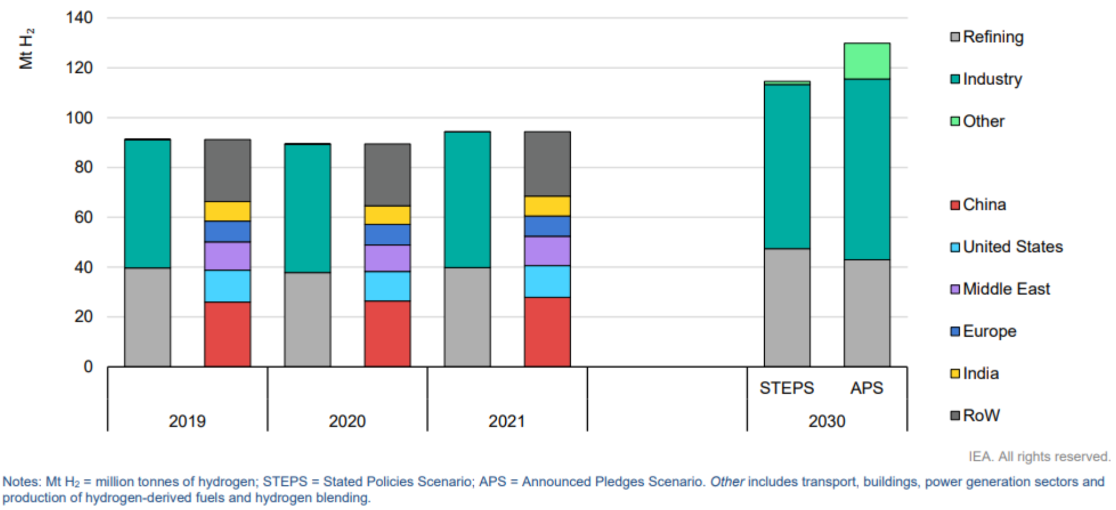
[12] Agriculture is the main driver for ammonia demand in Brazil, where it is used as a nitrogen fertilizer in the form of urea or ammonium salts (IEA, 2021a). In 2019, Brazil was responsible for about 8% of the global consumption of fertilizers, being the fourth country in the world, behind only China, India and the United States. The speed of growth of the Brazilian demand has surpassed the capacity of growth of domestic manufacturers, leading to the increased importation of fertilizers.

is to open the Brazilian market to new opportunities for exporting low-carbon hydrogen and green commodities, such as green steal or green ammonia (used to produce fertilizer).[13] Globally speaking, there is a significant development in the demand for clean hydrogen and green commodities, which represents a potential market for Brazil.

According to IEA's report, the Global Hydrogen Review 2022 (IEA, 2022), global hydrogen demand reached more than 94 million tons (Mt) in 2021. Hydrogen was mostly used in traditional applications, particularly in chemicals and in refining. Demand for new applications, such as in heavy industry, transport, power generation and the buildings sectors or hydrogen-derived fuels, was low in 2021, at around 40 kilotons (kt), accounting for about 0.04% of global hydrogen demand. However, if we assume that all climate commitments made by governments—including the Nationally Determined Contributions and longer term net zero targets—are met in full and on time, the outlook for hydrogen demand by 2030 would account for 25% of the total production for new applications and low-emission hydrogen.

[13] Gray Hydrogen: Production from the Steam Reforming of Natural Gas.

Figure 5: Current Hydrogen Demand and Future Scenario[14]



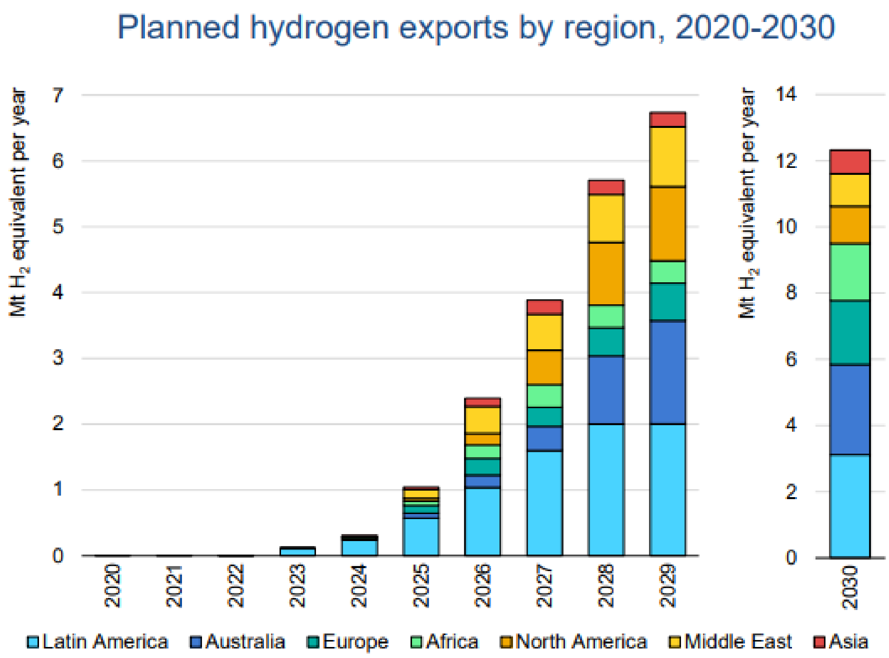
Source: IEA (2022)

Regarding hydrogen international trade, the IEA (IEA, 2022) estimates that 12 million tons (per year) of low-emission hydrogen could be exported by 2030, based solely on the export–oriented projects under development, of which 2.4 million tons (per year) are planned to be exported by 2026. As to the location of

[14] As explained in IEA Report, p. 19: "*The IEA Stated Policies Scenario (STEPS) reflects current policy settings based on a sector-by-sector assessment of the specific policies that are in place, as well as those that have been announced by governments around the world. The outlook in the STEPS suggests that hydrogen demand could reach 115 Mt by 2030. Most of this growth would be from traditional applications with small demand (less than 2 Mt) for new uses or the replacement of unabated fossil-based hydrogen in traditional uses. This would have limited benefit to achieving climate pledges. The IEA Announced Pledges Scenario (APS) assumes that all climate commitments made by governments around the world, including Nationally Determined Contributions and longer-term net zero targets, will be met in full and on time. The outlook for hydrogen demand in the APS is 130 Mt by 2030, of which about 25% would be for new applications and the use of low-emission hydrogen in traditional applications. This would require a step change to stimulate demand for hydrogen supported by ambitious and concrete policies actions.*"

the planned hydrogen export projects, these are geographically diverse, with significant volumes planned in every major region of the world, with the largest amount in Latin America (3.0 Mt H2/year), as shown in the graphic below.

Figure 6: Planed Hydrogen Exports (2020-2030) (by region)



Source: IEA (p. 163, 2022)

By analyzing the current and future hydrogen market, we can infer that there is plenty of room for Brazil to develop strategies to explore its privileged position in terms of its natural resources endowment.

Considering already existing international demand for low-carbon hydrogen,[15]

[15] In 2022, the German government launched a 900-million-euro auction scheme for green hydrogen imports, called the H2 Global mechanism. The purpose of the auction was to buy hydrogen (green ammonia) in the world market and sell it to local German businesses and other European countries. In this mechanism, Germany, represented by H2 Global (a foundation set up by German industry players such as Siemens Energy, Linde, Nordex

international net-zero regulations[16] and the current issues faced by the international fertilizer market, [17] and the current issues faced by the international fertilizer market,[18] we believe that, in this initial stage, the international hydrogen market should be prioritized in Brazil.

Simultaneously, the external market may leverage Brazil's internal market development, which in our view should be linked to a broader process of a green neo-industrialization wave.

An international study conducted by the German consultancy Roland Berger found that Brazil has the potential to become the world's largest producer of green hydrogen, with annual revenues of R$150 billion by 2050—of which R$100 billion would come from exports.

As seen, the economics suggest that Brazil indeed has a concrete opportunity for translating its comparative advantage into an effectively competitive one. This

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or ThyssenKrupp to help the green hydrogen market ramp-up) buys hydrogen made with renewable energy at the lowest possible prices and then sells them on to the highest bidder. As this is expected to generate deficits, the German government will cover the difference with subsidies. For more information access: https://www.bmwk.de/Redaktion/EN/Pressemitteilungen/2022/12/20221208-federal-ministry-for-economic-affairs-and-climate-action-launches-first-auction-procedure-for-h2global.html

[16] At the moment, European decarbonization targets for 2030 and 2050 are as follows: By the year 2030, a 40% reduction in CO2 emissions (compared to 1990), 32% share of renewable energy sources and 32.5% increase in energy efficiency. By the year 2050, a 100% neutrality of emissions. In the same sense, China aims to cut its net carbon-dioxide emissions to zero by 2060 and the United States government is committed to reaching net zero emissions by 2050 at the latest.

[17] Since 2020, the international fertilizer market has faced many challenges, due to the Covid-19 pandemic (causing the interruption of the supply chain due to the lack of the product), the rise in the price of natural gas, the economic embargo imposed by the European Union and the United States on Belarus (since 2021) and the conflict between Russia and Ukraine. According to data from market research and advisory firm Mordor Intelligence, the fertilizer market was valued at $155.80 billion in 2019 and is estimated to register a compound annual growth rate (CAGR) of 3.8% during the period 2020-2025.

prospect, however, critically depends on the policies to be adopted and their proper timing.

5. THE BRAZILIAN STRATEGY AND POLICIES FOR LOW-CARBON HYDROGEN

According to the IEA (IEA, 2022, p. 184), as of 2022, a total of 25 countries (in addition to the European Commission) had announced plans that included hydrogen as a source of clean energy, with some countries also introducing financial support schemes, for example China, the United States and the European Union. As the IEA states, "policy makers will need to develop a tailored and carefully timed mix of policy and regulatory measures guided by strategic priorities to reap the benefits of low-carbon hydrogen."

Although Brazil has been developing hydrogen–related policies for over 20 years so far, only recently has fuel been looked at from a more strategic standpoint.

In 2002, the Ministry of Science and Technology (MCT) launched the Brazilian Hydrogen and Fuel Cell Systems Program (initially called PROCAC) (BRAZIL, 2002). In 2005, this program was renamed, becoming the Science, Technology and Innovation Program for the Hydrogen Economy, with the acronym PROH2.[18]

[18] Data available at: https://www.h2verdebrasil.com.br/no-brasil/.

Also in 2005, the Ministry of Mines and Energy ("MME") coordinated the "Roadmap to Structure the Hydrogen Economy in Brazil" (BRAZIL, 2005), a study drafted with the Ministry of Science and Technology (MCT), focusing on valuing different technological routes in which the country could have competitive advantages, such as electrolysis and the use of ethanol and other biomass fuel.

At the time, this Roadmap established some parameters that had to guide the governing national strategy under development, including: (i) identification and consideration of different technological routes in which Brazil could have competitive advantages; (ii) recognition of the role of natural gas in facilitating the transition to the green-hydrogen- only phase; and (iii) the definition of key routes to diffuse hydrogen use, such as distributed energy generation, energy production in isolated regions, and urban buses.

In 2006, however, pre-salt gas changed energy policy priorities resulting in the suspension of the Government Program for the Production and Use of Hydrogen in Brazil, though several projects associated with hydrogen have continued to be developed (EPE, 2019).

In 2010, the Center for Strategic Studies and Management (CGEE), commissioned by the MCTI, launched a report entitled "Hydrogen Energy in Brazil: Subsidies for Competitiveness Policies: 2010-2025" (CGEE, 2010). The document provides a detailed and broad diagnosis of the hydrogen market in Brazil, identifying the bottlenecks to be faced and putting forward proposals for a hydrogen economy, where production and logistics development would define an economy less dependent on fossil fuels.

Both the CGEE study and the MME Roadmap advanced key aspects to give form to a more coherent and articulated plan in Brazil. The studies highlight the importance of articulating a strategy that explores the country's competitive advantage in terms of the vast availability of renewables (ethanol, hydroelectricity, wind and solar energy, natural gas, nuclear biogas and other biomasses) for developing new competitive advantages in the energy transition, with a particular focus on the potential role hydrogen ought to play. That view informed the MME's 2019 strategy, which adopted a neutral technological approach where all colors[19] (routes) matter, a so–called "rainbow" hydrogen strategy (EPE, 2019).

In 2020, the MME launched the 2050 National Energy Plan (PNE 2050), which pointed to hydrogen as a disruptive technology and, in addition, stressed its important role within the context of Brazil's energy mix decarbonization process, in the promotion of distributed energy resources and, also, in the advancement of storage technologies, given its characteristics of being both an energy carrier and a battery. The PNE 2050 also provides recommendations for regulatory improvements related to quality, safety, transport infrastructure, storage and

[19] See note n. 9.

supply of hydrogen (BRAZIL, 2020).

An additional relevant point raised by the PNE 2050 is related to the perspective of blending minimum percentages of hydrogen in the natural gas pipeline networks for transport and storage purposes, indicating the measure as an enhanced way of using natural gas pipelines in the current climate context and as a tool to scale the use of hydrogen for energy purposes.

In 2020, the MME in partnership with Germany authorities launched the German Hydrogen Strategy, aimed at identifying and reinforcing channels of cooperation between the countries, especially with regard to the supply of green hydrogen to address Germany's future demand. In 2021, the cooperation initiative delivered a study entitled "Sectorial Mapping of Green Hydrogen in Brazil" (GIZ, 2021), which mapped the industry and identified key academic and institutional players as starting points for designing a Brazilian green hydrogen roadmap. In addition, the report presents an overview of the main clean hydrogen technologies and applications,[20] assessing their state of maturity in Brazil compared to the leading countries in these technologies (GIZ, 2021).

In addition to government initiatives, low carbon hydrogen and clean technologies

[20] According to the German certification and inspection body Tüv Süd: "Power-to-X refers to all processes that convert renewable electricity into energy sources from chemical energy to electricity storage, electricity-based fuels for mobility or raw materials for the chemical industry. PtX can be used to produce hydrogen for vehicles powered by fuel cell, or kerosene for aircraft with low climate and environmental impact, for example the term "Power" refers to the temporary surplus of energy electricity above demand and the term "X" means the form of energy or the intended use". Available at: https://www.tuvsud.com/de- de/indust-re/klima-und-energie-info/power-to-x.

have been the subject of several academic research initiatives that have been a relevant contribution to Brazil's institutional capacity development.

In 2021, the Brazilian National Council for Energy Policy (CNPE) established hydrogen as a priority area for R&D resources[21] and tasked the Ministry of Mines and Energy, in collaboration with other entities, to prepare guidelines for a National Hydrogen Program[22]. In 2022, the Brazilian National Hydrogen Program (PNH2) was formally established and it constituted a committee to manage the Program, the PNH2 Management Committee[23].

The PNH2 is based on eight main principles: (i) to promote the national potential of energy resources; (ii) to recognize the diversity of energy sources and technological alternatives; (iii) to carry out decarbonization processes; (iv) to promote and incentivize the development of national technology; (v) to develop a competitive market as well as to search for synergies and partnerships with other countries; and (vii) to recognize the contributions of domestic industries.

Given the cross-sectorial nature of the subject, the PNH2 Management Committee provided for the participation of various government bodies and entities, as well as created five thematic committees with the purpose of discussing, analyzing, developing studies and writing technical reports on their respective topic divided

[21] CNPE Resolution No. 02/2021.
[22] CNPE Resolution No. 06/2021.
[23] CNPE Resolution No. 06/2022.

as follow: (i) scientific-technological strengthening; (ii) human resources training; (iii) energy planning; (iv) legal and regulatory framework; and (v) market opening, growth and competitiveness.

The thematic committees were requested to prepare a 3-year plan, the Triennial Work Plan of the National Hydrogen Program (2023-2025), which will guide the federal government's actions in the development of the hydrogen sector in the years to come. From December 2022 to February 2023, the plan was put under Public Consultation[24] by the MME.

Discussions were conducted under the working groups' meetings held in each thematic committee, which identified their relevant priorities to be addressed in the next three years. The listed priorities were then turned into components, which unfolded into actions, with the specification of their responsible individuals, the stakeholders involved, the delivery time, as well as deliverables and indicators for measuring results.

Despite the obvious interconnection with the five themes discussed, for the purposes of this paper, the Legal and Regulatory Framework committee is the

[24] Until this article's publication, the results of the Public Consultation had not yet been published. The consultation is available at: http://antigo.mme.gov.br/pt/web/guest/servicos/consultas-publicas?p_p_id=consultapublicammeportlet_WAR_consultapublicammeportlet&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&p_p_col_id=column-1&p_p_col_count=1&_consultapublicammeportlet_WAR_consultapublicammeportlet_view=detalharConsulta&resourcePrimKey=3679250&detalharConsulta=true&entryId=3679252

most relevant.[25] The committee's objectives and goals were defined as: (a) to improve institutional, legal and infra-legal frameworks aimed at the development of low-carbon hydrogen in Brazil; and (b) to remove barriers in the legal and regulatory-normative framework that might hinder investments in the sector, taking into account the alignment of national regulations with international ones, the interrelationships between sectors, and the safety standards (BRAZIL, 2022, p. 78).

To achieve the objectives and goals proposed, the committee identified five main components and actions to follow: (i) identifying gaps and proposing improvements to the existing institutional, legal and infra-legal framework; (ii) drafting codes, norms, standards and certifications to be issued by national agencies in line with international rules and certification mechanisms for carbon intensity in the chains of hydrogen and derivatives; (iii) finding interrelated features between sectors to promote harmonization and cooperation between government agencies, e.g., the transport of hydrogen mixed with natural gas; (iv) elaborating additional standards related to safety; and (v) drafting regulation, codes, norms, standards for new uses and technologies (BRAZIL, 2022, p. 78).

For each component, a set of actions was identified.

[25] The author of this article, Dr. Maria João P. Rolim, is a member of the Legal and Regulatory Framework committee, representing two associations: the Rio de Janeiro's Lawyers Association (OAB-SP) Energy Committee and the Brazilian Association of Infrastructure and Basic Industries (ABDID).

i. Component 1: to propose institutional, legal and infra-legal improvements;

ii. Component 2: to draft both a general proposal for certification and its institutional governance and a proposal for detailing the certification regulations and technical governance;

iii. Component 3: to make out a list of governance instruments for the interrelationships between sectors to support a proposal for enhancing harmonization and cooperation among sectors; to recommend proposals for new governance instruments and/or review the existing governance instruments between government agencies, in different spheres; to study alternatives for mixing hydrogen in the existing natural gas network considering quality, transport service conditions, measurement systems and operational safety aspects;

iv. Component 4: to list additional safety standards or carry out a revision of standards; to propose new additional safety standards or revise existing standards;

v. Component 5: to identify regulations, codes, norms, and standards for new uses and technologies required for the development of low-carbon hydrogen.

The three-year work plan is an important step towards developing the Brazilian hydrogen market and helping to create conditions to consolidate Brazil as a world player in the competitive low-carbon hydrogen market. Another important point of the plan is the mapping and study of the competitiveness of the low-carbon hydrogen value chain, including ways to identify opportunities and bottlenecks for Brazil and steer public policies to stimulate and create the necessary incentives. Despite the importance of this initiative, the program and its dynamics have not constituted an effective strategy to develop a hydrogen economy as it was originally expected to do. It set up a procedure to be followed in order to come up with a working plan to develop a national hydrogen plan—a welcome and relevant initial step in terms of governance but clearly not sufficient to establish an effective national strategy.

According to IRENA (IRENA, 2020) regardless of the terminology used to designate a national development program, there are significant differences in terms of the effectiveness of a strategy compared to other policy initiatives. The figure below sums up this idea.

Figure 7: Formulation of a National Strategy

Source: IRENA (p. 20, 2020)

Accordingly, a strategy is a more structured policy initiative and, therefore, reaches a higher degree of regulatory status in terms of signaling to the market what rules and positions to expect from the government authorities. R&D programs tend to be more directed to testing new technologies, and a vision document and roadmap indicate an earlier stage for an effective strategy to be enacted.

The Brazilian PNH2, at that stage and even today, is closer to a vision document than a roadmap or strategy. The plan fails to provide production and consumption targets for low-carbon hydrogen. As highlighted by IEA (2022, p. 181), establishing targets and/or long-term policy signals would effectively create a vision about the role hydrogen will potentially play in the overall energy policy framework in order to provide stakeholders with the certainty that there will be a future marketplace for hydrogen.

In addition, the initiative misses a broader and articulated view on what regulatory tools could be effectively used to promote a hydrogen economy in Brazil, which, combined with an integrated and inclusive sustainable reindustrialization process, would enable the country to occupy a leadership position in the global run for decarbonization, allied to a new green economic development stage.

A common concern is that a lack of goals and focus, particularly regarding hydrogen produced by electrolysis, may put Brazil on a slower path in relation to other countries that may be better equipped from the regulatory standpoint to receive investments. Indeed, there is a red flag regarding the policy timing and its relevance to Brazil. The risk is that the country will miss the opportunity to position itself as a leader in the decarbonization process and, also, that it will lose out on the international market share due to a global trend towards taxing carbon emissions, which would have an impact on the market position of Brazilian commodities.[26] This is a risk that Brazil cannot afford to take.

[26] An important matter addressed by the European Commission is the EU's Carbon Border Adjustment Mechanism (CBAM), which would affect the prices of imported carbon intensive goods, leading to an advantage to low-carbon hydrogen by-products. Also regarding green taxation, the European Commission is currently undertaking a revision of the Energy Taxation Directive, to overhaul the way in which energy products are taxed in the EU and to make sure that it better reflects the EU's climate ambitions. If, indeed, energy products from fossil fuels used as motor fuel, heating fuel and electricity become taxed, low-carbon hydrogen, as an energy carrier and fuel, would have a market advantage.

6. GLOBAL HYDROGEM STRATEGIES: RELEVANT ASPECTS TO BRAZIL

The flexibility and multiple uses of hydrogen allow each country to tailor its strategy to its own context and long-term priorities, providing opportunities for leveraging advantages, industrial value chains, technological capabilities and infrastructure (IEA, 2021a, p. 9).

Some countries have launched policy initiatives mainly focused on developing sustainable hydrogen as a driver to propel their energy transition ambitions and to act as a decarbonization vector while placing themselves as technological leaders; others are focused instead on their potential to level up their market position as exporters.

Being one of the world's largest GHG emitters[27] and also big economic players, the United States, European Union and China have energy policies that affect the entire world, thereby justifying a closer look at their hydrogen policies to draw

[27] In 2021, the top four GHG emitters were China (11.47 $GtCO_2e$/year), the United States (5.01 $GtCO_2e$/year), the EU, 27 countries (2.79 $GtCO_2e$/year), and India (2.71 $GtCO_2e$/year). However, if we consider cumulative emissions across available years (1960-2021), the total amount would be the United States (305.64 $GtCO_2e$), China (244.65 $GtCO_2e$), the EU (212.12 $GtCO_2e$) and India (54.38 $GtCO_2e$). Data available at: https://www.wri.org/insights/interactive-chart-shows-changes-worlds-top-10-emitters and https://www.climatewatchdata.org/ghg-emissions?end_year=2019&start_year=1990

some relevant points for Brazil. In April 2021, United States President Biden pledged to reduce GHG emissions by 50% by 2030 and achieve net-zero emissions by midcentury**.** The ambitious target demands a complete reshaping of the country's energy landscape and economy in general. Hydrogen has then become a key piece to achieve such a target. The United States is among the "**affluent, energy-secure countries"**, having an abundant domestic energy production but needing to reconsider the sources used faced with the urgency to cut emissions.

Currently, the United States mainly uses oil and natural gas (68% of the total energy consumption) as its primary energy source.[28] The most pressing challenge to the country is to put forward renewable energy projects (12% of the total energy consumption) to transform its matrix. Hydrogen is part of the strategy with a major focus on its potential to decarbonize hard to abate sectors. With this view in mind, new United States policies have focused on promoting investments in renewables as well as investments in low– carbon hydrogen, thereby scaling up opportunities that will enable the country to be a leading hydrogen producer in no time.

The recently launched USD1 trillion Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act (IRA) create specific incentives for transitioning the

[28] United States primary energy consumption by energy source in 2021 was: oil (36%), natural gas (32%), renewable energy (geothermal, solar, hydroelectric, wind and biomass) (12%), coal (11%) and nuclear (8%). Data available at: https://www.eia.gov/energyexplained/us-energy-facts/. Visited on March 2023.

economy to net-zero emissions (UINTED STATES, 2021). As to hydrogen specifically, the BIL provides USD1 billion (B) for clean electrolysis research and development (R&D), USD8B for developing regional clean hydrogen hubs and USD500 million for Clean Hydrogen Manufacturing and Recycling Initiatives to support equipment manufacturing and strong domestic supply chains.[29] As for the IRA, it offers tax credits for clean hydrogen production and incentives for new enabling technologies and systems (EFI, 2023).

The European Union (EU) has also set an ambitious net-zero target to its member states, set within the European Green Deal.[30] Despite the specific realities and domestic targets of each country in particular, the EU needs to move away from its relative dependency on natural gas, both because of its net-zero goals and geopolitical concerns.[31] To advance its goals, the region will have to rely heavily on low-carbon hydrogen.[32] The EU hydrogen strategy (EUROPEAN COMISSION, 2020) was adopted in 2020 and suggested policy action in 5 main areas: investment support; support production and demand; the creation of a hydrogen market and

[29] Data available at: https://www.whitehouse.gov/build/. Visited on March 2023.

[30] See note 37.

[31] The Russian and Ukraine dimmed the European economy, especially in a post-pandemic scenario. More information on the impact of the conflict can be found in: Feng-lin Wu et al., *Stock market volatility and Russia–Ukraine conflict.* Finance Research Letters. https://doi.org/10.1016/j.frl.2023.103919 and Z. Umar et al. *The impact of the Russia-Ukraine conflict on the connectedness of financial markets*, Finance Research Letters (2022).

[32] Portugal, a longstanding partner to Brazil's investment plans, approved the National Hydrogen Plan in August 2020, which shows green hydrogen as a relevant vector for the energy transition in the country (PORTUGAL, 2020). Among the goals for 2030, the following are noteworthy: injection of between 10 and 15% of green hydrogen into the natural gas network; construction of 50 to 100 hydrogen fueling stations; 2-2.5GW of installed electrolyser capacity.

infrastructure; research and international cooperation. The goal is to produce 10 million tons and to import 10 million tons of renewable hydrogen by 2030.[33] In the EU context, Germany has a particular relevance to Brazil as a potential importer of clean hydrogen. In June 2020, the country consolidated its National Hydrogen Strategy, reinforcing funding of more than EUR1 billion to be invested in hydrogen projects under the German Decarbonization Program between 2020 and 2023, with an additional EUR7 billion to accelerate the development of the German market and EUR2 billion to support international partnerships, [34] effectively acknowledging that the country will need to import large volumes to achieve the established targets for reducing carbon emissions in its economy (GERMANY, 2020).

Today, China is the world's largest producer and consumer of hydrogen, with an annual output estimated at 33 million tons (Mt) (OXFORD, 2022). Almost all hydrogen is made from coal (60%)[35] and is mainly used in chemical feedstock.[36] In March 2022, China released its Medium- and Long-Term Plan for the Development of the Hydrogen Energy Industry (2021–2035). The NDRC Plan (NDRC, 2022)

[33] For more information, see: https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en#:~:text=The%20ambition%20is%20to%20produce,in%20energy%2Dintensive%20industrial%20processes.

[34] See note 36.

[35] Roughly 60% of China's hydrogen comes from coal and 25% comes from methane. Most of the remaining hydrogen (14%) is a byproduct of petrochemical industry processes. A very small percentage of China's hydrogen comes from electrolysis, 1%. For more information, see: Nakano, "China's Hydrogen Industrial Strategy", CSIS Commentary (February 3, 2022).

[36] Hydrogen is used mainly for ammonia synthesis, methanol production and petroleum refining. In smaller percentages, hydrogen is used in metal smelting, electronics, pharmaceuticals and other sectors.

consolidates China's hydrogen policy initiatives and reiterates previous plans, such as the deployment of 50,000 fuel cell vehicles by 2025; it also calls for the production of 100,000–200,000 tons of green hydrogen per year by 2025 (roughly 0.3% to 0.6% of the current hydrogen production). By 2035, Beijing is aiming to achieve a diversified application of green hydrogen, covering transportation, energy storage and industry. (OXFORD, 2022)

The NDRC Hydrogen Plan, focusing on promoting technological innovation, left the Chinese provinces to choose which hydrogen production routes would be preferable according to local conditions (including resource endowments and infrastructure). The aim is to encourage the provinces to experiment with different technological approaches, scaling up hydrogen infrastructure and on-site hydrogen markets. (NDRC, 2022)

As of 2022, 28 provinces have included the development of hydrogen energy in their provincial "14th Five-Year Plan for National Economic and Social Development and the Outline of Long-Term Goals for 2035" and many other provinces have adopted policies related to the construction and manufacture of hydrogen-related infrastructure. (ZANG, 2022)

These brief highlights on the different strategies indicate some interesting points for Brazil. First, it seems clear that hydrogen has become relevant worldwide for countries and regions having ambitious emissions targets. The interesting point is that, despite the similar end-goal (to fight climate change), not all countries are in the same position from the standpoint of international trade. On the contrary, there are some complementarities among all of these countries that allows each of them to explore their own advantages.

Hydrogen is considered in all the climate initiatives, for some countries as a potential opportunity to become a relevant exporter it and derived green commodities; for others, as an essential piece to accomplish domestic decarbonization targets and, finally, in some cases, as a means to achieve both ends. Despite the domestic need of some sectors to decarbonize, Brazil's position is clearly more prominent as a potential exporter to the market, a position which needs to be properly addressed. That said, it is relevant to note that there are also some competing positions among the countries. Primarily, the United States strategy is focused on its domestic market; however, in the future, the country may become a prominent exporter to Europe, the same position targeted by Brazil.

A second point worthy of note is that both the United States and China have included the development strategies of their hydrogen market in the bigger context of domestic reindustrialization. The idea is not only to produce hydrogen but, also, to promote the whole value chain domestically, as well as to invest in transforming the domestic industry to produce green commodities. This aspect potentially impacts Brazil competitiveness in the international trade arena, which increasingly demands green commodities. In addition, it may also impact Brazil's domestic production of green hydrogen due to the country's reliance on imported essential materials, in particular from China's hydrogen electrolyzers.

The main question is that, although all the circumstances indicate that there is an opportunity for Brazil, there are also signs that the market will reward the first movers. This is a call to an urgent establishment of coherent public policies to promote hydrogen production. The countries that are the first to invest will be able to establish their position, exploring their own advantages as well as overcoming their challenges.

7. EXPLORING OPPORTUNITIES FOR HYDROGEN IN BRAZIL

Brazil is one of the most competitive places in the world to produce green hydrogen. It has a prominent and promising position to become an exporter of low-carbon hydrogen, as it has excellent and favorable climate conditions for generating electricity through wind, solar, water and bioenergy sources.

The country's Northeast region, in particular, presents a huge potential to become a hydrogen production hub, as it has a high potential for wind and solar energy generation and its ports are geographically well located in relation to the main markets in Europe. In addition to Ceará, the state with the highest number of hydrogen projects announced, Rio Grande do Norte, Bahia, Pernambuco and Piauí already have several memorandums of understanding (MOUs) with private initiatives for hydrogen production (IPEA, 2022).

In addition, Brazil has an estimated 1,500 GW of potential in onshore and offshore wind[37], ranking sixth in the Global Ranking of Onshore Installed Capacity.[38] To produce wind energy, stable winds are needed, with the right intensity and without sudden changes in speed or direction. This type of wind is typical in Brazil.

The greatest wind potentials are located in the northern part of the Northeast. The average capacity factor verified for wind farms in the Northeast in the period from May, 2021 to April, 2022 was 39.8%, while in the same period, for wind farms in the South region of the country, it was 33.8%.[39]

There are currently 828 wind farms in operation in the country, 725 of which are located in the Northeast. The Brazilian states that generated the most wind energy in 2021 were Bahia, Rio Grande do Norte, Piauí and Ceará. Together, these states represented approximately 84% of the total energy generated by this source in that period.

As for photovoltaic solar generation, the Brazilian potential is also significant thanks to the high levels of solar radiation present all year round in a large part of

[37] On January 25, 2022, the Brazilian government issued Decree No. 10.946/2022, which provides rules for allocating the use of physical spaces and natural resources in open waters for energy production.

[38] Data available at: https://abeeolica.org.br/. Visited on March 2023.

[39]Data available at: https://www.gov.br/pt-br/noticias/energia-minerais-e-combustiveis/2022/08/energia- eolica-registra-primeiro-recorde-de-geracao-instantanea-de-2022#:~:text=O%20Brasil%20tem%2C%20atualmente%2C%20capacidade,sendo%20725%20parques%20no%20Nordeste. Visited in March 2023.

the country. According to the Brazilian Atlas of Solar Energy,[40] the daily solar incidence ranges between 4,444Wh/m² to 5,483Wh/m² in the country. According to the Ten-Year Energy Expansion Plan - PDE 2026 (BRAZIL, 2017) the installed capacity of solar generation is estimated to reach 13 GW in 2026, with 9.6 GW of centralized generation and 3.4 GW of distributed generation. This proportion may reach up to 5.7% of total power production.

Based on the MOU released, the vast majority of the intended projects will be at Port of Pecém (14), in Ceará, but there are also significant amounts of projects to be located in the Industrial Complex of Camaçari, in Bahia, in Porto do Açu (RJ), in Porto Suape (PE), as well as in the states of Rio Grande do Norte and Rio Grande do Sul.[41]

In addition to wind and solar energy, biomass–based hydrogen is another major opportunity for Brazil. Biomethane,[42] which is equivalent to natural gas, can be used to produce low–carbon hydrogen at a competitive cost, taking advantage of the already existing infrastructure used today in the production of hydrogen from

[40]Data available at: https://americadosol.org/potencial-solar-no-brasil/#:~:text=Segundo%20o%20Atlas%20Brasileiro%20de,5.483%20Wh%2Fm%C2%B2%20no%20pa%C3%ADs. Visited in March 2023.

[41] At Port of Pecém, for example, 24 MOUs have been signed (as of May 2023). For more information see: https://valor.globo.com/brasil/noticia/2023/04/28/hidrogenio-verde-desponta-como-o-combustivel-da-proxima-decada.ghtml

[42] Biomethane (also known as a "renewable natural gas") is a near-pure source of methane produced either by "upgrading" biogas, a mixture of methane, CO_2 and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen-free environment. For more information, see: https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/an- introduction-to-biogas-and-biomethane.

gas, namely "gray hydrogen". Moreover, Biomethane blending could reduce emissions further, even reaching negative emissions depending on the blending rate, when combined with CCUS. (IEA, 2021a, p. 49).

Biogas use also has positive social and economic impacts beyond reducing emissions. Anaerobic digestion plants allow for nutrient recovery (with the production of low-carbon fertilizers), developing local supply chains, often in rural areas, thereby promoting a circular economy and mitigating local pollution (IEA, 2021a).

The Brazilian Biogas Association (ABiogás) calculates that Brazil has the potential to produce 20,000 tons per day of hydrogen from biomethane, or seven million tons per year. Depending on the technology, every 4 or 5 cubic meters of biomethane produces 1 kg of hydrogen.[43]

From an international trade perspective, Brazil not only can become a relevant player in the export of the low-carbon hydrogen produced, but it can also export low-carbon products that are manufactured using low-carbon hydrogen, such as ammonia or steel, which are already traded internationally and may benefit from carbon adjustment mechanisms in some markets in the coming years.

As indicated by McKinsey, the total opportunity for Brazilian green hydrogen is at USD 15-20 billion. Exports to the United States and Europe can account for an

[43] Data available at: https://epbr.com.br/biometano-na-disputa-pelo-hidrogenio/.

immediate USD 4 to 6 billion as the landed cost of Brazilian green hydrogen in these regions should be competitive vis-à-vis potential competitors. The domestic market, which can leverage from international trade, has the potential of generating revenue amounting to USD 10- 12 billion by 2040, primarily driven by trucking and steel manufacture along with other industrial heat energy uses.[44] Therefore, a market demand for Brazilian green hydrogen is already in place.

Moreover, aligning the expectation of reducing costs in the generation of renewable energy with the trend of carbon taxation may favor the production of low-carbon hydrogen at very competitive costs. Carbon pricing can be a valuable instrument in the policy toolkit to promote a rapid deployment of low-carbon hydrogen.

Even though Brazil is in a unique position to become a powerhouse in support of the global transition and to take on a leading role in the international low-carbon hydrogen market, it is essential that the country take advantage of this opportunity and do it fast. As already mentioned, other countries, such as the United States, Australia[45] and China are already moving forward and putting in

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[44] Ibid.

[45] On November 22, 2019, the Council of Australian Governments (COAG) Energy Council endorsed a National Hydrogen Strategy. Australia aims to position its green hydrogen industry as a major global player by 2030, on both an export basis (mainly Asia, but also Europe) and for the decarbonization of Australian industries (with a focus on mining). Due to global developments—and in Australia since the original strategy was developed, including the impact of the Inflation Reduction Act and other policies to support hydrogen emerging overseas—, the Australian government is planning to review its hydrogen strategy in February 2023 (as of the date of publication of this article, the strategy review was still in progress). As for the provinces' specific plans: In October 2021, the province of New South Wales

place all the necessary incentives to develop their hydrogen production, and Brazil cannot fall behind and lose its advantages.

8. LEGAL AND REGULATORY CHALLENGES

Despite all the promises, as already put forward here, hydrogen production costs, storage, transport, distribution, conversion systems and certification still face technological and economic bottlenecks (IEA, 2022). Among all the challenges, reducing production costs, creating a certification scheme and ensuring an adequate public policy able to attract enough investments are particularly pertinent to Brazil's scenario.

The production cost of low-carbon hydrogen using renewables currently ranges from USD3/kg to USD8/kg, well above the cost of hydrogen produced with CCUS-free natural gas, which is as low as USD1/kgH2 in the Middle East (IEA, 2021b). Pursuant to the IEA (2021b, p. 205), the cost gap between fossil fuel and low–

(NSW) released its NSW Hydrogen Strategy. The Strategy provides up to $3 billion in incentives to commercialize hydrogen supply chains and significantly reduce the cost of green hydrogen. In March 2020, the Tasmanian Government published its Renewable Hydrogen Action Plan, with a funding package of $50 million to encourage investment in the hydrogen industry. On February 25, 2021, the Victorian Government released the Renewable Hydrogen Industry Development Plan. Victoria has a pilot project, Hydrogen Energy Supply Chain (HESC), to produce and transport clean hydrogen from Victoria's Latrobe Valley to Japan. Western Australia has a Renewable Hydrogen Strategy launched in July 18, 2019. The Strategy sets out the State Government's strategic areas of focus for the development of the industry in Western Australia: Export Remote applications; Hydrogen blending in natural gas networks and Transport. For more information, see: https://www.dcceew.gov.au/energy/publications/australias-national-hydrogen-strategy and https://h2council.com.au/government-hydrogen-policies/#:~:text=In%20October%202021%2C%20the%20NSW,the%20cost%20of%20green%20hydrogen.

carbon hydrogen is a barrier that needs public policy stimulus to be overcome. There is significant room for cutting production costs by gaining scale and innovation, which could lead to low-carbon hydrogen costing as low as USD1 per kg (ranging from USD1.0 to 3.0 per kg) by 2030 (IEA, 2021b). However, to fulfill this, following the initiatives of other countries, it is essential to put in place an articulated public policy focused on promoting hydrogen at this early stage of development. A remark that Professor Dernbach clearly points in his article "The Dozen Types of Legal Tools in the Deep Decarbonization Toolbox": "it is likely to be difficult or even impossible to achieve deep decarbonization without any additional public law regulation (DERNBACH, 2018, p. 322).

Climate change law is fragmented and covers international and national legislation. Although different, to some extent, it also blends in with environmental[46] and energy law.[47] It encompasses the use of several regulatory tools to address climate change mitigation or adaptation aspects directly or indirectly. Because it is also a recent human concern, climate change mitigation

[46] "Because the great majority of GHG emissions are due to the use of fossil fuels for energy production, climate change law necessarily includes or is based on a good deal of energy law—a field of law that historically has been considered separate from environmental law. While environmental law regulates the environmental effects of energy extraction and production, energy law regulates the way in which energy is priced, marketed, and distributed. It is impossible to address climate change without also addressing those features." Dernbrach, 2018, p. 322. For a more detailed view on Energy Law see: RAPHAEL J Heffron and others, A treatise for energy law, The Journal of World Energy Law & Business, Volume 11, Issue 1, March 2018, Pages 34–48, https://doi.org/10.1093/jwelb/jwx039.

[47] Many of the typologies, particularly the more recent typologies, do not distinguish between environmental law instruments and climate change law instruments, effectively treating climate change as a form of environmental law. Dernbach 2018, p. 322.

and adaptation also require a significant amount of new legal and regulatory apparatuses specifically designed to deal with the problem. Fostering new technologies is an important part of finding ways to put the climate on a good track. While hydrogen production and its uses are not exactly a new technology, to produce clean hydrogen is for sure a technology that has yet to mature.

There are several legal and regulatory instruments available to promote or accelerate new technologies to scale up. This paper draws on Professor Dernbach's work (DERNBACH, 2018) to select some of the possible avenues to promote hydrogen, which could be applied to overcome part of the challenges faced in the case of Brazil. According to Dernbach, the legal toolbox aimed at mitigating climate change include, among others, additional regulations, the reduction or removal of legal barriers, market-leveraging approaches, removal incentives for fossil fuel use, tradable permits or allowances, information/persuasion, infrastructure development, insurance and social equity instruments. Each of them can be looked at from the perspective of promoting hydrogen.

Additional regulations, in particular the command-and control type, which directly limits GHGs emissions, have the effect of incentivizing research and the use of new technologies. Hydrogen is currently used in the value-chain of many economic sectors. Agriculture, steel and mining are particularly relevant to Brazil's economy. Regulations that restrict GHGs in these sectors will favor the exchange of fossil fuel–produced hydrogen use for sustainable alternatives such as low–carb hydrogen. Similarly, regulations could also incentivize new uses for clean hydrogen in aviation and shipping as a new fuel, for instance. Despite the many challenges that always exist in the introduction of new restrictive regulations, it is undoubtedly a useful and powerful mechanism to promote the shift from a fossil-fuel economy to one based on clean alternatives.

The reduction or removal of legal barriers is a more subtle approach to promote hydrogen use. There are several legal instruments that intentionally or unintentionally promote the use of specific sources of fossil fuel energy or technology. The inventory of these pieces of legislation and the reevaluation of their aim in the current decarbonization process is a necessary, albeit complicated, task to stimulate clean technology innovation. As an example, the recently enacted Law No.14,182/2021, which requires new public tenders to buy natural gas, has been seen as a future limitation to consolidate a domestic market for renewable–based hydrogen production in regions endowed with plenty of favorable conditions for renewable projects.[48] In the same direction, continuous permits for new fossil fuel projects may delay the transition process as infrastructure

[48] "Concerns about the reliability of hydropower amid growing water scarcity have led the government to seek to expand gas-fired power production, potentially increasing the carbon intensity of the Brazilian economy. In June 2021, as part of a new law to privatize Eletrobras, the largest generation and transmission utility in Brazil, the National Congress required that 8 gigawatts (GW) of thermal capacity be installed by 2030. These plants are required under the law to be at least 70 percent inflexible, resulting in a substantial increase in thermal power in Brazil's baseload power supply." World Bank Group. Brazil Country Climate Development Report, p. 14. 2023.

undertakings have a long lifetime. An affirmative action in this respect would be to facilitate the permit process for renewables and hydrogen plants, reducing the burden on these projects.

Market-leveraging approaches are key to developing new technologies. They represent "a mode of governance that intends to affect market behavior by using prices, incentives, and other market signals within already-existing markets." These approaches leverage existing "markets by either adding penalties or providing subsidies in accordance with environmental objectives." Thus, one category of market-leveraging tools creates negative financial incentives, making disfavored actions more expensive. They include pollution charges, taxes and fees. The other category of market-leveraging tools embraces positive financial incentives to engage in the desired behavior. Subsidies, for example, "provide economic incentives for environmentally friendly behavior or investments." Financial incentives also include tax credits, tax deductions, and other tax incentives. A variety of tax credits and other financial incentives exist for renewable energy, energy efficiency, and alternative fuel vehicles." (DERNBACH, 2018, p. 333).

Temporary subsidies are particularly relevant to nascent industries. Although tax waivers are controversial in developing countries such as Brazil, the positive impacts that new sustainable technologies can have in the country's future economic development model will probably be rewarding in social, economic and environmental terms.[49] In the case of hydrogen, subsidies can be directly applied to the final production as well as to the cost of energy since clean electricity is the most relevant component of hydrogen cost production. The green strategies of the United States, China and the EU[50] involve subsidies both to hydrogen production itself and to investments in renewable energy production and transmission costs, the latter in particular is an option that might accelerate their decarbonization path. Tradable permits or allowances are also, in a sense, marketed leveraging tools. (DERNBACH, 2018, p. 335). In a very simplistic account, Cap and trade regulations impose limits on the amount of emissions allowed while simultaneously creating a market for trading allowances. Cap and trade mechanisms are different from carbon taxes;[51] both instruments, however, have the same objective, which is to price the carbon. Pricing carbon emissions reduces the cost gap between clean

[49] Regarding the possibility of creating jobs while developing the hydrogen value chain in Latin American countries, the IEA (2021, p. 13) stated: "*Scaling up low-carbon hydrogen and use will require timely investments in enabling infrastructure, including new transmission lines (for low-carbon electricity to reach the electrolysers for on-grid projects), hydrogen transport and storage infrastructure and port terminals. New value chains will be needed to support this scaling up, such as the installation of electrolyser manufacturing plants in the region, creating jobs and economic opportunities*. […] *Developing capabilities across the hydrogen value chain, such as equipment manufacturing, hydrogen production, infrastructure development and end uses, could bring additional benefits beyond emission reductions, including economic development, jobs and opportunities for investors".*

[50] The United States and the EU are implementing their own subsidy schemes to boost investments in renewable energy. The IRA has committed $400bn in investments and subsidies to cut down the country's greenhouse gas emissions and accelerate the adoption of renewable technologies. In response, the European Union has proposed its own €250 billion green subsidy package—the Green Deal Investment Plan—which will introduce new tax breaks and loosen the bloc's state aid rules to further boost private sector renewable investment. For more information, see: https://www.energy.gov/lpo/inflation-reduction-act-2022 and https://www.weforum.org/agenda/2023/03/what-do-green-subsides-mean-for-the-future-of-climate-and- trade-099a016307/

[51] "Analyses and extensive public consultations done under the Partnership for Market Readiness (PMR) Brazil Project determined that in Brazil, an ETS tends to draw more political support than a carbon tax". (WORLD BANK, 2023, p. 28)

technologies and fossil fuel–based ones and, by doing so, have a positive impact in terms of incentivizing new technologies.

In this regard, Brazil has already established the foundations for an emissions trade system with the issuance of Executive Decree No. 11,075/22.[52] However, while establishing a Carbon Cap and trade system is an important step, implementing a national mandatory GHG measurement, reporting, and verification (MRV) system for large emitters—a required step towards the setting-up of an ETS—remains essential. (WORLD BANK, 2023, p. 28).

Another way of reducing the cost gap existing between clean and fossil fuel technologies is by reducing subsidies in the latter case. In Brazil, "Subsidies to fossil fuels totaled US$ 21.9 billion in 2021, a 4.17% reduction from 2020. A total US$ 13.3 billion were given to consumption, while production received US$ 8.58 billion, which means consumption received 60.84% of the subsidies" (INESC, 2022). Even though it is a highly controversial proposal given that part of the fossil fuel subsidies is thought to ease consumer costs— and that a significant amount of these go to pay government royalties—reducing fossil fuel subsidies over time is essential to level the play field between technologies.

[52] The Bill of Law (PL 528/2021, later attached to PL 2.148/2015) has yet.to receive a vote. The decree is an important initial step towards establishing a carbon market and calls for relevant ministries to establish sectoral emissions reduction targets, while also providing for the creation of a centralized registry for corporate GHG emissions, GHG mitigation projects and resulting carbon credits. However, the decree does not imply any mandatory participation (World Bank, Brazil Country Climate Development Report 2023, p. 28).

Information requirements can also act as regulatory instruments to promote new decarbonization technologies. Legal instruments "requiring information production and dissemination" can change behavior, not by compelling outcomes, but by causing people to think about what they are doing and, thus, encouraging them to change their behavior (DERNBACH, 2018, p. 335).

In the case of hydrogen, information requirements by the industrial sectors enable the government to access relevant data allowing for the establishment of appropriated decarbonization targets and this can be used by consumers to guide their choices. Dernbach (2018, p. 337) cites some examples of information tools that could be useful in this context; for instance, the disclosure of GHG emissions could be used to measure and manage environmental impacts; eco-labeling requirements could unveil a product's carbon footprint, allowing for a more conscientious choice by the consumer; and the development of information systems could facilitate the use and comparison of data.

In the same direction, the standard setting also plays an important part in terms of creating markets for new environmentally friendly technologies. Legally established standards are intended to harmonize processes within an activity, having a significant influence on urging the hard to abate sectors such as steel and mining to adhere to decarbonization practices and technologies. Once the market values a specific standard, it shapes the industry path to meet demand.

Certification is a kind of procedure for setting standards that significantly impacts the clean hydrogen market in development. At this stage, it is crucial that Brazil make its way to have a say on certification discussions as hydrogen tends to be a very international market.[53] Since Brazil seeks to occupy a relevant position in the market, domestically produced hydrogen and its products will be required to comply with international certification requirements and guarantees of origin schemes. It is noteworthy that private organizations, universities and NGOs can also establish monitoring, measurement and verification schemes within a particular industry.

The "establishment of an international hydrogen market will depend on the development and acceptance of certification systems that provide information on the emissions footprint of the hydrogen production value chain" IRENA (2023, p. 11).

IRENA (2023, p. 9) evaluated eight voluntary and five mandatory schemes of hydrogen certification to identify the existing gaps. In its conclusion, the agency stated that "none of the existing hydrogen certification systems are suitable for cross-border trade." The main gaps were in standards and in ecolabelling and certification design, resulting in insufficient information in the certificates to allow

[53] For a detailed discussion on certification impacts, see: Vazque, M. and Hallack, M. The International Implications of the European Process for Low-Carbon Hydrogen Certification, European Energy & Climate Journal, 2022, Vol. 11, No. 2, 2022, 66-75.

a fair comparison across borders; a lack of clear information on greenhouse gas emissions produced during hydrogen production and/or transportation; insufficient reference about standards used; and lack of proof regarding compliance with environmental, social and governance criteria.

All these gaps and lack of a certain degree of harmonization in standards hinder the development of an international market for sustainable hydrogen as well as impact the domestic markets, which tend to postpone their own legislative initiatives in anticipation of an international standard to come up; thus, a vicious cycle ensues. On the other hand, this gap also offers a huge opportunity for first comers to set the market through their initiatives.

Infrastructure development has always been an important part of promoting any industry that relies on it to scale up as is the case of hydrogen. "Because deep decarbonization would transform the way in which energy is produced and used, it necessarily involves changes in infrastructure—the physical structures and systems for transportation, energy production and supply, and buildings. While infrastructure is threatened by climate change, it must also play a significant role in reducing GHG emissions" (DERNBACH, 2018, p. 340).

In order to incorporate new technologies, Brazil needs improvements in its infrastructure in many sectors.[54] The transportation sector illustrates the case. The sector is one in much need of investment to promote the connection of Brazil's far–flung regions in order to interconnect regions and allow for the exportation of commodities under competitive conditions.

In legal terms, most of Brazil's transportation at the federal level is regulated by concession law and characterized by long–term concession contracts that were not originally thought out to promote sustainability aims. These contracts would need to be revisited to be able to reflect the new logistic demands related to vehicle recharges, for instance.

Port infrastructure investment is another essential action to advance a sustainable hydrogen industry. Today, Brazil has some important and strategically located ports[55] that can work as port-industries for hydrogen production. Legally

[54] To accelerate the penetration of hydrogen in national markets, governments need to support investments in infrastructure (Hydrogen Council, 2020). Pursuant to the EPE (2019), "the production and industrial uses of hydrogen in Brazil are relatively consolidated. However, the broader use of hydrogen-based energy projects will require a more continued investment in research, development, and innovation to allow the country to become a relevant actor in the Hydrogen Economy. The diffusion of new technologies, the development of an infrastructure of production, storage, transport, and distribution of hydrogen are important topics to be addressed in this context." Likewise, the PNE 2050 highlights the need "to design regulatory improvements related to quality, safety, transportation infrastructure, storage, and supply, as well as to encourage and to promote the use of new technologies," in order to develop the hydrogen market in Brazil.

[55] The National Port System is made up of Organized Ports, Private Use Terminals and groups of Port Facilities. There are currently 37 organized ports and around 194 Private Use Terminals (ANTAQ, 2020; Ministry of Infrastructure, 2020; EPE, 2020). For the purposes of this paper, we highlight the ports that have already shown interest in developing hydrogen projects, either by signing MOUs or creating partnerships with European Countries: (i) Açu Port, in Rio de Janeiro; (ii) the Pecém Complex, in Ceará, which is developing a hydrogen hub. The project has the ambitious goal of producing 900 thousand tons of H2V per year from an electrolysis capacity of 5 GW (Machado, 2021); (iii) The Industrial Port Complex of Suape, in Pernambuco, which signed a research initiative with the United Kingdom; (iv) Porto RS, a public company responsible for organizing, managing and supervising the entire hydroport system in the state of Rio Grande do Sul, which signed an intentions protocol with the Rotterdam Port and the Dutch government to develop hydrogen in the region. The international search for these ports is strategically based

speaking, legislation governing the sector needs to be remodeled to attract private investments to modernize the industry's capacity and efficiency. Tax legislation also needs to be adapted for that same purpose. There are currently some special tax port systems aimed at boosting the Brazil's competitiveness in international markets.

Insurance and financial reports can also play a role as regulatory tools to accelerate the process of decarbonization, boosting the use of new fuels such as sustainable hydrogen. Insurance can be shaped to modify behavior in many contexts. It provides a way of readjusting and relocating risk; therefore, it can be an instrument to incentivize environmental and sustainable business practices (DERNBACH, 2018, p. 345). Technically, this strategy does not completely fit into a legal instrument categorization, falling more into a private governance tool. However, as most hard–to–abate sectors need insurance at some point of their value chains, changing the insurance requirements in favor of more sustainable practices has a huge impact on the decarbonization process of such sectors.

In general, carbon–intensive practices can be seen as risk enhancing from the perspective of insurance standards, thereby increasing the premium paid by GHG emitters' activities with a significant impact on companies' propensity to allocate

on factors such as location, export logistics, tax incentives, proximity to industrial centers, and the regions' ability to develop renewable energies.

more investment towards new technologies. In the same vein, green financing standards can have a similar impact since access to capital is also rated according to risk allocation.

In addition to working as a GHG emitters' deterrent, insurance and financing can play a particularly important role in supporting new technologies. The availability of insurance and low–rate financing can help sustainable technologies to get off the ground. (DERNBACH, 2018, p. 346)

In this regard, a recent report from the Carbon Capture Storage Brazil – CCS (CCS Brasil, 2023) organization has highlighted the need for regulation and finance alternatives to promote CCS technologies that are most relevant towards developing low–carb hydrogen.

Accordingly, "like any embryonic economic activity, the existence of an attractive institutional environment is a crucial and determining aspect for the implementation of CCS projects in Brazil" (CCS Brasil, 2023). The report goes on to indicate that such an institutional environment must be structured based on three pillars: adequate regulations for guaranteeing the implementation and safe operation of these projects, clarity in decarbonization goals and obligations, and clear policies for economic projects.

According to the report, since structuring the CCS chain, all stages have witnessed a need to be capital intensive, i.e., heavy investments are necessary for equipment acquisition to make viable CCS routes that can be driven by the creation of designed purpose financing pushed by development banks, reinforcing the role of the State in stimulating the decarbonization of the economy (CCS Brasil, 2023, p. 42). This illustrates the relevant role that finance arrangements play in the initial stages of new technologies such as CCS technologies and sustainable hydrogen production. Currently, in Brazil, there are already some financing mechanisms aimed at promoting low–carbon hydrogen projects.[56] For example, the Brazilian Development Bank (BNDES)[57] has developed a Sustainability Bond Framework (BNDES, 2021) under which a company is able to issue Green, Social and Sustainability Bonds domestically and abroad, and use the proceeds to finance and refinance expenditures related to new and existing eligible projects. According to the framework, green hydrogen (BNDES, 2021, p. 9) production is an eligible green category classified under a Renewable Energy projects title. Another example are the possibilities springing from federal Decree 10,387/2020, which establishes special tax benefits for debentures issued with the specific aim of financing infrastructure projects with environmental and social benefits.

However, despite the positive aspects of these mechanisms, incipient markets and

[56] Brazil is one of the largest green finance markets in Latin America, with nearly USD 6 billion in green debentures issued since 2016. For more information, see: https://www.bndes.gov.br/wps/wcm/connect/site/82a951ca-d413-4abf-8a62-f7337624d4f3/BNDES_011_GEDIT_framework_INGLES_final.29.03.pdf?MOD=AJPERES&CVID=o82sgow

[57] The Brazilian Development Bank (BNDES – Banco Nacional de Desenvolvimento Econômico e Social, in Portuguese), established in 1952, is a wholly owned federal government company supervised by Brazil's Ministry of Economy. It is the main instrument of the Federal Government for long-term financing and investments in several sectors of the Brazilian economy.

technologies such as sustainable hydrogen projects need specific target incentives and policy efforts to scale up to the levels needed to address climate change impacts.

Ensuring social equity throughout any decarbonization process is also an essential requirement to guarantee fairness throughout the transition process towards a more sustainable economy. This also demands the use of legal tools specifically designed to promote social ends. "Even if many of these tools do not directly reduce GHG emissions, they should be considered as part of the package or suite of tools needed for deep decarbonization" (DERNBACH, 2018, p. 346). Regulation and funding aimed at providing clean energy access to low–income communities illustrate some of those tools. Promoting a sustainable hydrogen economy in Brazil has a particular impact in this regard. Currently, a large part of the Amazon region's energy supply comes from fossil fuels; sustainable hydrogen could replace a significant part of those demands. Additionally, the development of a green economy based on hydrogen production may have a positive impact in job generation in Brazil, allowing for a fair transition in terms of the labor force.[58]

As seen above, there is a significant variety of legal and regulatory tools that are

[58] The European Commission estimates that every billion of investment in green hydrogen will create 20,000 jobs along the supply chain – production, transmission, storage and utilization. It is also estimated the green hydrogen economy could create as many as 5.4 million upstream jobs in the EU by 2050, of which about one-third of new jobs would be associated only with fuel cells. That is almost three times the number of jobs in the EU chemical industry. For more information see: https://knowledge4policy.ec.europa.eu/publication/gas-climate-%E2%80%93-job-creation-scaling-renewable-gas-europe_en.

able to foster economy decarbonization. This urgent issue demands the deployment of a mix of policies and the use of several tools in a coordinated fashion. Far from being prescriptive or exhaustive, the purpose of this paper is to draw attention to some possibilities and to contribute to a broader discussion on what would be the role of the State and the lines of action in the much needed unleashing of new decarbonizing technologies.

9. CONCLUSION

Hydrogen will play a key role in the energy sector transition and decarbonization of hard- to-abate sectors that cannot be feasibly electrified yet, as well as help to unleash the potential to boost the country's economic growth in a more sustainable way. When analyzing the role of low-carbon hydrogen in Brazil, it cannot only convey social and economic benefits, but also contribute to the country and the world's decarbonization process.

Brazil is one of the most competitive places in the world to produce green hydrogen. It has a prominent and promising position to become an exporter of low-carbon hydrogen, as it has excellent and favorable climate conditions for generating electricity through wind, solar, water and bioenergy sources. This extremely advantageous position in the global scenario assumes even better contours when coupled with the possibility of stimulating a domestic process of green neo–industrialization. The Brazilian economy significantly relies on commodity exports such as steel, mining and agriculture products and green hydrogen has a huge potential to play a key role in the decarbonization of those industries, enabling the transformation of current Brazilian exports to a high value–added market of green commodities. The evidence suggests that Brazil indeed has a concrete opportunity for translating its comparative advantage into an effectively competitive one. This prospect, however, critically depends on the policies to be adopted and their proper timing.

As shown in this paper, Brazil already has a set of regulatory instruments to become a sustainable hydrogen powerhouse. However, the existing legal, institutional and economic structures need to be coordinated and refined to keep up with the ongoing worldwide race for hydrogen. Brazil needs to use these existing instruments to draft an adequate public policy that will create a safe and thriving scenario for investments in order to boost Brazil's hydrogen industry, as other countries are already doing. Brazil's hydrogen moment is here and now, and the country must use all its advantages (geographical, regulatory, and financial) to create sustainable and equally distributed growth of its population while simultaneously contributing to the global fight against climate change. It is the perfect opportunity to ally climate change action with sustainable development.

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