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12 Insights on Hydrogen – Brazil Edition

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PtX Hub Berlin

IKI International Climate Initiative

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Preface

Dear reader,

Brazil is in the spotlight when the role to be played by renewable hydrogen in the global pursuit of climate neutrality is being discussed. Brazil boasts a unique combination of renewable energy sources, minerals and other raw materials, has a consolidated bioenergy industry and extraordinary human capital.

This enables the country to play a key role in decarbonising global carbon-intensive value chains. The trading potential of hydrogen and its derivatives also presents an opportunity for Brazil to create the social and economic benefits of a hydrogen economy.

This report leverages Brazil's current political momentum to strive for a more ambitious global industry decarbonisation agenda with the G20 presidency in 2024 and the hosting of COP 30 in 2025. At the same time, it contributes to the national debate and enhances international understanding of Brazil's industrial and energy potential – through hydrogen and PtX – to promote a new green industrialisation process in the country, fostering green and future-proof jobs.

Our analysis shows that good governance is needed to secure investments and technology development. Internationally, Brazil is in a good position to establish strategic partnerships for creating win-win situations for both Brazil and its partners.

We wish you a pleasant reading!

Yours sincerely,

Rosana Santos
Executive Director, Instituto E+ Transição Energética

Frank Peter
Director, Agora Industry

Key findings at a glance

1 **Brazil's vast energy resources, together with its experienced industrial sector, position the country as one of the world's potential hubs for the production and trade of power-to-x products.** Hydrogen and PtX production represent an opportunity for sustainable growth of the Brazilian industrial sector; with cost-competitive and abundant renewable energy resources, Brazil can attract industrial value chains to advance business models, while providing important socio-economic benefits to the country.

2 **Direct use of renewable power may be prioritised, with hydrogen playing a secondary role.** Brazil's National Hydrogen Programme (PNH2) may prioritise the use of hydrogen and PtX products in key sectors such as industry, shipping and aviation, where direct electrification or direct use of biomethane from residual biomass is not feasible. This will require an integrated planning across sectors such as energy, industry, transport, infrastructure and environment.

3 **There is a need to assess the complementarity of resources and their hydrogen potential in each of Brazil's regions to harness their unique capacities**. The country's vast territory offers opportunities to explore different technological pathways for industrial development and production of PtX products based on Brazil's diversity of energy and natural resources.

4 **Given its relevant role in the international geopolitics, Brazil can be a leader in advancing the industry decarbonisation agenda and developing strategic partnerships for a global PtX market.** As the president of the upcoming G20 meeting in 2024 and host of the UN Climate Conference in 2025, Brazil can be a pioneer in developing strategic partnerships to create benefits within and across regions.

Content

Hydrogen to position Brazil as a global leader in energy transitions

The projections for global hydrogen consumption, from 95 million tonnes (Mt) in 2022 (IEA, 2023f) to between 400 and 1 200 Mt per year in 2050 (as shown in Figure 1), create a unique opportunity for countries with a high availability of renewable energy sources, such as Brazil, to become global leaders in the energy transition.

These various scenarios, which estimate a rapid increase in global hydrogen demand, assume that it will be driven by applications that truly need hydrogen to become climate-neutral in industry and transport (mainly aviation and shipping).[1]

1 In the power sector, hydrogen will mainly be used in storage applications to further integrate variable renewable energy into the grid. However, hydrogen demand in the power sector is the most difficult to forecast due to the high availability of dispatchable hydropower in the country and the fact that the technological landscape is more complicated than in other options available for industrial heating and mobility applica-tions. On the other hand, given the many applications outside the power sector, hydrogen may be more scalable than any other technology.

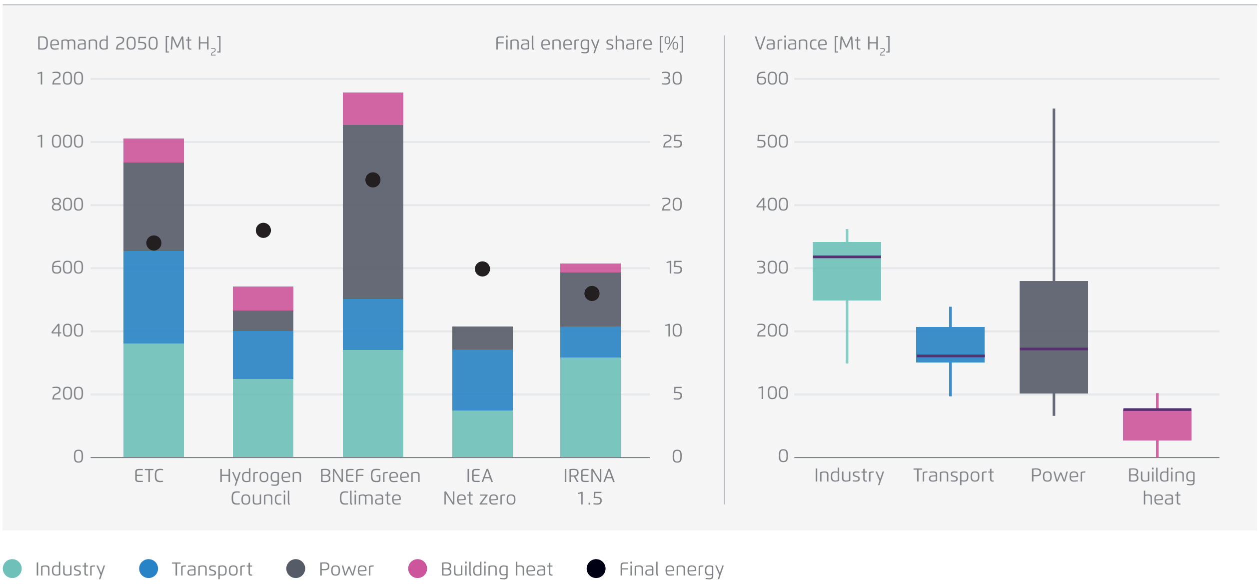
The new global hydrogen economy offers a window of opportunity for Brazil to contribute significantly to decarbonising its national industry and top-emitting industries abroad while creating economic, environmental and social benefits for its population.

An overview of Brazil's energy context

Brazil is already a global benchmark in the promotion of renewable energy. The country has achieved a high penetration of renewable energy sources, which account for around 45% of its total energy supply. By comparison, the share of renewables in the OECD is about 12% (EPE, 2023b) (see Figure 2).

This difference is greater in the case of power generation: the share of renewable sources in Brazil's electricity mix reached almost 90% in 2022 but only a little above 30% in the OECD (EPE, 2023b).

Estimates of global hydrogen demand in 2050: selected scenarios → Fig. 1



Agora Energiewende and Agora Industry (2023). Note: Final energy does not include feedstocks and other non-energy use; ETC = Energy Transition Commission; BNEF = BloombergNEF; IRENA = International Renewable Energy Agency; IEA = International Energy Agency. Final energy figures taken from respective sources.

With a contribution of nearly 60%, Brazilian hydropower is the primary power source and can serve as an energy storage reservoir. Over the years, other renewable energy sources, such as biomass, wind and solar PV, have progressively increased their share. Notably, solar PV and wind energy have exhibited the most substantial growth in recent years, with the share of wind energy increasing from 9 to 12.6% between 2019 and 2022, and solar PV rising from 1.5% to 3.9% over the same period (EPE, 2023b).

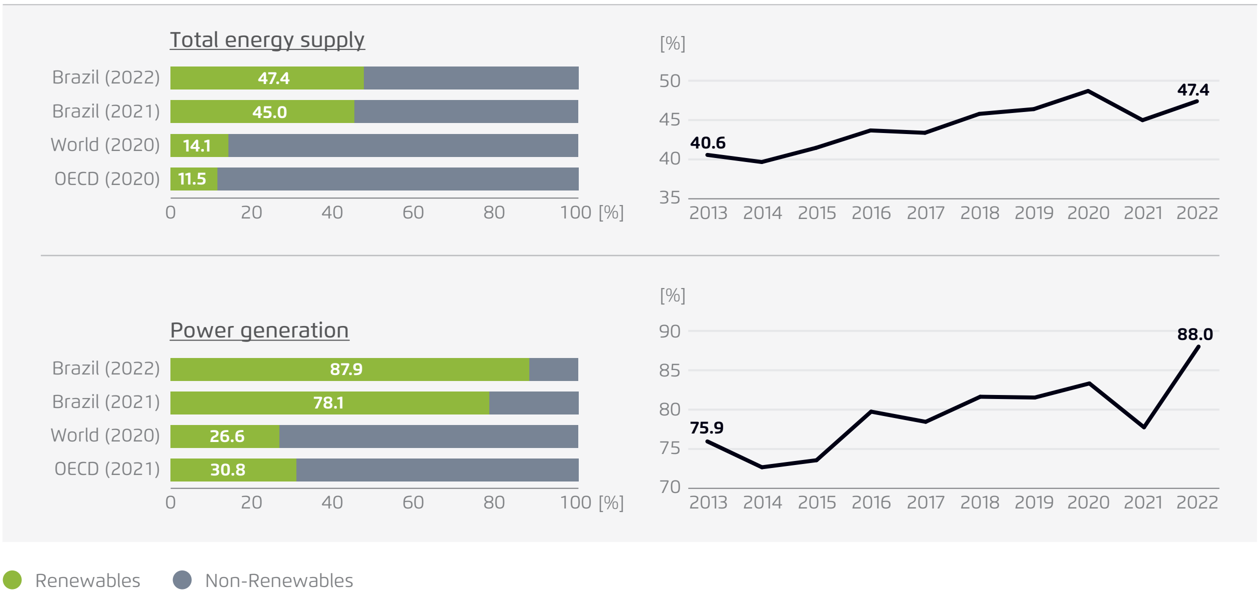
Thanks to its high availability of renewable energy resources and the priority traditionally given to the use of low-carbon generation technologies, the Brazilian energy sector contributed only 18% of the country's gross greenhouse gases (GHG) emissions in 2021 (SEEG, 2023a) (see Infobox 1) – whereas worldwide, the energy sector was responsible for 73.2% of emissions in 2019 (Ritchie, Roser, & Rosado, 2020).

Brazil's diverse and vast energy resources provide the country with the potential to use different technological pathways to produce hydrogen that the country aims to define as low-emission hydrogen, i.e. hydrogen produced by renewable energy sources or processes with low greenhouse gas emissions (see Infobox 2), at competitive costs. Brazil can achieve low-emission hydrogen production of around 1 Mt H_2 per year by 2030 (Klevstrand, 2023) and further upscale this to become one of the key players in the global hydrogen market by 2050. Some analysts expect that Brazil will be able to produce more competitive renewable hydrogen than new fossil-based hydrogen plants with carbon capture and storage (CCS) from 2024 onwards (BloombergNEF, 2022).

Furthermore, Brazil's abundant and cost-competitive renewable energy resources, together with its experienced industrial sector, position the country as one of the world's potential production hubs for Power-to-X (PtX) products such as green steel, green direct reduction iron and hot briquetted iron (DRI-HBI), green ammonia, e-methanol and e-kerosene, among others.

Comparison of total energy supply and power generation: Brazil, the World and the OECD

→ Fig. 2



Infobox 1: Brazil's NDC and climate-neutral aspirations

Brazil emitted 2.4 billion tonnes of GHG in 2021, a 12.5% increase from 2020. This rise in emissions is the second-largest increase in more than two decades, in both absolute and percentage terms, surpassed only by the 20% growth observed in 2003, when emissions reached their historic peak. This increase is over twice the estimated global average for the same year (SEEG, 2023b).

As a signatory to the Paris Agreement, Brazil submitted its first Nationally Determined Contributions (NDCs) in 2016, which were reviewed in 2020, 2022 and 2023 (Chambers and Partners, 2023). Both the 2020 and 2022 revisions presented emissions that were less ambitious than those initially submitted in 2016. The target set in 2022 (1.28 $GtCO_2eq$), while less ambitious than Brazil's 2016 NDC for 2030 (1.2 $GtCO_2eq$), already represented an improvement over the 1.62 $GtCO_2eq$ presented in 2020 (Talanoa, 2022). In September 2023, the expectation of increased climate action from the current government, based on its campaign proposals, was confirmed when Brazil's Inter-Ministerial Committee on Climate Change unanimously returned to the 2016 NDC ambition levels. This decision is in line with campaign pledges to more aggressively reduce carbon emissions and reaffirms Brazil's commitment to achieving near net zero emissions by 2050 (MMA, 2023).

The agriculture, forestry and land use (AFOLU) sector has historically been the largest contributor to carbon emissions, accounting for more than two thirds (73.8%) of Brazil's total GHG emissions. More than 93% of AFOLU-sector emissions are generated primarily by deforestation, land degradation or conversion between rural activities (61%), followed by enteric fermentation from livestock (21%) and nitrogen increase through fertiliser use and inadequate cropland management (10%). The second largest contributor to Brazil's emissions is energy use and consumption, at 17.9% (transport, power generation, industries, fuel production, buildings, agribusiness and government), followed by industrial processes at 4.5%. The remaining 3.8% comes from waste emissions (SEEG, 2023a).

In 2022, carbon emissions from power generation in Brazil were around 61.7 kg CO_2eq/MWh. When comparing emissions from the generation of 1 MWh electricity, for instance, the Brazilian power sector emits approximately 34% of the emissions of the European OECD, 24% of the United States, and 12% of China's power sector (EPE, 2023b).

Hydrogen as a driver of Brazilian neo-industrialisation

Hydrogen and PtX products could introduce and promote the concept of domestic green and sustainable neo-industrialisation in Brazil, framing the potential industrial growth that necessarily requires decarbonisation and innovation. Neo-industrialisation and the expansion of exports in energy commodities and industrialised green products could lead to local job creation, economic development, social equality and environmental sustainability.

A neo-industrialisation agenda is gathering momentum with the support of the government and the private sector (CNI, 2023; EBC, 2023). Brazil's Multi-annual Plan 2024–2027 acknowledges renewable hydrogen potential as a new opportunity for the country and prioritises neo-industrialisation (MPO, 2023). This strategy aims to counteract the decline in industrial GDP and tap into Brazil's rich renewable resources and biodiversity.

In this regard, Brazil has a substantial domestic market for low-emission hydrogen that has yet to be fully exploited. The low-hanging fruit is to replace imported embedded hydrogen, mainly fertilisers, which are of strategic importance for Brazilian agribusiness. The agricultural and livestock sector currently accounts for around 8% of the country's GDP (CNA, 2023; IBGE, 2023a). In 2021, Brazil was the third largest consumer of fertilisers, after China and India (IFA, 2023). At the same time, the country was the second largest importer of fertilisers in 2022, after the EU (WTO, 2023), so the production of green ammonia for fertilisers has great potential in Brazil.

In 2022, the industry and transport sectors represented around 65% of total energy consumption in Brazil (EPE, 2023b). The steel and cement industries combined contribute over 60% of the sector's GHG emissions in 2021 (SEEG, 2023c). As a major steel producer, Brazil could use DRI-HBI for the necessary decarbonisation of its steel production. For the aviation and shipping sectors, hydrogen and its derivatives are also one option for mitigating emissions.

Brazil's contribution to global decarbonisation

Brazil's hydrogen and PtX products have the potential not only to promote domestic neo-industrialisation but also to contribute to global decarbonisation. Brazilian low-emission products can be used in other countries to diversify value chains, reduce fossil fuel dependence and promote international cooperation in the fight against climate change.

Latin America's hydrogen demand accounts for only around 5% of global hydrogen demand (IEA, 2021a), which amounted to almost 91 Mt H_2 in 2019 (IEA, 2022a); Brazil only accounted for about 0.44% of global demand in 2019, at around 0.4 Mt H_2 (IEA, 2021a). These figures place Brazil far behind the largest global consumers, such as China (almost 30% of the world market), the United States and the Middle East, which are both in second position (at 13%), and Europe and India, which jointly rank third (both 8.5%) (IEA, 2022a).

It is quite likely that some countries with higher hydrogen demand will not be able to satisfy their own domestic requirements for low-emission hydrogen. Some Asian countries such as Japan and South Korea, and some European countries such as Germany, have already positioned themselves in their national hydrogen strategies as importers of low-emission hydrogen in the medium and long term.

Renewable-rich countries like Brazil can play a key role in supplying PtX products to major world demand centres while reaping additional benefits. These include not only the domestic economic, social and environmental benefits generated by a neo-industrialisation project, as mentioned above, but also additional trade-related benefits such as avoiding being taxed at the border (e.g. the Carbon Border Adjustment Mechanism-CBAM)[2]. Brazil can enhance its approach by aligning trade and foreign direct investment strategies. Such coordination is the key to reducing market risks for all economic agents involved, while fostering a mutually beneficial environment. This strategy not only puts Brazil in a position to excel at exporting higher value-added products, but also strengthens the financial attractiveness and feasibility of projects for potential investors.

2 CBAM is a mechanism allocating emissions tariffs on imports of goods to the EU, including cement, ammonia, fertilisers, iron, steel, aluminium and hydrogen. The CBAM transitional phase (with reporting obligations) starts on 1 October 2023 and runs until the end of 2025. The definitive methodology is expected to be fine-tuned by 2026. Financial obligations will only begin in 2026 when products imported into Europe will be taxed in euros per tonne of CO_2 emitted, according to the price of the EU emissions trading system (ETS) carbon allowances (European Comission, 2023a).

Infobox 2: Definition of low-emission hydrogen

In February 2021, the Brazilian Energy Research Office (EPE) presented a technical note on conceptual aspects of hydrogen for consolidating the Brazilian hydrogen strategy (EPE, 2021), including a discussion of the effectiveness of classifying hydrogen by colour. The document points to the lack of a consistent definition of hydrogen, with different countries considering different technological pathways for each colour. In its national strategy, Germany for example defines turquoise hydrogen as the methane decomposition pathway, but only if the heat source is carbon neutral. When referring to green hydrogen, certain renewable technological routes have not been included, such as pyrolysis, gasification or bio-digestion of biomass, or end-of-life plastic waste. Other colour codes also vary between regions and technologies.

At the same time, the Brazilian government and some international initiatives are seeking a broader definition of hydrogen that would embrace a wider range of sources such as nuclear, geological hydrogen, biomass and biofuels, among others. The term "renewable hydrogen" has been used to designate hydrogen produced by electrolysis, mostly using wind and solar PV energy, while the term "low-carbon hydrogen" has been used to designate hydrogen produced from non-renewable fuels with carbon capture and storage (CCS) technology. These definitions do not clearly identify the status of biomass production routes.

For this reason, Brazil has recently adopted the term low-emission hydrogen, following the IEA recommendation, to refer to all technologies capable of producing hydrogen with low carbon emissions. The country is interested in adopting a more technical definition to classify hydrogen by using an index that reflects the carbon footprint associated with its life cycle.

In this report, we refer to renewable hydrogen as being hydrogen produced by all types of renewable sources, including hydropower and biomass, but highlighting the important role that solar PV and wind will play in the production of hydrogen in the future.

12 Insights on Hydrogen for Brazil

1. Brazil is well-positioned to produce renewable hydrogen due to its abundant and cost-competitive renewable energy resources

Brazil's large renewable energy potential and successful track record in developing the renewable power supply chain are considered very attractive to investors, as they can help achieve the Paris climate goals and decarbonise carbon-intensive industries.

Brazil's high renewable energy potential to harness renewable hydrogen

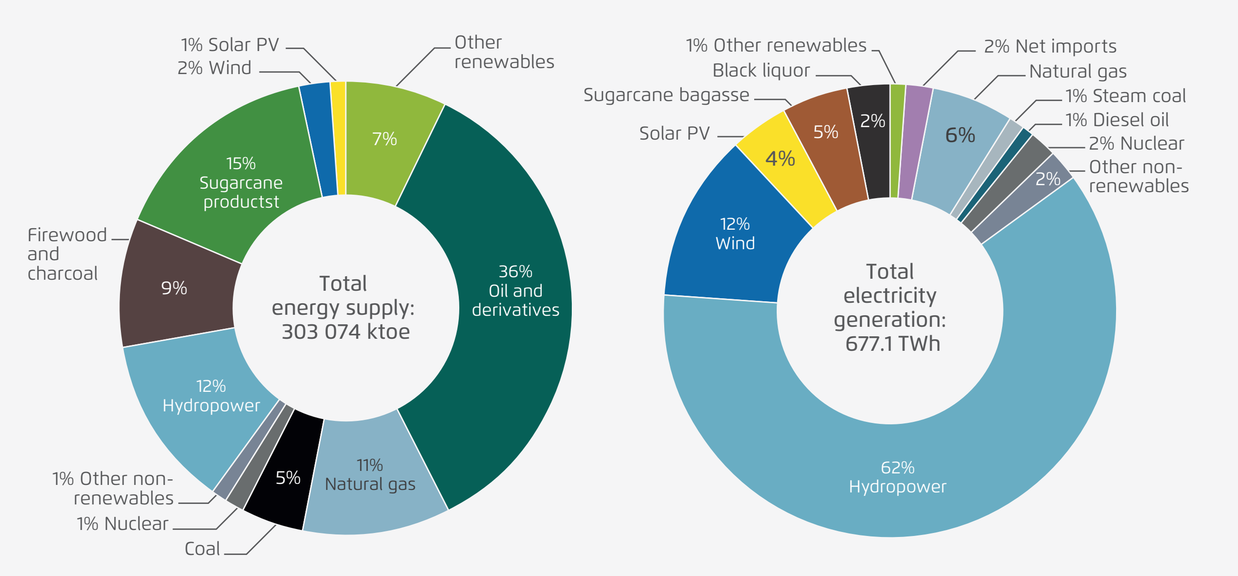
Based on an average price[3] of 32.75 US dollars (USD) per MWh for solar PV and wind energy auctions held in 2022 (MME, 2022a), and considering that 70–80% of the cost of renewable hydrogen production is dictated by electricity prices, Brazil has the potential to become a major player in the trade of renewable hydrogen (BloombergNEF, 2023a).

As shown in Figure 3, Brazil's energy matrix and power generation are very diverse, with solar PV and wind playing a more important role over the years. Other important energy sources for power generation are hydro, natural gas and biofuels (EPE, 2023a). To this end, Brazil is using contract auctions to stimulate investment in new generation and transmission infrastructure.

Brazil has an estimated solar PV potential of 307 Gigawatt-peak (GWp) – assuming optimal irradiation levels (6.0 – 6.2 kWh/m²) and excluding potential offshore PV opportunities (EPE, 2018). By 2050, 90 GWp of solar PV is expected to be added to

3 For comparison: the maximum auction prices for solar PV in Germany at the end of 2022 were around USD 63.5 per MWh, and in 2023 the country increased the maximum auction prices by 25% to USD 78.3 per MWh (IEA, 2023d).

Brazil total energy supply and electricity generation, 2022 → Fig. 3



EPE (2023a)

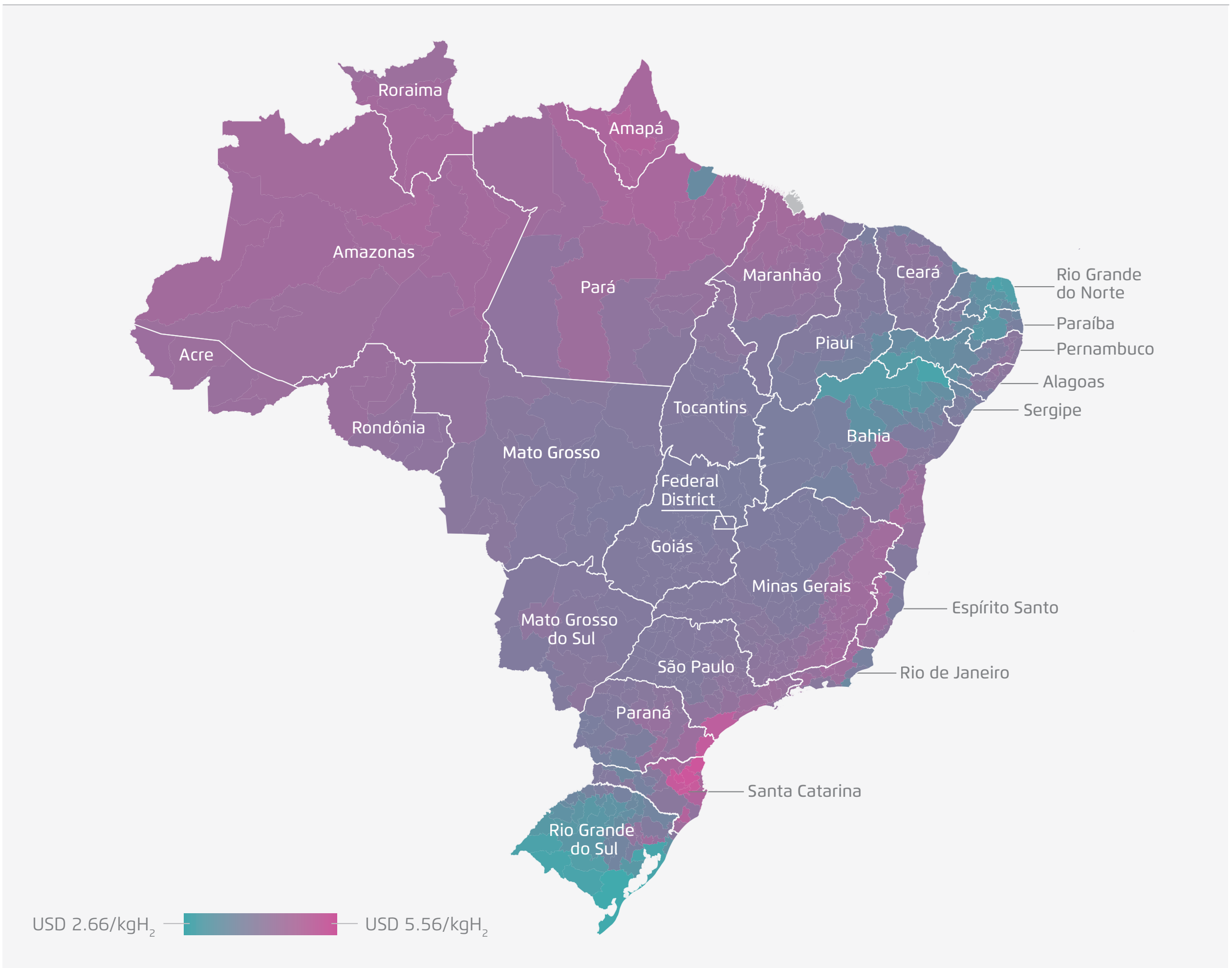
the grid (EPE, 2020), leaving more than two thirds of this potential available for other uses, such as the potential production of renewable hydrogen.

The onshore wind potential is estimated to be around 441 GW at a height of 150 metres, for example (EPE, 2018). Similarly, the offshore potential ranges from around 60 to 500 GW, at distances of 10 and 100 km from the coast respectively (EPE, 2018). Although it is expected that up to almost 200 GW of wind power could be used in the country by 2050 (EPE, 2020), a large untapped potential would still be available for other uses, such as the production of renewable hydrogen.

Without considering Brazil's remaining hydro potential of 176 GW (108 GW harnessed or under construction as of 2019, and 68 GW untapped) and biomass potential (estimated at 29 GW in 2050), only the untapped solar PV and wind potential expected by 2050 (200 GW solar PV and 241 GW onshore wind at a height of 150 metres) would allow up to 25 Mt H_2 per year to be produced by water electrolysis, which could supply about 2–6% of the global consumption expected in that year[4] (EPE, 2018).

4 Calculation made assuming 1 800 full load hours (FLH) for solar PV and 3 200 FLH for wind, with an efficiency of 45kWh/kg H_2. The global demand by 2050 was calculated using the lowest and highest values presented in Figure 1.

Levelised cost of hydrogen (LCOH) for hybrid (solar PV and wind) production in selected regions of Brazil, 2030 → Fig. 4



Agora Energiewende and Agora Industry (2023). Note: Island system (renewables not connected to the grid) with underground geological storage to maintain near constant hydrogen delivery for industrial off-take.

Brazil's regions have different energy endowments

Brazil has a vast territory, equivalent to about 84% of the total area of Europe (UN, 2022)[5]. As a result, the country has a diversity of energy resources in its different regions and an untapped renewable energy potential that is spread out across the country's territory and includes for example wind and solar PV, especially in the Northeast region.

The Southeast, Central-West and South regions have also been very successful in using biomass in both the energy and transport sectors and have a big untapped potential for biogas[6]. Current biogas capacity is concentrated in regions with the highest potential for the production of organic matter and agricultural, municipal, industrial and forest wastes (EPE, 2023b).

Brazil's renewable resources (hydro, biomass, onshore wind and solar PV) are also strategically complementary throughout seasonal and daily cycles. Offshore wind farms, for example, are expected to increase synergies by complementing hydro generation across different regions in Brazil (Nogueira, Morais, & Jr, 2023).

Brazil, even if only its wind and photovoltaic potential is considered, will be able to achieve very competitive values for renewable hydrogen by 2030. As shown in Figure 4, the levelised cost of hydrogen (LCOH) values for Brazil in 2030 range from USD 2.7 to USD 5.6 per kg of H_2, depending on the region, resource availability and storage costs. The South and Northeast regions have the most competitive LCOH in the country, with the South region benefiting from more constant wind, which reduces the amount of hydrogen storage required.

5 Including UK and European Russia.

6 Such huge untapped potential for biomethane and biogas in Brazil's Southeast, Central-West and South regions has been called the "pre-salt caipira". These regions have the potential to produce up to 120 million m³/day of biomethane and biogas – almost the volume of natural gas produced in the pre-salt in 2021 – without considering concurrent markets and other techno-economic parameters (Soares, 2023).

It is important to emphasise that if other renewable sources for hydrogen production are considered, the results may differ from those presented here. This applies to regions such as the South, Southeast and Central-West, where hydro and biomass resources are widely available.

Certain challenges need to be overcome

Brazil had the third-largest hydropower park in the world in 2018 and is currently evaluating the modernisation of 51 fully amortised hydropower plants with a capacity of more than 50 GW and a lifetime of 50 years. This could increase power generation and reduce the average marginal operating costs of the national system by up to 12% (EPE, 2019).

Brazil's historical hydropower capacity has been fundamental in ensuring cost-effective power generation during the regular wet seasons. However, the seasonality/complementarity on a monthly scale of total average hydropower generation varies between wet and dry periods over the years, affecting the electricity system's marginal costs, which are lower during wet periods than during dry periods. This variability has become more pronounced with the impacts of climate change, making the country's dependence on water resources and the way they influence electricity system costs more visible (EPE, 2017).

During dry periods, hydropower capacity drops and system costs are higher as the electricity system relies on thermal generators, which have higher variable unit costs.[7] The use of thermal generators can therefore increase operational costs. For example, between February 2022 and July 2023, the average system cost was USD 47.1 per MWh, but during the

7 Different thermal generation sources show significant dif-fer-ences in their variable unit costs. In 2019, compared to the lowest cost nuclear generation (Angra II) at around USD 5.1 per MWh, costs ranged from 13 times (coal) to 84 times (fuel oil and diesel) higher, with biomass and natural gas at 25 and 30 times higher respectively. The need to supplement hydro-power during Brazil's dry seasons includes not only conven-tional thermal plants, but also wind, biomass and solar PV sources. As a result, the thermal park and, counterintuitively, renewables now act as virtual capacity storage (ONS, 2020).

dry season in February 2022, this cost peaked at USD 75.3 per MWh (ONS, 2023a; ONS, 2023c). Higher system costs also affect electricity prices for final users, so alternatives aimed at reducing the dependency on thermal generation need to be suggested, as the risk of longer dry seasons will increase as climate change progresses.

Renewable hydrogen to provide flexibility to the power system

Renewable hydrogen and PtX production can be integrated into the Brazilian power system, reducing its reliance on conventional thermal generation, especially during the dry season when hydropower generation cannot meet demand. Renewable hydrogen and PtX can help integrate more variable renewable energy by increasing the flexibility of the Brazilian power system, complementing baseload sources such as biomass and relieving some of the pressure on hydropower generation.

Considering the impact of thermal generation on the marginal costs of the system and the variability of solar PV and wind, the application of hydrogen as a practical way to store electricity can contribute to the stability of power grids and the normalisation of supply in the long term (EPE, 2021). In this respect, the role of hydrogen storage can be instrumental in reducing the trade-off between hydro and thermal production (ONS, 2020; IEA, 2022b). Among the available technologies, hydrogen is one of the options for storing large blocks of energy for long periods, as there are no losses while it remains in tanks or reservoirs. Similarly, PtX products such as synthetic ammonia and methane can also be stored for long periods of time, under simpler and cheaper storage conditions than the hydrogen molecule.

Hydrogen and PtX as a flexibility measure do not necessarily require the use of these molecules for power generation, but they can help mitigate the curtailment of variable renewable generation during periods of high generation, thus providing a reliable feedstock for the industrial sector. Coupling the power and industry sectors will therefore be a key factor in reaping the flexibility benefits that hydrogen and PtX production can bring to the energy system.

2. Renewable hydrogen is best considered to decarbonise applications where the direct use of renewable electricity is not possible.

The need to prioritise hydrogen applications

There is a global technical consensus that the deployment of renewable energy will be the main driver of the energy transition, with the direct use of renewable electricity being the main carbon abatement mechanism in the energy sector. For example, the IEA's net-zero emissions scenario highlights the role of electrification in decarbonising the global energy sector. This scenario envisages electricity playing a dominant role in end-use sectors, accounting for more than half of total end-use consumption by 2050 (IEA, 2023a). Therefore, renewable energy must be prioritised for electricity generation as the main carbon abatement mechanism, and renewable hydrogen production should not compete with the direct use of renewable electricity.

In line with this, global scenarios highlight the role of hydrogen in the future energy system, with its share of final energy demand ranging from 10–20% by 2050 (see Figure 1). Despite the important role of electrification in global decarbonisation, some applications – most of them in the industrial and transport sectors – cannot be electrified and therefore rely on hydrogen and its derivatives.

However, the use of hydrogen should be carefully assessed as its production is not as efficient as other low carbon technologies. For example, renewable hydrogen production includes 20–30% losses in water electrolysis and additional energy losses during use. Hydrogen's efficiency can be as much as 84% lower than that of heat pumps when it comes to providing equivalent energy for direct electrification in the residential sector. Similarly, in the transport sector, hydrogen can be up to 60% less efficient than battery electric vehicles. For the same final energy use, renewable hydrogen requires two to four times more renewables capacity than direct electrification. Consequently, while hydrogen is a pivotal element in global decarbonisation efforts, it takes a secondary role to electrification in the net-zero pathway (Agora Energiewende, Agora Industry and Fundacion Torcuato di Cuella, 2023). In the Brazilian context, other sources can also be used for certain applications that are difficult to electrify, as is the case with the country's untapped biogas potential[8].

As shown in Figure 5, Agora has drawn up an overh view of the different hydrogen applications that should be prioritised across different end-use sectors. These applications have been identified on the basis of a review of prominent global energy system scenarios. Those applications commonly suggested across scenarios have been classified as "no regret". Applications with large variation across scenarios are referred as "controversial". Hydrogen use with few references, if any, in the scenarios are highlighted as a "bad idea".

Some of these applications will need to consider other aspects in the Brazilian context. For example, hydrogen for power storage would have to compete with other storage technologies in the country, such as pumped hydropower storage; however, as discussed in Insight 1, it can also serve to increase flexibility, especially given the hydrological changes in the country. On the other hand, heating grids may not be the most relevant application for the Brazilian building sector in view of the country's climatic conditions[9].

8 Other aspects of the Brazilian biomass sector are discussed in Insights 1, 5 and 6.

9 Energy consumption patterns in buildings differ greatly according to the climate. In moderate and warm climates like in Brazil, usage primarily focuses on heating water and cooking, whereas the emphasis in colder climates is on space heating and appliances (BloombergNEF, 2021).

Need for molecules in addition to green electrons → Fig. 5

Green molecules needed for climate neutrality by 2050?	Industry	Transport	Power sector	Buildings
No-regret	Non-energy use[1]: • Feedstock: ammonia, chemicals, fertilisers • Reaction agents: DRI steel	• Long-haul aviation • Maritime shipping	• Renewable energy back-up depending on wind and solar PV share and seasonal demand structure	• Heating grids (residual heat load[2])
Controversial	• High-temperature heat	• Trucks and buses[3] • Short-haul aviation and shipping • Trains[4] • Non-road mobile machinery	• Absolute size of need given other flexibility and storage options	–
Bad idea	• Low-temperature heat	• Cars • Light-duty vehicles • Two- and three-wheelers	–	• Building-level heating

Agora Energiewende and Agora Industry (2021).
[1] Hydrogen may also be used as a reaction agent and/or feedstock in bio-refineries.
[2] After using renewable energy, ambient and waste heat as much as possible. Especially relevant for large existing district heating systems with high flow temperatures. Note that according to the UNFCCC Common Reporting Format, district heating is classified as being part of the power sector.
[3] Series production currently more advanced on electric than on hydrogen for heavy duty vehicles and buses. Hydrogen heavy duty to be deployed at this point in time only in locations with synergies (ports, mines, industry clusters).
[4] Depending on distance, frequency and energy supply options.

Further decarbonisation of Brazil's energy sector through electrification

As mentioned above, the Brazilian power sector is not a big contributor to the country's greenhouse gas emissions, mainly due to the high share of renewables in electricity generation. However, the country's further progress in the electricity sector should not be hindered by its hydrogen ambitions. Brazil can use renewable hydrogen production to further exploit its untapped renewable energy resources for power generation, thereby supporting further decarbonisation of the end-use sectors.

As shown in Figure 6, other sectors in Brazil such as transport and industry still rely on fossil fuels to meet their energy demand. In the transport sector, fossil fuels (liquid fossil fuels and natural gas) account for around 78% of the sector's energy consumption in the period 2015 to 2022, with biofuels also playing an important role and accounting for about 22% of the energy consumption.

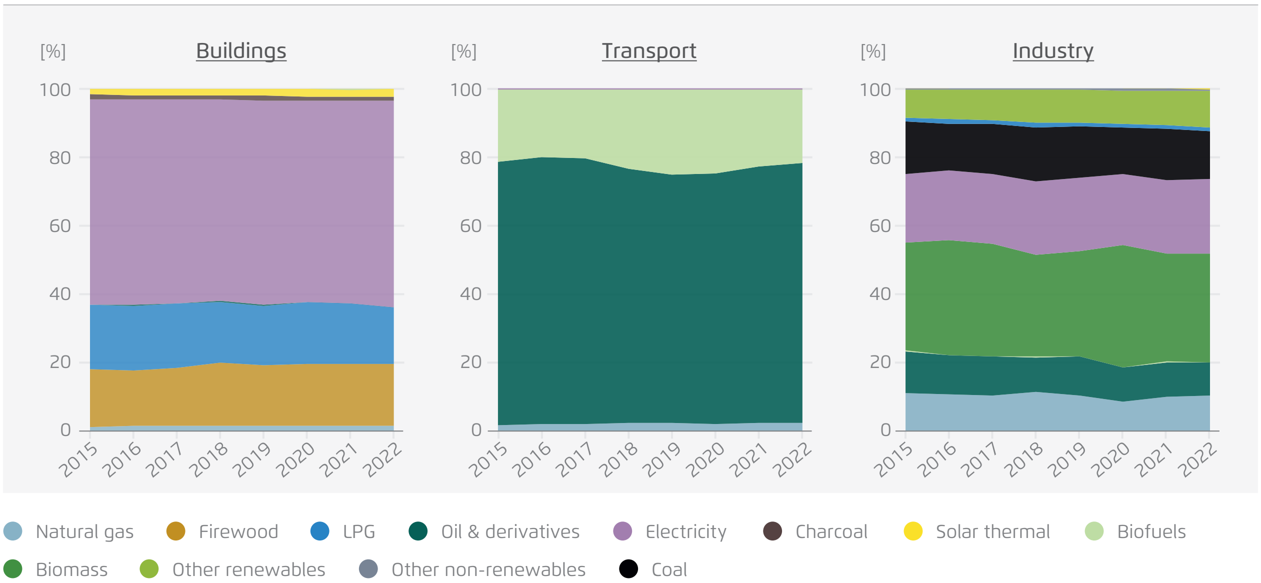
In the short term, biofuels will continue to play an important role in the sector, especially with new emerging technologies that enable more efficient use of bioethanol in light passenger vehicles (see Insight 5).

In the medium and long term, the transport sector could support its decarbonisation with electrification, especially for road transportation. Brazil could accelerate the sector's decarbonisation, building on its well-established biofuels industry and complementing it with support for electrification strategies. The latter will require the development of a more complex infrastructure in the country.

The industrial sector has a more diverse energy matrix in which fossil fuels reduced its role from 40% in 2015 to around 35% in 2022. Though fossil fuels in energy use and biomass as feedstock will also play a relevant role in the short term, electrification and hydrogen will in the medium term complement efforts to mitigate emissions in the sector, accelerating its decarbonisation and potentially boosting its low-emission growth. The buildings sector is the major electricity user with an average of 60% of electricity required to meet its energy needs since 2015, and it is expected that electrification will continue playing the most prominent role in reducing emissions in the sector.

Fuel share of final energy consumption per sector, 2015–2022

→ Fig. 6



EPE (2023a)

3. Infrastructure will be key, with low-emission hydrogen production integrated into medium- and long-term energy development plans

Brazil's energy infrastructure requires further development

As mentioned above, Brazil is not currently a major user of hydrogen and therefore has a long way to go in establishing a hydrogen storage and transport infrastructure, especially considering its vast territory, as the primary industrial demand for hydrogen is not necessarily located in regions close to the untapped renewable energy potential.

However, the country does have an extensive electric grid infrastructure connecting different regions (see Figure 7), which serves as a strong base for expanding renewable energy generation and renewable hydrogen production. Nevertheless, efforts are still needed to enhance the existing electricity system by integrating new generation technologies, transmission and distribution systems.

At the same time, the country's natural gas resources make fossil-based hydrogen with carbon capture and storage (CCS) a potential bridging technology for boosting the hydrogen economy. Gas infrastructure is mainly concentrated along the coastline, so further development of fossil-based hydrogen with CCS will require an assessment of pipeline retrofitting and expansion of the existing transport infrastructure.

In the short term, decentralised or off-grid projects (especially for renewable hydrogen) may provide a solution to alleviate pressure on the existing national electric infrastructure. Decentralised renewable energy could boost renewable hydrogen production in the early years of development and later be integrated into the interconnected energy system, contributing to the further decarbonisation of the Brazilian economy.

Electricity infrastructure supports renewable hydrogen production nationwide

As shown in Figure 7, Brazil has a robust electrica ity grid that has been continuously upgraded and expanded, especially with a view to integrating the rapidly growing generation of solar and wind power.

This reliable infrastructure offers a unique advantage for hydrogen production, as it facilitates the transport of electrons from the power generation points to areas close to the industrial centres where hydrogen can be produced and used, minimising the risks and costs of developing hydrogen transport infrastructure. An obvious example is the steel industry, this being one of the potential users of low-emission hydrogen. The steel industry is mainly located in the Southeast, while the best photovoltaic and wind potential is in the Northeast. The existing electricity grid allows electrons to be transported for hydrogen production in the Southeast, close to industrial demand.

In addition, Brazil's low-carbon grid may eventually allow hydrogen producers to connect directly to electrolysers so that they can receive green electrons from the grid. However, this will require close coordination with grid operators and energy planning organisations to ensure a reliable power supply to all users, as well as expansion of the grid and implementation of the flexibility measures needed to maintain good system operation while ensuring that the expansion of the system continues to be driven by renewable sources so that the high level of renewability in the generation mix is not compromised.

Assessing the development of natural gas infrastructure

Fossil fuels are an important energy source in Brazil, and natural gas reserves have the potential to produce fossil-based hydrogen with CCS as a bridging technology. However, the existing gas infrastructure limits the potential for nationwide use of this resource.

Most of the natural gas pipelines are located in the coastal region, with no connection to the central regions of the country. Potentially, fossil-based hydrogen with CCS could be produced near existing port infrastructure and considered for export. However, the international market is mostly focused on green products from renewable hydrogen and this option may affect Brazil's competitiveness in the international trade of PtX products.

The development of natural gas infrastructure is a controversial and expensive issue in the country. In 2021, the country implemented the Eletrobras privatisation law, which included the expansion of 8GW of natural gas thermal power plants with at least 70% inflexibility[10] in regions without existing gas infrastructure. Two years later, however, the single auction for several regions attracted limited or no bids, resulting in the contracting of only 754 MW (IEMA, 2022).

The thermal plants outlined in the Eletrobras law aim to promote the internalisation of the grid, but in a way that is quite costly for the consumer and detached from any kind of integrated resource planning.

In the medium and long term, Brazil could evaluate the potential repurposing of natural gas pipelines and storage and transport infrastructure for hydrogen, as this could facilitate the transport of preferably green molecules, especially in coastal regions, to the export market. This potential repurposing of natural gas infrastructure needs to be carried out carefully, implementing tough safety measures and considering the unique physical and chemical properties of hydrogen (NREL, 2022; Steiner, Marwski, & Silcher, 2023).

Existing port infrastructure could complement Brazil's offshore wind potential

Brazil has approximately 7 500 kilometres of coastline, with a large number of public and private ports of varying capacity. This is complemented by the country's substantial offshore wind potential (supported by a well-established onshore wind industry), which is beginning to be explored. This condition, in conjunction with the coastal gas pipeline infrastructure, creates a favourable environment for the export of renewable hydrogen and PtX products. However, existing ports would need to be adapted to handle the required processing of these products.

Improving port infrastructure and regulating the offshore wind sector could further position Brazil as a producer and exporter of renewable hydrogen and PtX products, attracting new investment in renewable energy in the medium to long term.

PtX products to be part of country's medium- and long-term energy plans

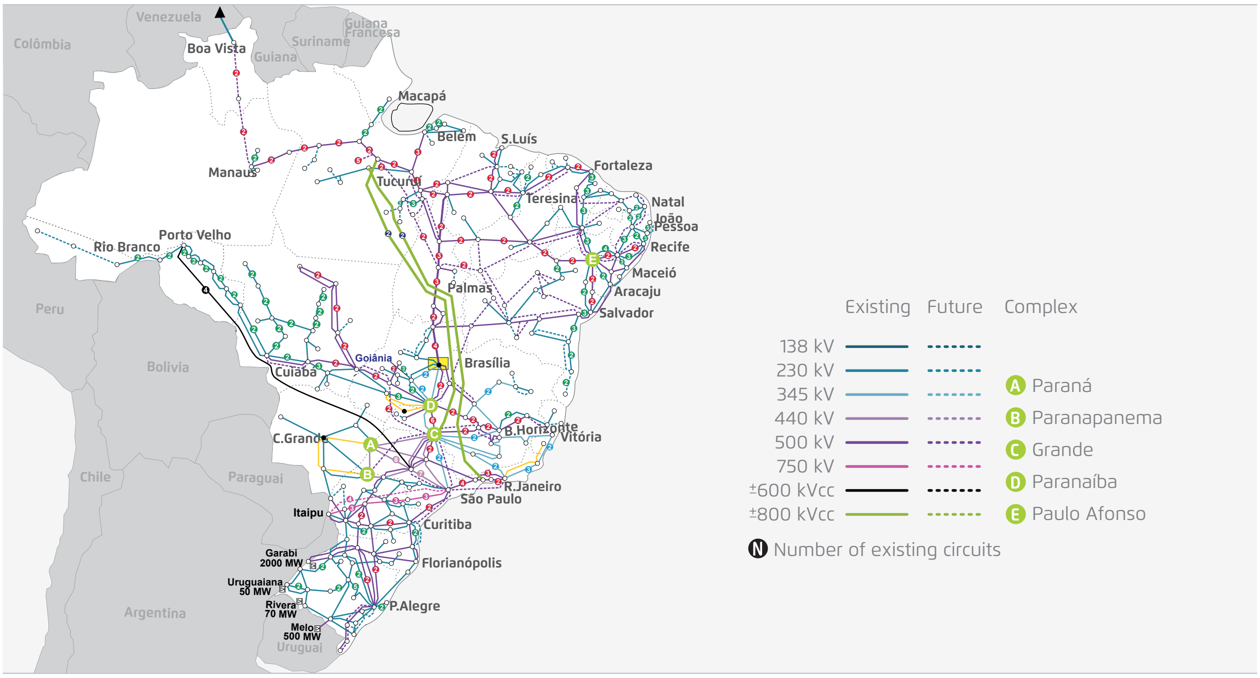
Brazil has a structured and well-developed energy planning process, driven by the Energy Research Office (EPE). The planning process includes a medium-term plan - the Ten-Year Energy Plan (PDE) – and a long-term plan for 30 years – the National Energy Plan (PNE).

Published in 2020, the PNE 2050 addressed hydrogen mainly in its special section on disruptive technologies, with no specific projections for hydrogen production or use (EPE, 2020). By contrast, the PDE 2031, published in 2022, was the first document to include a specific and comprehensive chapter on

10 This means that the power plant has to operate at least 70% of its capacity, thereby ensuring a consistent demand for natural gas. This supply contract security for large gas volumes could then guarantee and justify investments for the expansion of the pipeline network.

Brazilian Power Transmission System

→ Fig. 7



ONS (2023b)

low-emission hydrogen that assessed the technical production potential from various energy resources, including fossil fuels, biomass and onshore/offshore renewables, up to 2050 (EPE, 2022).

Future energy plans may include further information on the production and consumption of low emission hydrogen to facilitate a robust flow of information to potential investors in this technology and improve coordination between sectors such as industry and agriculture. This is also noteworthy to ensure that expansion plans in the energy sector consider the additional infrastructure necessary for the development of the hydrogen industry, while at the same time highlighting the key role of sector coupling[11] to enhance the benefits that hydrogen development and investment can bring to the country.

11 Sector coupling, often used in the broader context of energy systems, involves the strategic integration of different sectors, including electricity, heat, transport and industry. In the context of the hydrogen industry in Brazil, sector coupling is of paramount importance. It requires not only the integration of traditional energy components, but also complex links with industrial processes and infrastructure improvements. The coordinated development of all stages of the chain – from production to transport, storage and consumption – is made possible by a sector coupling approach, ensuring the successful development of the industry.

4. Fossil-based hydrogen with carbon capture and storage (CCS) can serve as a bridging technology, but will be outcompeted by renewable hydrogen

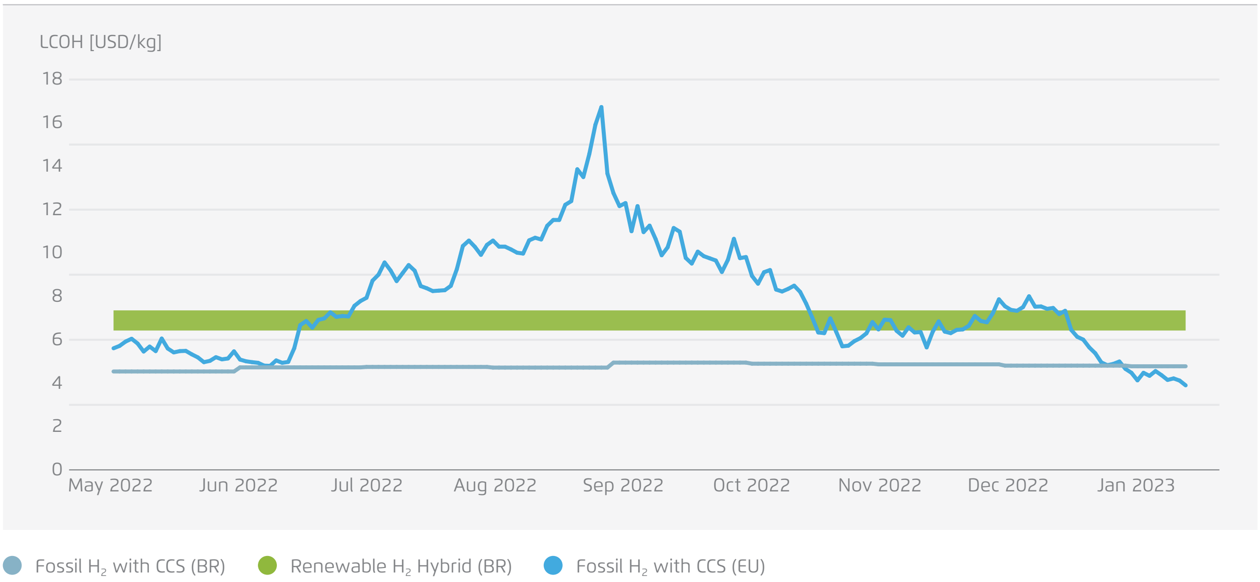
The cost of using natural gas to produce hydrogen

Natural gas prices have been very volatile in recent years, a situation exacerbated by the war in Ukraine. In Europe, for example, natural gas reached record prices of up to USD 70 per one million British thermal unit (MMBtu) in August 2022 (IMF, 2023a). As shown in Figure 8, the price of natural gas affects the competitiveness of fossil-based hydrogen with CCS, as it is its main feedstock. With the price fluctuations in Europe, this hydrogen production pathway has become more expensive than renewable hydrogen in Brazil in certain timeframes.

Brazil has local gas reserves in the pre-salt reservoir, which are currently estimated at 600 billion cubic metres (ANP, 2023a), making it one of the world's 25 countries with the largest oil and gas reserves in 2021 (BP, 2022). This local natural gas production has mitigated the impact of global natural gas price fluctuations in Brazil, keeping the estimated cost of fossil-based hydrogen with CCS at a competitive level (see Figure 8). For technical and economic reasons, however, around 50% of the natural gas produced is reinjected as part of the enhanced oil recovery (EOR) process, while around 10% is consumed on oil platforms, making the country dependent on natural gas imports from Bolivia and LNG imports from other regions (ANP, 2023b).

The fluctuations in the price of natural gas in 2022 led to an increase in the price of fossil fuels, prompting countries around the world to increase subsidies for fossil fuels to back up energy prices. Globally, fossil fuel subsidies rose by two trillion USD compared to 2020, reaching seven trillion USD (7.1% of global GDP) (IMF, 2023a; IMF, 2023b). Natural gas subsidies in Brazil accounted for three billion USD in 2022, which had a significant impact on the country's fiscal balances. Brazil does not have the world's highest

Costs of renewable H_2 and fossil-based H_2 with CCS for Brazil and EU → Fig. 8



Calculated with Agora LCOH tool (2023). Note: Full load hours of renewables are collected for Rio Grande do Norte and Rio Grande do Sul. Natural gas prices: Ministério de Minas e Energia (BR) and TTF (EU). Fossil H_2 with CCS is based on steam methane reforming with 95% of capture rate. Renewable H_2 is based on the optimised hybrid capacities of wind & solar PV including electricity and hydrogen storage costs but excluding transport costs.

natural gas subsidies, however: China's are 103 times higher, while subsidies in the Netherlands are three times higher than in Brazil (IMF, 2023a).

Expanding fossil-based hydrogen production in Brazil could increase the demand for natural gas, which would require new investment in the sector to meet the country's natural gas needs. At the same time, meeting the growing demand for hydrogen and shifting the existing demand to renewable hydrogen could help lower the natural gas demand for some consumers, such as the industrial sector, thereby reducing the need for natural gas subsidies.

Fossil-based hydrogen as a bridging technology in Brazil

As shown in Figure 8, Brazilian fossil-based hydrogen with CCS currently has more competitive costs than renewable hydrogen from wind and solar PV. This technology can therefore be viewed as a bridging technology in the country, helping to decarbonise existing hydrogen applications and develop the hydrogen infrastructure. However, investments in fossil-based hydrogen with CCS need to consider the transition to renewable hydrogen as soon as possible. This is particularly important in Brazil, which has the potential to achieve very competitive costs for renewable hydrogen as early as 2030 (see Figure 4).

In addition, Brazil has recently passed legislation to open up its natural gas market with a view to promoting equitable access to the network and state unbundling. Discussions are underway to introduce a gas release programme to expand gas availability and foster a more competitive market environment (Brattle, 2023). Reforming the gas market poses challenges, however, as a well-established company currently controls significant natural gas resources. Nonetheless, new players are already entering the market to expand the supply of natural gas to the domestic market by signing contracts totalling more than 480 thousand cubic metres per day (EPE, 2023a). Furthermore, the IEA scenarios take into account Brazil's increasing investment in offshore oil production areas, which would increase total production by between 1.4 and 4.4 million Barrels per day by 2030, with Brazil expected to contribute around 45% of global deepwater oil production by 2030 (IEA, 2022b). A more dynamic gas market and increased production of natural gas may, in the short term, favour the potential use of natural gas for the production of hydrogen with CCS.

New investment in the use of fossil-based hydrogen with CCS in Brazil will require careful assessment to avoid stranded assets, as the international market is clearly focused on renewable hydrogen and PtX products. For instance, the European Union is setting targets for 2030 for renewable hydrogen and hydrogen-based fuels in the transport and industrial sectors. At the same time, international mechanisms such as H2Global aim to create a green market with a compensation mechanism to make PtX products more competitive by closing the price gap between fossil-based and renewable hydrogen (see Insight 9).

To avoid stranded assets, Brazil could also assess the repurposing of existing gas infrastructure for biomethane from residual biomass. Biomethane from residual biomass in combination with CCS can lead to negative emissions and enable new business models (see Insight 6). However, current efforts should prioritise policy instruments that focus on closing the cost gap for renewable hydrogen.

Moreover, leveraging existing infrastructures and the current demand for hydrogen at refineries, predominantly supplied by fossil-based hydrogen in Brazil, could boost renewable production without substantial government incentives.

Ensuring sustainability of potential fossil-based hydrogen with CCS production

If hydrogen is to be produced using natural gas with CCS, very high standards of sustainability will need to be reached in order to realise the emissions reduction benefits of this technology pathway. The fact that CCS requires high carbon capture rates (above 95%) has been a challenge for technology development, as it requires capture not only of the emissions from the steam methane reforming (SMR) process, but also of the emissions from the combustion of natural gas to produce the thermal energy needed for the reaction, which account for one third of the total emissions from the process. The concentration of CO_2 in this flue gas is low, making its capture energy-intensive and expensive (Ausfelder, Herrmann, & González, 2022).

At the global level, a study analysed 13 CCS projects representing more than 50% of global carbon capture capacity and found that only half of them met their sequestration targets (JP Morgan, 2023). Another study in the US yielded similar results, with only half of 39 CCS projects achieving the sequestration targets (JP Morgan, 2023). However, the majority of these projects use enhanced oil recovery (EOR), where CO_2 is used to enhance the recovery of oil from active fields. It is unclear whether EOR is an appropriate method of carbon storage, as it increases fossil fuel production in some regions, offsetting the benefits of CO_2 storage[12] (OIES, 2023).

CCS technology is expensive due to the costs of CO_2 pipelines, installing compressors and monitoring emissions. The costs are potentially high even in Brazil, with considerable uncertainty due to the combination of several complex elements along the CO_2 transport and storage chain. To date, Brazil has only explored EOR for carbon storage in two ultra-deepwater fields located 300 km off the coast of Rio de Janeiro (IEA, 2021b); as mentioned above, however, this method is controversial when it comes to carbon storage.

However, Brazil appears to have good geological potential for CO_2 storage close to industrial hubs in the Paraná Basin in the country's Southeast region (Pelissari, Relva, & Peyerl, 2023).

12 Life cycle assessment (LCA) of EOR should use a consequential methodology to understand the balance between the CO_2 emissions stored and those generated by the oil and gas produced from this practice. Consequential LCA is a dynamic practice that will help to estimate the extent to which EOR can be considered a carbon storage technology before the mitigated emissions are surpassed.

On the other hand, the extraction and use of natural gas entails the risk of fugitive methane emissions, which are very harmful as greenhouse gas and potential air pollution. Methane contributes to localised ozone smog pollution which can provoke asthma attacks, respiratory problems and premature deaths. In 2021, Brazil was the world's fifth largest emitter of methane, emissions totalling about 19.6 Mt (IEA, 2023b). However, 75% of Brazil's methane emissions come from agriculture, followed by the waste sector at 15% (SEEG, 2023a). Fugitive emissions in Brazil account for 1% of total methane emissions, mostly from gas pipelines (IEA, 2023b). Brazil has joined the Global Methane Pledge, aiming to achieve a 30% reduction in its methane emissions by 2030, compared to 2020 levels. Although most of Brazil's methane emissions come from the agricultural sector, the promotion of natural gas for hydrogen production with CCS can increase the risk of fugitive emissions along the entire extraction and production chain, thereby compromising Brazil's commitments to mitigating methane emissions and the positive effects that this technology pathway can potentially have in reducing carbon emissions in its various applications.

CCS technology in Brazil presents several technical challenges that need to be addressed, such as a lack of reliable data and information, as well as regulatory challenges related to the monitoring of stored emissions, ownership of storage sites, and legal uncertainties. The Senate approved a bill[13] to establish a regulatory framework for CCS in Brazil in August 2023. The bill has been under review in the Chamber of Deputies since September 2022 (SENADO, 2023). It is important that the country considers the possibility of assessing the effectiveness of carbon capture and the climate risks of methane, carbon and hydrogen leakage. Fossil-based hydrogen with CCS may have a greater climate impact than the continued use of fossil fuels, see Infobox 3 (Ocko & Hamburg, 2022).

13 Bill 1425/2022.

Leveraging the potential of offshore hydrogen production based on experience with oil and gas

Brazil's expertise in the offshore industry, driven by deepwater oil exploration, is characterised by the advanced construction and operation of platforms, subsea systems and extraction technologies.

In the geological field, Brazil excels in understanding submarine formations and has extensive experience in geophysics, which is crucial for reservoir identification and accurate decision-making in offshore exploration. The country also has expertise in reservoir management for natural gas exploration and production. This mix of skills has considerable potential for the hydrogen sector.

In terms of geological formations, the country has good offshore capacity for hydrogen storage. A recent study suggests that depleted offshore fields in Brazil could potentially store around 5 483 TWh of renewable hydrogen (Ciotta et al., 2023). This is about ten times Brazil's annual electricity consumption. Harnessing this storage capacity alongside offshore wind power could significantly enhance Brazil's energy security and benefit other countries.

Infobox 3: Hydrogen leakage and its potential climate implications

The hydrogen molecule is much smaller than other gases such as CO_2 and methane and is therefore more difficult to store or contain. In a hydrogen-based economy, hydrogen leakage can be expected at various points of the production process. In some cases, hydrogen is purged into the atmosphere. The molecule has indirect warming effects that will become more relevant when hydrogen production is scaled up. Currently, there is uncertainty about the amount of hydrogen leakage that will occur. However, more attention should be paid to hydrogen leakage due its relevance in future decarbonisation scenarios.

Hydrogen molecules in the atmosphere can have indirect climate effects by extending the lifetime of other greenhouse gases. Given the impact of hydrogen leakage when combined with methane leakage, this production pathway plays an important role in assessing hydrogen's climate impact versus that of CO_2 emissions from fossil fuels. In the first ten years, fossil-based hydrogen with CCS could have a 40% higher warming impact than fossil fuels in the worst case of hydrogen leakage (around 10% per unit of hydrogen used). Renewable hydrogen in the same scenario could mitigate only 65% of the impact of fossil fuels (Ocko & Hamburg, 2022).

In the best case of hydrogen leakage (around 1% per unit of hydrogen used) in the first ten years, fossil-based hydrogen with CCS can mitigate 65% of the warming impact of fossil fuels. Under the same conditions, renewable hydrogen can mitigate more than 95% of the warming impact of fossil fuels. Though the climate impact of hydrogen tends to decrease over time, estimates indicate that in more than 100 years, fossil-based hydrogen with CCS will only be able to reduce up to 85% of the warming effect of fossil fuels in the best case scenario (Agora Energiewende, Agora Industry and Fundacion Torcuato di Cuella, 2023; Ocko & Hamburg, 2022).

Current methodologies for developing hydrogen standards and labels lack strategies for managing potential hydrogen leakage. To realise the climate benefits of large-scale, low-emission hydrogen or ammonia, it's crucial to minimise fugitive emissions of hydrogen and other pollutants (BEIS, 2022; IEA, 2022b; Wolfram, Kyle, Zhang, Gkantonas, & Smith, 2022).

5. Brazil's potential future market for hydrogen-powered vehicles is constrained by more mature technologies

Will hydrogen-powered vehicles play a role in the transport sector worldwide?

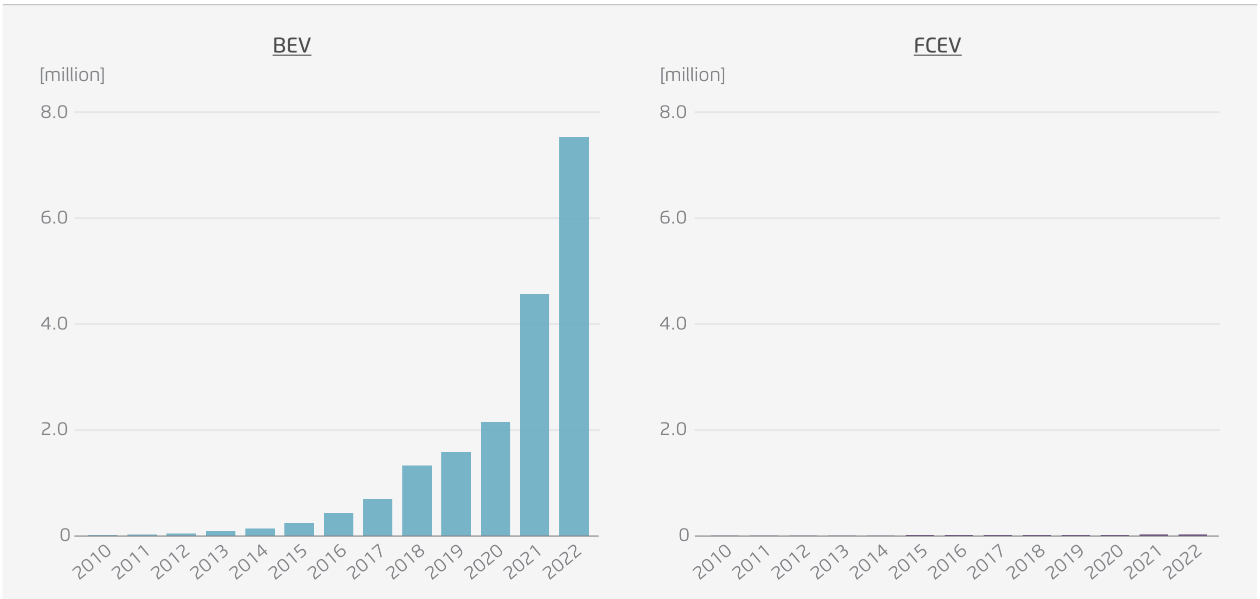
In the race to reduce emissions in the transport sector, several technology options are available, especially for road transport. However, battery electric vehicles (BEVs) dominate the passenger car market globally, particularly by comparison with fuel cell electric vehicles (FCEVs), as shown in Figure 9.

In 2022, BEVs reached global sales of about 7.5 million vehicles with an annual growth rate of 68% since 2019. Global sales of BEVs in 2022 are concentrated in just three major markets (China, Europe and the US, accounting for 60%, 25% and 8% of total global sales in 2022 respectively). BEVs still face economic barriers in less developed countries (IEA, 2023c).

On the other hand, FCEVs had sales of around 15 400 vehicles in 2022, with an average annual growth rate of 26% since 2019 (BloombergNEF, 2023b). In 2022, however, FCEVs experienced a decline, with sales falling slightly in comparison to 2021 (15 500 vehicles). This trend continued in 2023, with a first-quarter drop in sales in the most important markets, such as the US (30% drop), Japan and South Korea (BloombergNEF, 2023b; Hydrogen Insight, 2023).

With FCEVs representing less than 0.02% of global passenger vehicles sales in 2022 (BloombergNEF, 2023b), they are not expected to play a major role in the decarbonisation of the road transport sector, especially when it comes to passenger cars, though there will be some hydrogen-powered vehicles in certain areas, especially in heavy-duty and freight transport.

Passenger BEVs vs. FCEVs in terms of global annual sales → Fig. 9



BloombergNEF (2023b)

Biofuels are the main decarbonisation strategy for the transport sector in Brazil

Contrary to the global trend, Brazil is still far from becoming a significant market for electric vehicles. BEVs in Brazil also face political and economic opposition from the biofuels industry, which accounts for around 20% of the fuels used in the Brazilian transport sector, see Infobox 4. At the same time, the road infrastructure poses challenges for electrification (only 12% of roads in Brazil are paved) (S&P Global, 2023).

In the future, the more efficient use of biofuels (direct ethanol fuel cells, DEFC) is expected to play a greater role in the country. Ethanol fuel cell vehicles, which are still under development, can use the bioethanol currently used in most Brazilian cars and pass it through a reforming process to produce hydrogen and oxygen, which are fed into a fuel cell to generate the electricity that powers the car, achieving 10–20% higher efficiency than conventional fuel cells. The CO_2 emitted in the reforming process is offset by the planting of sugarcane. Technology development challenges include reducing the temperature of the reforming process and the number of critical metals in the fuel cells (Zaparoli, 2021). This technology is seen as a potential facilitator in the transition of the Brazilian transport sector, as it could require less infrastructure development than electrification and hydrogen-powered vehicles.

Brazil's passenger vehicles have benefited from the country's strong biofuels sector, and innovative technologies such as direct ethanol fuel cells are likely to contribute to defossilisation. Nonetheless, the country has made initial investments in public transport electrification in large cities such as Sao Paulo and Curitiba. This could be a first step towards promoting electrification in the transport sector by contributing to the development of charging infrastructure, mainly in major urban centres. At the same time, the development of electrification strategies in the sector to complement the use of biofuels in the medium to long term could be evaluated.

Brazilian hydrogen trucks face further challenges

In 2022, diesel was the main fuel for trucks over 6 tonnes, accounting for 99.5% of the total, followed by natural gas and electricity at 0.4% and 0.1% respectively. In the medium term, however, biodiesel, biomethane, natural gas and LNG are expected to play a more important role in the sector. Freight electrification faces the same challenges as passenger cars, with opposition from the biofuels sector and issues related to the country's road infrastructure, underdeveloped recharging infrastructure, fleet age and technology costs, among others (S&P Global, 2023). Battery technology is developing rapidly, with battery electric trucks expected to cover the majority of freight transport globally. Most trucks in Brazil travel an average distance of 430 kilometre (ICCT, 2021), which can be covered by battery electric trucks, so this technology could make a significant contribution to reducing the use of diesel in the sector. However, this technology is expected to be less widespread in the country in the long term.

Hydrogen trucks will face similar challenges to battery trucks in Brazil, with the result that their penetration may be limited to certain regions where hydrogen production will be available, such as the northeast of the country, where hydrogen hubs are expected to be built in the medium term.

Despite the nascent development of battery-electric mining trucks[14], hydrogen will play a key role in decarbonising transport in the mining sector in particular, as it is one of the few viable alternative fuels for mining vehicles. As in Chile, where mining trucks are one of the priorities of its national green hydrogen strategy, Brazil's thriving mining sector is likely to embrace the technology, especially in the iron ore export segment.

14 Companies in the US and Germany are making progress with developing battery-electric mining trucks that are currently being tested at mining sites, with plans to expand and offer them to mining sites around the world (Caterpillar, 2022) (Engineering, 2023).

Infobox 4: Decarbonising Brazil's transport sector

Brazil's transport sector has significantly lower greenhouse gas emissions than its counterparts in many developed countries. This is largely due to the widespread use of biofuels such as ethanol in passenger cars and a 12% blend of biodiesel in the diesel available at fuelling stations, which is mainly used in heavy-duty vehicles (from April 2023, biodiesel is required to be blended at 12%, rising to 13% in 2024 and 15% in 2026) (BRASIL, 2023a). In addition to reducing greenhouse gas emissions, these biofuels stimulate economic activity via the agro-industrial sector, creating jobs, tax revenues and regional development.

The inception of this biofuel-centric approach can be traced back to the National Alcohol Programme (Proálcool) launched in 1975 (Cortez, 2016). It was further consolidated in 2005 with the establishment of the National Programme for the Production and Use of Biodiesel (BRASIL, 2005). Both programmes have developed in tandem with Brazil's burgeoning agricultural sector, resulting in strong lobbying and political support for biofuels. This political support has created challenges for alternative transport modes, particularly electric vehicles (EVs). Attempts to incentivise EVs have met with significant resistance, as some studies suggest that biofuels and EVs offer similar environmental benefits (Villaça & Paixão, 2023).

Therefore, any efforts to introduce hydrogen-powered vehicles are likely to face similar opposition due to their potential impact on the biofuel market. Most current decarbonisation proposals prioritise expanding the use of biofuels and biomethane, particularly in commercial vehicles such as trucks and buses (Bioenergia, 2019).

The new Programme for Accelerated Growth outlines key initiatives to advance low-carbon fuels and transport solutions, including redoubling existing efforts related to sustainable low-carbon mobility, the National Sustainable Aviation Fuel Programme, the National Renewable Diesel Programme, the regulatory framework for carbon capture and storage, an increase in the mandatory blending of ethanol in petrol, and an increase in the mandatory blending of biodiesel in diesel (BRASIL, 2023b).

Despite the many initiatives related to biofuels in the new Programme for Accelerated Growth, there are also targets and programmes focused on electrification technologies, such as (i) the second phase of the Rota 2030 programme, which concentrates on hybrid and electric vehicles; and (ii) a special credit line from the Finem/Climate Fund (BNDES) for the electrification of municipal bus fleets. These initiatives represent a comprehensive approach to low-carbon transport, in line with Brazil's National Sustainability Goals for 2023 (BRASIL, 2023b).

6. Brazilian bioenergy industry can strongly contribute to the PtX market in the country

Biomass has been a valuable resource for reducing greenhouse gas emissions in Brazil and will play a key role in the country's ability to achieve climate neutrality by 2050. In addition to its potential for low-emission hydrogen production, Brazil is poised to become a major player in the green PtX industry, with its diverse biomass serving as an ideal PtX feedstock.

As the world's reliance on coal, oil and natural gas diminishes, the role of sustainable carbon sources is becoming increasingly important to meet the growing demand for PtX products. Consequently, existing bioenergy and biofuel production systems will evolve to achieve better resource utilisation, opening up new markets for the sector to explore.

Direct electrification as an enabler

The continuing decline in the cost of electricity generated from wind and solar PV, coupled with recent developments in low-emission technologies, will create attractive conditions for the direct electrification of the industrial sector (Madeddu et al., 2020). For example, applications requiring low temperature heat (e.g. steam production) will be supplied by large and highly efficient modern industrial heat pumps (COP ~3)[15]. This will make an important contribution to the phase-out of fossil fuels currently used in conventional boilers and allow biomass (i.e. firewood) to be used as feedstock for more valuable products.

Similarly, sugarcane by-products such as bagasse and straw can be used more efficiently for power generation, allowing higher levels of bioelectricity to be fed into the grid as renewable baseload, or alternatively producing surplus biomass for second-generation bioethanol and biomass-to-liquid (BtL) products. Meanwhile, residues such as filter cake and vinasse can be used for anaerobic digestion to produce biogas and biofertiliser, improving the sustainability of the sugarcane value chain. For first[16]- and second-generation bioethanol, the technology is already on its way to commercialisation, enabling new markets to be developed.

These measures, combined with the gradual electrification of light road transport, will enable biomass in a variety of forms (solid, liquid and gaseous) to become a key feedstock for future industrial and biorefinery applications, producing green added-value products (Oliveira et al., 2021).

The unique case of the Brazilian bioenergy sector

For economic reasons, a variety of biofuels may be the preferred option to decarbonise most domestic long-distance transport in Brazil, including road, shipping and aviation (Müller-Casseres, et al. 2022).

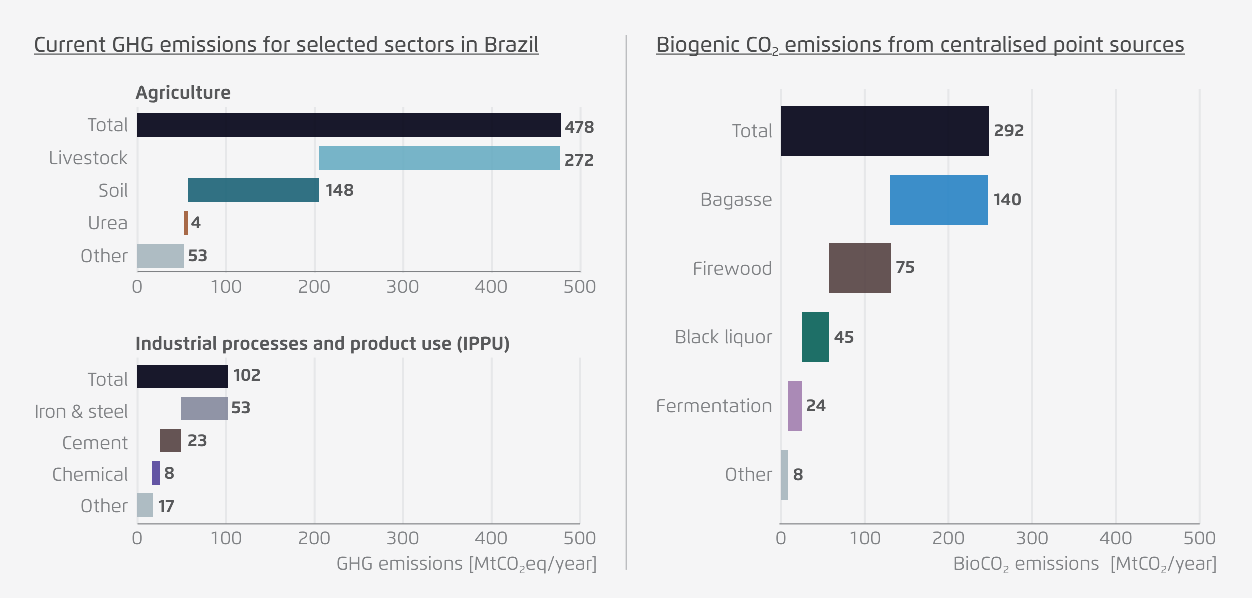
The different production pathways depend on the biomass feedstock and the target biofuel for each application. For some of them, exogenous H_2 will be required, at least as a chemical reagent for hydrocracking and deoxygenation during the production of hydrotreated esters and fatty acids (HEFA) and hydrotreated vegetable oils (HVO). For others, hydrogen is an option when it comes to exploring synergies between BtL and PtX in hybrid systems for bio- and electro-based production of jet kerosene, diesel and naphtha.Due to the composition of different types of biomass, the conversion processes and the targeted fuel/product, biogenic CO_2 is generated as a by-product that will play a key role in a future carbon-neutral Brazilian economy.

15 COP - coefficient of performance, i.e. the thermal energy output per unit of electrical energy input.

16 The production and use of first-generation biofuels must ensure that it does not lead to environmentally harmful.

Current GHG emissions from agriculture, industrial processes and product use (IPPU) in Brazil (upper charts), and current biogenic CO_2 emissions from centralised point sources (lower chart)

→ Fig. 10



Agora Energiewende and Agora Industry (2023). Note: GHG emissions obtained from Estimativas Anuais de Emissões de GEE no Brasil (2022) and biogenic CO_2 emissions (except fermentation) calculated based on Balanço Energético Nacional (2023) and default emission factors from IPCC (2006). Ethanol fermentation was calculated based on 600 Mtcane/year, 38 litres of ethanol per tonne of cane, and 0.75 kilograms of CO_2 per litre of ethanol.

The challenge of reducing emissions in Brazil's agricultural sector

As discussed above (see Infobox 1), most of Brazil's GHG emissions originate in the AFOLU sector. With clear action being taken in the forestry sector to reduce deforestation, the agricultural sector may be more difficult to mitigate. This is due to the nature of emissions generated by livestock, fertilisers and lime application to soils. Although measures exist to reduce these emissions, they may not be sufficient to make the agricultural sector fully climate neutral. Together with unavoidable industrial emissions (e.g. cement), they will form the majority of the so-called residual emissions that will need to be removed from the atmosphere in order for the country to become net-zero by 2050.

Although there are various options for generating negative emissions through carbon dioxide removal, the most discussed option within the Brazilian bioenergy sector is bio-CCS (or BECCS), in which biogenic CO_2 is permanently stored in geological formations. At present, large quantities of biogenic CO_2 exist, mainly as a result of the combustion of sugar cane by-products and firewood (see Figure 10).

It is uncertain how much biogenic CO_2 will be available from these sources in future, however, as these types of biomass will be in high demand as feedstock for industrial and biorefinery applications. On the other hand, smaller sources of biogenic CO_2 from black liquor and ethanol fermentation, and other biomass sources such as charcoal and biogas may increase or at least remain at the same level in the future.

Carbon capture and storage (CCS) or carbon capture and utilisation (CCU)?

The nascent PtX industry will require sustainable CO_2 to be synthesised with electrolytic hydrogen to produce a wide range of products such as green urea and e-methanol, as well as purely electro-based Fischer-Tropsch (FT) e-fuels/products such as e-SAF (Sustainable Aviation Fuels), e-diesel, e-naphtha and others.

Brazil is in an excellent position to become a major producer of PtX products for international markets, not only thanks to its low-cost electrolytic hydrogen from wind and solar PV, but also because of its various existing point sources of biogenic CO_2. These sources represent an important competitive advantage for Brazil compared to countries that will have to rely on expensive direct air capture (DAC) of CO_2. Today, DAC costs are estimated at between USD 125–335/tCO_2 and could fall to around USD 100/tCO_2 by 2030 in locations with high renewable energy potential (IEA, 2022c). By comparison, the specific cost of CO_2 capture from concentrated point sources such as ethanol fermentation in Brazil is around USD 11/tCO_2 (Tagomori, 2018).

However, the need to compensate for its large carbon budget may pose a risk to the country's ability to fully exploit its PtX potential, as a large proportion of its existing biogenic CO_2 resources will have to be dedicated to bio-CCS if significant emission reductions are not achieved in all sectors, particularly agriculture and industry.

To put this in perspective, if the existing amount of biogenic CO_2 from ethanol fermentation (23.5 MtCO_2 per year) were used for FT fuel production, approximately 7.4 Mt of e-fuels per year could be produced for export to international markets, generating around USD 24 billion per year in revenues based on a future e-SAF production cost/market price of USD 2.4 per litre [17] (ICCT, 2022) (Oeko-Institut, Agora Energiewende & Agora Industry, 2023).

In order to be compatible with evolving international markets such as the H2Global policy support mechanism, only e-fuels based on sustainable CO_2 sources will be able to participate in the long term, in line with the recently adopted EU Renewable Fuels of Non-Biological Origin (RFNBO) regulations.

For this reason, Brazil could fully exploit its biomass potential and benefit from international PtX markets by keeping residual emissions to a minimum; otherwise, the competition between bio-CCS and bio-CCU might affect the country's competitive advantage of having relatively abundant and low-cost biogenic CO_2 sources.

17 Calculated based on a typical C6 Schulz-Flory distribution (6.89 kgCO_2/kg H_2; 2.25 kg FT-fuel/kg H_2; density of 740 kg/m^3).

7. Low-emission hydrogen production in Brazil offers business opportunities and decarbonisation options for industrial sectors such as fertilisers, steelmaking and chemicals.

Brazil can attract foreign investment for low-emission industrial development

Historically, Brazilian industry has relied on a mix of domestic, state and foreign investment. Multinational companies alone contribute more than a third of the country's industrial revenue (Corecon-RJ, 2018). Brazil remains a safe option for foreign direct investment, with more than USD 900 billion in foreign investment in 2021: Europe (63%), North America (22%) and other regions (15%) (BACEN, 2022).

However, the importance of Brazil's industrial sector for the country's economy has declined. Its contribution to GDP fell from over 35% in 1985 to less than 12% in 2020, accompanied by an unfortunate decline in the industrial complexity index (Considera & Trece, 2022). As a result, Brazil's economic engagement in the global market has weakened, reaching its lowest participation in global GDP (2.3%) in over 40 years (IMF, 2023c). In addition, Brazil's share of global trade in manufactured goods has fallen below 0.5% for the first time in at least a decade (Valor, 2023b).

The current geopolitical situation, triggered by the war in Ukraine and the fossil fuel crisis, has led countries to seek more diversified supply chains. In many regions, the industrial sector has been exposed to higher energy prices and the search for alternatives has focused on countries with vast sustainable energy and mineral resources as well as competitive energy prices. In this respect, Brazil is a very attractive destination for industrial sectors looking to relocate their energy-intensive industrial value chains.

The availability of renewable power, biomass and low-emission hydrogen at competitive costs in Brazil opens up the possibility of the country's neo-industrialisation, which would position Brazil as a benchmark in the production of green industrial intermediates and final products, capable of reducing the country's exposure to levies such as the EU's CBAM.

Brazil could use its competitive advantages to attract investment and promote the low-emission growth of its industrial sector. Similarly, attracting foreign industry to the country could promote a just and inclusive energy transition by bringing important economic growth and new employment opportunities. Trade agreements will be key to positioning Brazil as a hub for green industrial exports, though global trading conditions must be fair to importing and exporting countries, so Brazil could use forums such as the current EU-MERCOSUR trade agreement to establish guidelines and conditions that ensure economic dynamism is brought to the region.

Brazil as a contributor to global steel decarbonisation

Brazil's substantial iron ore resources make the Brazilian steel sector an attractive industry to contribute to the global decarbonisation of the sector. In 2021, Brazil exported 22% of the world's iron ore, making it one of the top five exporters (Agora Industry and Wuppertal Institute, 2023). However, with its vast renewable energy resources and potential for cost-competitive low emission hydrogen production, Brazil could explore the possibility of becoming a green iron exporter by attracting the energy-intensive steel production supply chain. Exporting green iron is an opportunity for Brazil to capture an additional value-added part of the steelmaking value chain.

Around 80% of pig iron production (SINDIFER, 2019) and 65% of steel production in Brazil use coal[18], which is the largest energy supply in the sector, accounting

18 11% of Brazilian steel production uses charcoal (Instituto Aço Brasil , 2023b) and around 24% is derived from electric process (Instituto Aço Brasil , 2023a). This results in the remaining 65% being produced using coal.

for 70% in 2020[19] (Instituto Aço Brasil, 2021). Green iron, in the form of sponge iron or hot briquetted iron (HBI), can be produced using hydrogen in directreduction iron (DRI) furnaces (E+ Transição Energética, 2023). This could reduce the Brazilian steel industry's dependence on coal, which is mostly imported into the country.

Exploring the export of green iron, rather than low emission hydrogen and iron ore separately, could be a cost-effective way to transport embedded hydrogen (see Insight 10) and bring significant benefits to Brazil. For example, green iron could increase local employment by around 16% (95 jobs per Mt of DRI produced) and increase value added by 18% in green iron exporter countries compared to exporting iron ore and green hydrogen separately, as shown in Figure 11 (Agora Industry and Wuppertal Institute, 2023). The strategy of producing intermediate products in the steel value chain could promote the growth of the green iron sector in Brazil, creating new jobs and positioning the country as an exporter of this product[20], while it continues to use its mineral resources.

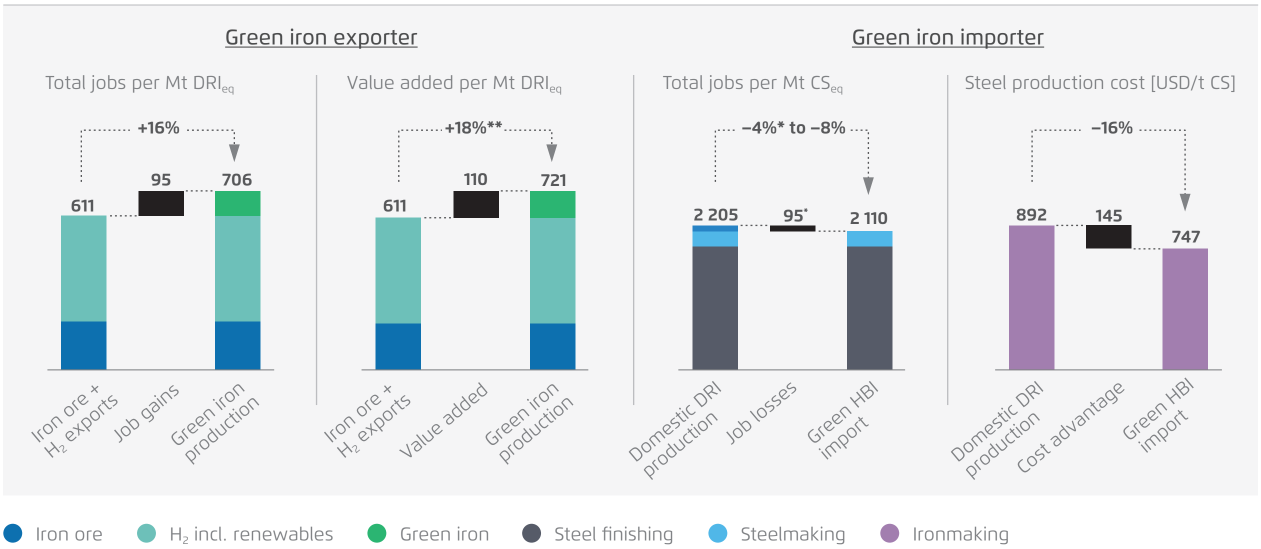
In addition, Brazil currently has a significant advantage. It already produces green steel, using charcoal in the production of pig iron. Charcoal accounted for 9% of the total energy supply of the steel sector in 2020[21]. Charcoal can contribute to the decarbonisation of the steel sector, in particular by meeting local demand with a low-carbon product and complementing the country's potential strategy of exporting green iron. Much of the charcoal is produced by the steel companies themselves. However, the participation of independent wood and charcoal producers has increased (E+ Transição Energética, 2023). It is important to highlight that not all mills can use charcoal since it has lower mechanical strength compared to coal, creating a risk of obstruction in blast furnaces

19 Data from ten industrial groups responsible for 85% of Brazilian steel production.

20 Brazil is already the second-largest exporter of pig iron in the world. In 2022, Brazil's exports accounted for nearly 30% of the world's total exports of 12.5 million tonnes (WSA, 2023).

21 Data from ten industrial groups responsible for 85% of Brazilian steel production.

Green iron trade can be a win-win for importers and exporters → Fig. 11



Agora Industry and Wuppertal Institute (2023). Note: The job intensity of steelmaking varies significantly across different countries. For our calculations we used a weighted average for iron ore mining jobs in the largest five iron ore exporting countries and assumed a job intensity of 8 full time equivalents for the production of 1000 t renewable H_2 per year and 53 kg H_2/per t of DRI. The numbers for green iron importers are derived from employment numbers in steelmaking from Germany. *The 4% share includes direct jobs in DRI ironmaking but does not include potentially associated jobs in administration and logistics. **Wages of jobs per Mt DRIeq used as proxy +2% depreciation rate of CAPEX. DRI = direct reduced iron; CS = crude steel

(Fastmarkets, 2022). Thus, the development of the steel industry in Brazil also creates opportunities for further development of the forest industry[22].

Brazil could explore strategies aimed at transitioning its domestic steel production by promoting the use of charcoal and possibly natural gas as a bridging technology to minimise the use of coal in the industry. At the same time, new steel production could aim to integrate DRI technology, especially in regions where low-emission hydrogen production has considerable potential in the country. Strategic partnerships with international stakeholders will be key to supporting Brazil in this ambition and to creating a global green iron trade capable of diversifying the green steel supply chain and reducing the cost of near-zero emission steel production, thereby safeguarding over 90% of jobs in the sector (Agora Industry and Wuppertal Institute, 2023).

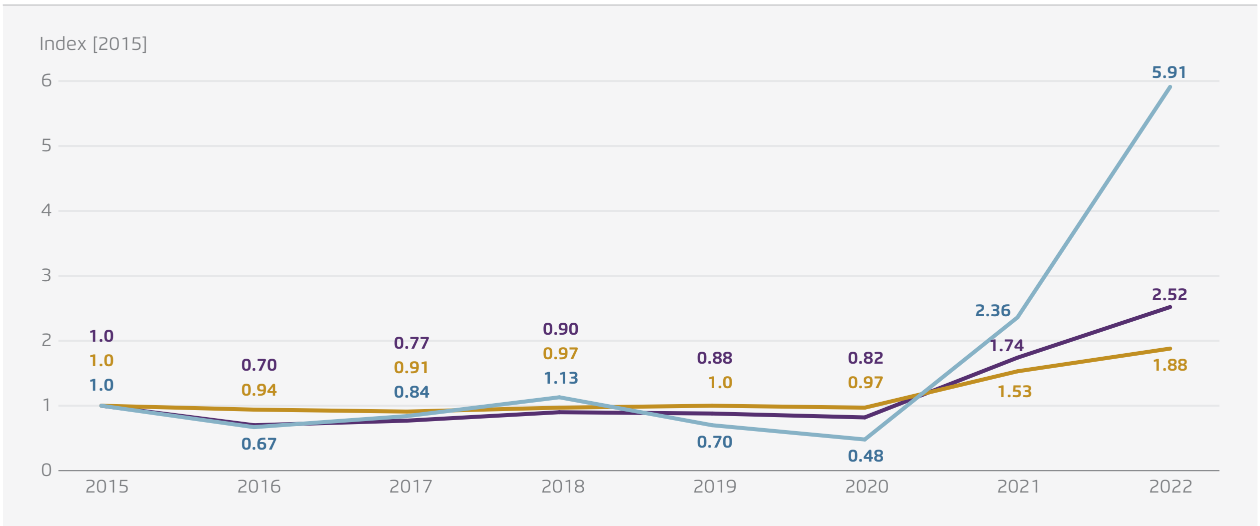
22 It is critical to ensure that proper sustainable and EESG practices are continually maintained and improved (G1, 2023; CBHSF, 2016; WWF, 2012).

Reducing fertiliser imports through green ammonia production

As mentioned above, Brazil's agricultural sector is an important contributor to the country's economy; however, it has also positioned the country as one of the world's largest importers of fertilisers, with imports worth around USD 16 billion in 2021 (OEI, 2023). This equates to around 7% of the income generated by agricultural exports and as such has a significant impact on the country's balance sheet. This is all the more relevant given that global fertiliser prices have tripled since mid-2020, driven by high natural gas prices over the past two years, as shown in Figure 12 (Agora Energiewende, Agora Industry and Fundacion Torcuato di Cuella, 2023). High fertiliser prices also have an impact on food prices, which in turn affect the global food supply chain. In 2022, Brazil therefore launched its National Fertilisers Plan, which aims to increase domestic production and reduce dependence on imports (MAPA, 2022).

Local production of fertilisers is particularly important for nitrogen-based fertilisers, which accounted for 31% of the country's fertiliser consumption in 2021 (FAO, 2023) and whose demand cannot be

Natural gas, urea and maize price index (1=2015) → Fig. 12



World Bank (2023). Note: Prices are for European market.

currently met by the two domestic producers in the country, with imports reaching around 11 Mt in 2022 (GlobalFert, 2023). Nitrogen-based fertilisers are produced from ammonia, which uses natural gas as the main feedstock for its synthesis, making it very vulnerable to global natural gas prices. Renewable hydrogen production in Brazil may provide an opportunity to decouple ammonia and fertiliser production from natural gas, reducing the impact of its cost on fertiliser production, which would reduce the cost pressure on food production.

Brazil's dependence on the international fertiliser market puts the country in a vulnerable position, with implications for food security and agriculture. Domestic production of green ammonia is a sustainable way to promote the development of the chemical sector, as the use of renewable hydrogen mitigates around 1.8 tonnes of carbon per tonne of ammonia produced using natural gas as a feedstock (Agora Energiewende and Wuppertal Institute, 2020). In addition, Brazil's biomass sector can serve as a source of biogenic CO_2 in the production of nitrogen-based fertilisers such as urea. Currently, Brazil is also exploring the potential for decentralised and small-scale fertiliser production from electrolysis and biomass, particularly in agricultural areas that are not well connected, with a focus on providing important local economic development.

Given the high demand for fertilisers in the country, Brazil will not be able to meet demand for fertilisers domestically in the short to medium term, but it could explore trade agreements with other Latin American countries willing to produce green fertilisers, as many countries in the region are interested in developing green ammonia and fertilisers from low-emission hydrogen. This strategy would strengthen regional partnerships, create new ventures for south-south cooperation in the region and promote a more diverse global supply of fertilisers.

Low-emission hydrogen provides new opportunities for green commodities

Brazil's efforts to develop green chemicals through biorefineries can be complemented by producing hydrogen by electrolysis to enable the manufacture of new products such as synthetic methanol. Methanol is one of the basic chemicals needed to produce other products, including solvents, and is likely to play an even bigger role in the future as a key feedstock to chemical supply chains. At the same time, methanol is emerging as a potential clean fuel for the marine sector, making it more attractive to the shipping industry.

Hydrogen-based fuels such as e-SAF are also attractive products that Brazil could consider producing and exporting, which would complement the country's strategy of producing chemicals from the biomass sector. This could be done on a regional basis, depending on the availability of resources in the country, with the Northeast region evolving to become a producer of renewable hydrogen and possibly exploring the potential export of e-SAF to the international aviation sector.

8. Conducting a comprehensive social and environmental assessment and integrated planning for hydrogen and PtX projects in Brazil to ensure social and economic development

Brazil's socio-economic development challenges, opportunities and industrial recovery

Despite its declining importance in recent decades, Brazil's industrial sector has a significant socio-economic impact in the country. For example, it provides employment for around 21% of the country's workforce, with most of the jobs coming from manufacturing, see Figure 13.

The country's unemployment rate is 8%, with the Northeast region having the highest regional rate at over 11%. This region also has the highest level of inequality (IBGE, 2023b).

In response to a declining industrial GDP and widening social inequalities, Brazil is exploring new avenues by capitalising on its wealth of biodiversity and renewable energy resources. The federal government's 2024–2027 multi-year plan recognises the potential of low-emission hydrogen as a new opportunity for Brazil. It places a strong emphasis on neo-industrialisation as a means of countering industrial decline, with a focus on job creation, social equity and environmental sustainability through cutting-edge technologies. At the same time, the plan aims to improve Brazil's global competitiveness by implementing key business reforms (BRASIL, 2023c).

This is an opportunity for all regions of the country to benefit. The Northeast, with its proximity to global markets and rich renewable energy potential, is well placed to drive Brazil's industrial revival and become an export hub, which could help reduce regional disparities.

One example is a renewable hydrogen project that is planned in Pecém in the state of Ceará[23] in the Northeast region (SEMACE, 2023a). The project will include a 2.1 GW electrolyser and is expected to create up to 5 572 jobs, employing 3 375 people per month on average during the 48 months of the installation phase. These jobs will be in engineering, procurement and construction, as well as office and field supervision. 100 people are expected to be employed on average during the operational phase, including administrative and operational tasks (FFI, 2023).

Besides the Northeast, and in addition to wind and solar PV potentials, several regions of the country have significant potential for biogas and biomethane production thanks to a well-developed agricultural and bioenergy sector. Close to major industrial centres, the Southeast, Central-West and South regions offer the greatest potential for these resources, making them crucial for the further development of a sustainable industrial sector in the country through green steel (from charcoal) and biorefineries, among other things.

Brazil's robust foundation in agriculture and bioenergy, coupled with its considerable expertise in basic industries, oil and electricity, positions the country with the domestic capabilities necessary to produce all components and inputs for hydrogen plants in the medium to long term, paving the way for economic and industrial development via various production routes and creating local hydrogen clusters in the country.

The potential hydrogen developments in Brazil will thus go hand in hand with the growth of the energy and industrial sectors, thereby creating high demand for professionals, technicians and trained personnel

23 In 2022, Fortescue industries announced the development of this project, with the aim of starting operations in 2026. The project is still awaiting FID.

in the sector. Brazil could consider building its capacity by creating programmes and increasing collaboration with the academia and other institutions, such as CEFET[24] and SENAI[25], with a view to providing the market with skilled professionals to achieve these ambitions. In the medium to long term, education and training could also shift from theoretical to practical skills, particularly in the operation of machinery and equipment.

Overall, Brazil could carefully assess the social benefits that potential PtX industrial development can bring to the country and ensure that these benefits are made available to local and vulnerable communities. This would improve social equity in the country. It is essential to conduct a social assessment in the context of export plans, as foreign investment and trade agreements are expected, all of which will need to ensure that the expansion of the Brazilian industrial sector gives rise to genuine socio-economic benefits. Further developing local capacities to integrate the population into these new projects will play a key role in achieving social and economic development for Brazil.

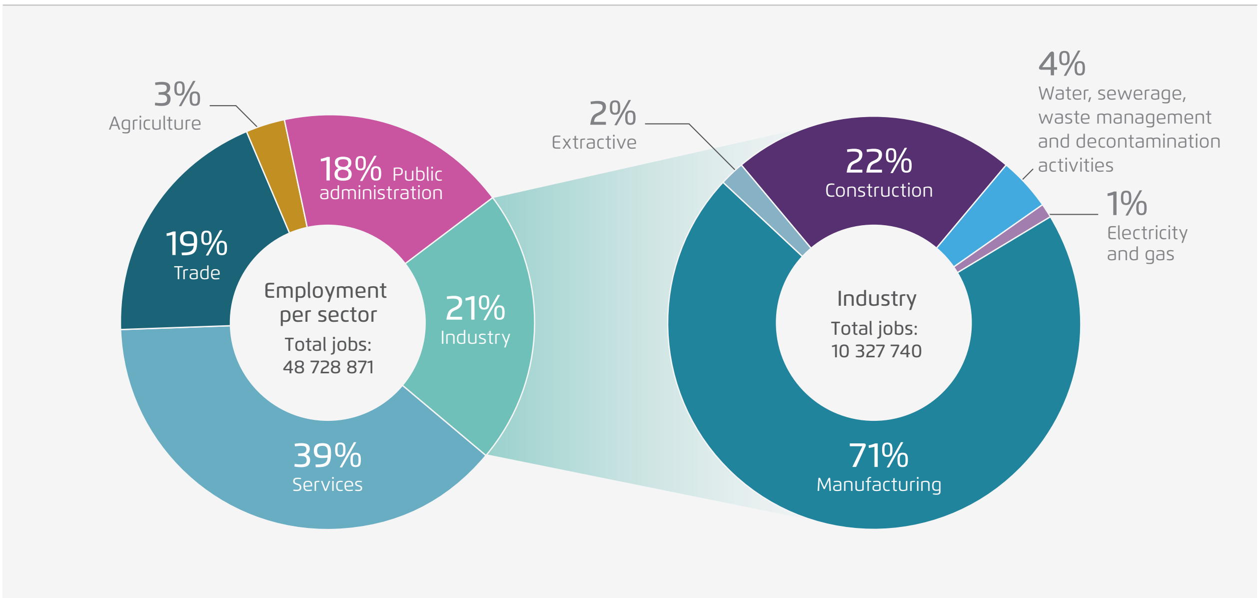
Private and public consensus on the role of hydrogen, but cross-sectoral view and integrated planning needed

The energy transition involves a system-wide change. Energy policies can no longer be sectoral (IEA-IRENA-UN, 2023). Expanding renewables, investing in infrastructure for direct electrification and the direct use of renewables and hydrogen will bring benefits to the whole economy (green recovery), create jobs, overcome the risks of hydropower (droughts) and decarbonise transport, industry, buildings, food production etc. See Figure 14.

24 CEFET *(Centro Federal de Educação Tecnológica)*: Federal Centers for Technological Education are federal institutions in Brazil that specialise in technical and technological education.

25 SENAI *(Serviço Nacional de Aprendizagem Industrial)*: The National Service of Industrial Learning is a Brazilian institution focused on industrial training and education.

Distribution of jobs in Brazil per sector, 2021 → Fig. 13



Sebrae (2023)

One of the goals of the government's multi-year plan is to strengthen Brazilian industry and boost exports, in line with the National Confederation of Industry's 2022 vision of a low-carbon economy. While there is broad consensus among experts, officials and business leaders about the opportunities in the hydrogen industry, the success of this endeavour will depend on well-coordinated government planning. Such planning includes establishing regulations and infrastructure, implementing certification processes and guaranteeing a minimum market for different types of hydrogen, all of which are essential to ensure secure and profitable investment.

As discussed above (see Insight 3), the PtX industry has important links with several key sectors in Brazil, such as energy, transport and industry, as well as synergies with the biomass and agricultural sectors. These sectors will be key to increasing the country's competitiveness in potential international trade, but also to developing a local hydrogen and PtX market, given the Brazilian industry's interest in developing both supply and demand for hydrogen in the country.

The intersectoral nature of hydrogen, combined with Brazil's abundant resources, provides a good environment in which to develop business models that haven't yet been explored in the country. In addition, the ability to integrate technologies such as electrolysis, biomass utilisation and refinery reconfiguration creates an important opportunity for the development of a Brazilian hydrogen industry. This linkage between technologies and innovative business models can potentially bring cost benefits, while at the same time encouraging innovative thinking about the circular economy for the production of low-emission hydrogen.

Integrated planning is therefore required, taking into account energy, infrastructure, decarbonisation and industrial development strategies. Identifying hydrogen hubs in Brazil would mean assessing the existing power and energy system, transport and port infrastructure and potential industrial off-takers, among other things, in each region of the country. Elements related to feasible options for hydrogen transport and storage also need to be linked to the integrated planning process.

In the light of the work undertaken by Brazil's federal government, an open consultation process can help civil society and local community representatives understand the potential challenges involved in expanding energy and industrial development in specific areas of the country. This integrated approach is essential to ensure a sustainable and coordinated energy future for Brazil, aligning the nation with its goals for a low-carbon economy and harnessing the full potential of hydrogen as a pathway for social and economic development.

Environmental and social justice as key enablers of Brazil's economic development

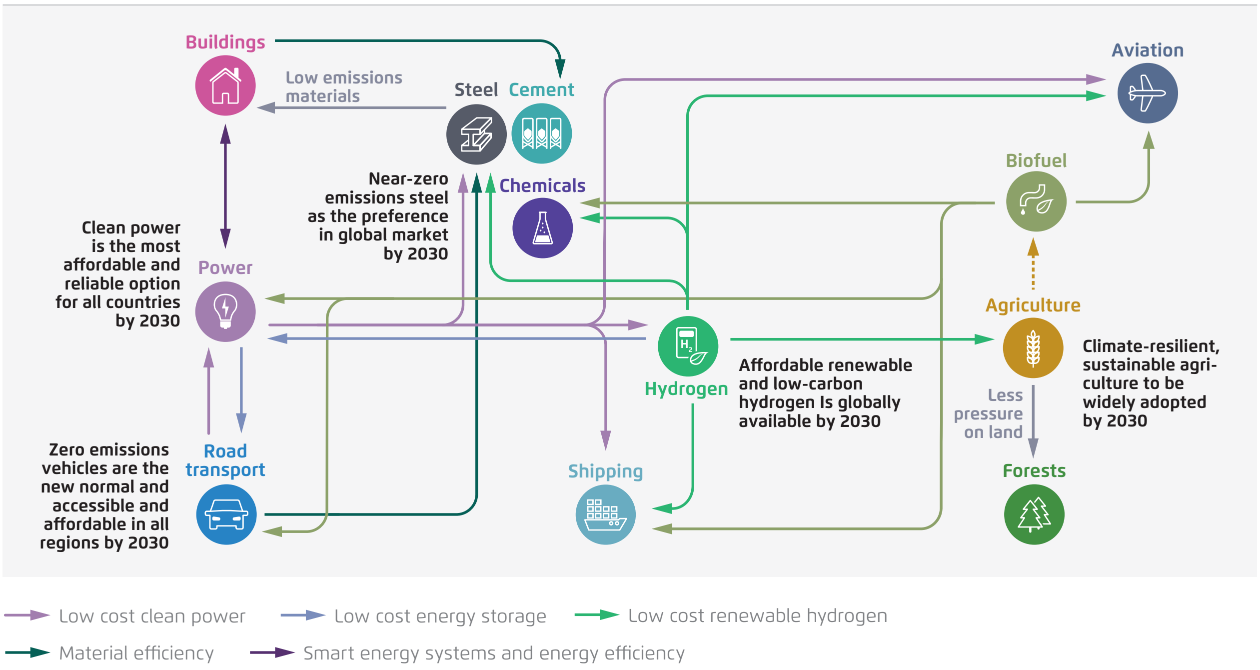
Hydrogen and PtX projects in Brazil have the potential to become enablers of the country's sustainable economic development, driven by a low-carbon industrial sector capable of creating new employment opportunities, technological innovation and equality of opportunity for all regions of the country, in line with its energy and natural resources.

To mitigate potential negative socio-economic impacts, all new renewable energy, hydrogen and PtX projects in Brazil should follow a comprehensive economic, environmental, social and governance (EESG) framework[26], with the open and active participation of all stakeholders. However, the trade in hydrogen and PtX products is also a challenge for Brazil, as it runs the risk of becoming an extractive industry with economic benefits for importing countries and foreign investors, but no long-term benefits for the Brazilian population, especially for vulnerable communities. The development of integrated plans for hydrogen and PtX products must therefore include open discussions with different stakeholders such as civil society and local communities, with a view to informing them and agreeing with them on the necessary considerations for the development of such projects. Involving local communities from the start of the planning process, with clear grievance

26 For example, the PtX Hub has developed a scoping paper identifying the different sustainability dimensions of the EESG framework for renewable hydrogen and PtX projects: https://ptx-hub.org/ptx-sustainability/

Energy transition as a system-wide change: how action in each sector can contribute to progress in others

→ Fig. 14



Agora Industry based on IEA-IRENA-UN (2023)

mechanisms and the possibility to invoke rights, will be a key component in ensuring social development, especially in areas close to indigenous communities. Civil society representatives can be allies of the hydrogen and PtX industry if they are involved early enough in the consultation and planning processes for the industry.

In addition, a comprehensive environmental evaluation needs to be carefully developed as part of the integrated plans for hydrogen and PtX development. This includes not only the environmental approval process for each project, but also strategic land use planning and water management. Inventories of the availability of water and land resources need to be drawn up for Brazil's different regions. Issues such as water availability and rights, disposal of brine from the desalination process, demarcation of protected biodiversity areas and other aspects could be considered. A robust environmental assessment of hydrogen and the PtX process is a key component that can be clearly defined as part of PNH2 in Brazil.

9. Hydrogen production must be seen not only as an energy issue but also as a climate issue, to pave the way for a blend of financing instruments

The importance of establishing a hydrogen policy and regulatory framework for the entire supply chain

To create an attractive market for private and international investors, countries need to provide a clear and reliable environment for low-emission hydrogen development. In addition, by framing low-emission hydrogen production as both an energy and a climate issue, renewable-rich countries can attract a broader range of investors and tap into various sustainability and clean energy financing instruments (World Bank, 2023). Indeed, as the international community has committed to rapid global decarbonisation in the Paris Agreement, instruments are available to finance climate change mitigation projects. A clear hydrogen strategy, based on cohesion between a range of different stakeholders, from governmental bodies to the private sector and international partners, is therefore key to boosting hydrogen in Brazil.

The following dimensions should be assessed when developing a strategic roadmap for the creation of a new sector:

1. **Regulatory framework:** a solid legal foundation is essential in order to define the rules governing the new activity in the country and to ensure the security of investments in new ventures.
2. **Demand pull:** incentives need to be put in place to create a local market. These can include economic tools such as subsidies, taxes and tariffs, or regulatory measures such as guaranteed access to the electricity grid and environmental responsibility laws. Coordinated development of hydrogen demand hubs is also necessary to promote infrastructure sharing and joint purchasing arrangements in potential industrial parks.
3. **Supply pull:** incentives are also needed to develop a local production chain. These could take the form of economic measures such as preferential loans, tax incentives and R&D grants, or regulatory instruments such as local content requirements and technology/performance standards.
4. **Infrastructure planning:** given the challenges associated with the development of hydrogen storage and transport, it is important to have a clear understanding of the infrastructure requirements for hydrogen and PtX products. Regulations for the transport and storage of hydrogen are needed to ensure a coordinated production flow for both export and domestic consumption.

Brazil is developing its National Hydrogen Programme (PNH2) and a three-year work plan for 2023–2025, signalling the country's intention to align its hydrogen market with national industrial development and to position itself internationally as a trader of green intermediate and final goods and products with high added value. The objectives of the programme include aligning national and international standards, interaction between different economic sectors, increased cooperation between government agencies and the development of new, safe technologies (MME, 2022b). However, Brazil's approach to the hydrogen economy has suffered from discrepancies between different levels of government. Some individual states have made more progress with formulating their policies, primarily focusing on local interests and resource utilisation (Castro, Leal, & Costa, 2023). Thanks to PNH2 guidelines and the sectoral regulation currently under discussion in the Brazilian Parliament, it is expected that actions and measures will be unified and accelerated to contribute to the development of the hydrogen industry and its derivatives in the country, and to ensure equitable economic and industrial development in all regions of Brazil as well as integrated value chains across the country.

Attracting investment for hydrogen development in Brazil

As mentioned above, the development of hydrogen and PtX will require multi-sectoral coordination and therefore open discussion with all relevant stakeholders at different levels. In addition, the infrastructure necessary to scale up the deployment of PtX products will involve significant long-term investment and will thus require widespread support and agreement. A concerted set of instruments is essential, including the development of blended finance instruments to reduce the financial costs of establishing this new value chain. These instruments can take into account the importance of low-emission hydrogen in the fight against climate change.

Brazil has already established a financing scheme, namely the National Financing Mechanism for Hydrogen Development, with the support of local institutions such as the Brazilian Development Bank (BNDES), though only for pilot projects. By further developing instruments to develop PtX products and scale up hydrogen production, Brazil could significantly increase the pace of economic and environmental transition. At the same time, certain hydrogen funding support mechanisms have been put in place at the regional and global levels, providing Brazil with more options to finance hydrogen developments in the country (see Table 1).

The private sector has shown great interest in Brazil and rapidly formed state-level partnerships to build hubs and facilities for future export sources of renewable hydrogen. Port hubs such as Pecém in Ceará for example are using new business models such as the definition of tax-friendly export processing zones (EPZs) that offer tax exemptions for both local and foreign purchases and allow companies to keep all foreign currency from exports. One important recent step was the approval of the Preliminary Installation Licence for the Pecém Hydrogen Hub, which simplifies the investment process and significantly improves procedures (SEMACE, 2023b). At the state level, companies are able to negotiate state tax reductions, which can reduce the VAT (ICMS[27]) tax by 75% to 99% (ADECE, 2022). This framework aims to attract investment and increase Brazil's competitiveness in the global market. Based on these scattered initiatives, Brazil could design an integrated tax and duty structure to meet the needs of this emerging industry and define the building blocks of the future hydrogen value chain.

Creating domestic demand through green public procurement can set the tone, reducing potential off-taker risks and stimulating industrial demand in sectors such as steel and chemicals. In addition, the Brazilian government's announcement to create a carbon market may contribute to the development of the sector.

Coordinating national climate policies can also lead to inflows of foreign capital investment earmarked for climate change mitigation efforts, notably under the EESG commitments from private and public investors. Brazil could also consider taking advantage of the upcoming international carbon market mechanism developed under Article 6 of the Paris Agreement, among other climate finance options.

The interplay of local industry and R&D to promote economic development and resilience

By aligning the development of its hydrogen market with national industrial development, hydrogen could become the country's flagship technology, attracting investment in the green sector and providing an opportunity to reindustrialise the country while at the same time developing local technologies and expertise.

On the technical front, Brazil could leverage its national expertise in fuels and materials to address infrastructure and industrial development challenges. Indeed, the country has a robust scientific community that can work with private companies to address issues such as material challenges for hydrogen

27 *Imposto sobre Circulação de Mercadorias e Serviços*

storage and transport, e.g. pressure tanks, gas pipes, valves and compressors. Brazil can therefore safely intensify R&D to promote local technology development in line with its broader neo-industrialisation intentions.

Available financial instruments for hydrogen projects → Table 1

Name	Institution	Status	Beneficiary	Mechanism
BNDES Finem / Environment (BNDES, 2023)	BNDES	Effective	Brazil-based companies, public entities (state, municipality, federal districts)	Direct and indirect financial support for (among others): • studies and projects • renewable hydrogen equipment and machinery acquisition • technical services and training Minimum funding: ten million reals
CAF Energy Integration and Transformation (CAF, 2023)	Development Bank of Latin America and the Caribbean (CAF) & BNDES	In finalisation	Private investors	Credit line of up to USD 500 million in "powershoring"* projects, green development, economic reactivation and financial inclusion, improvements in access to industrial zones and ports, new industrial plants and green manufacturing (steel, fertilisers).
CIF Renewable Energy Integration (CIF, 2023)	Climate Investment Funds (implemented by IDB and World Bank)	Approved	Private and public	USD 70 million in concessional finances to support grid flexibility for clean energy integration in Brazil. Brazil estimates that the funding will mobilise USD 9.1 billion from partners, including eight billion USD in private investments.
Climate Fund / Renewable Energy sub-programme (Climate Bonds, 2022)	Brazilian Development Bank - BNDES	Effective – until 28/12/24	Private companies and local administrations	Support in investments for: • Renewable H_2 technological development • Production or use of green hydrogen Minimum funding: 40 million reals
European Hydrogen Bank (European Comission, 2023b)	European Commission	In finalisation	PtX Producers	Based on the H2Global mechanism (see below), the programme will most likely consist of a double-sided auction to purchase PtX from outside the EU via long-term purchase agreements.
Export Processing Zones (MDIC, 2023)	Brazilian states	Effective	Private companies and others	Free trade areas (mainly ports) to attract foreign direct investments via tax incentives for renewable hydrogen companies and other benefits.
Global Gateway Initiative (EIB, 2023)	European Investment Bank	Approved	Undetermined	Financing through loans facilitating long term investments in the renewable hydrogen industry. Details are currently being defined.
H2Global (H2Global, 2022)	Hint.co – (German and Dutch governments)	Effective – first results expected in 2024	PtX producers	Double-sided auction mechanism for long-term hydrogen purchase agreements for export to Europe.

* Powershoring refers to the decentralisation of production to countries that offer clean, safe, cheap and abundant energy and are close to consumption centers, in addition to other virtues to attract industrial investment.

Available financial instruments for hydrogen projects → Table 1

Name	Institution	Status	Beneficiary	Mechanism
Hydrogen for Development Partnership (H4D) (ESMAP, 2023)	ESMAP	Effective	Open to all hydrogen stakeholders and already counts several industry, academic and research institutions among its partners.	Aimed at helping catalyse significant financing for hydrogen investments from both public and private sources. Intended to foster capacity-building and regulatory solutions, business models and technologies for hydrogen deployment in developing countries.
Sustainability Bond Framework / Green Bonds; (BID, 2021; BNDES, 2021)	BNDES & IDB (Inter-American Development Bank)	Effective	Private companies specialised in sustainable projects	Development of a sustainable credit market by issuing green, social and sustainable bonds by BNDES in Brazil and abroad.
The PtX Platform (KfW, 2023)	KfW	Effective	Private companies in Global South	Funding is provided to projects along the entire PtX value chain, with the aim of closing the bankability gap in the countries of the Global South. Potential of €2.5 billion euros in funding for private investment.

Agora Industry, Agora Energiewende (2024)

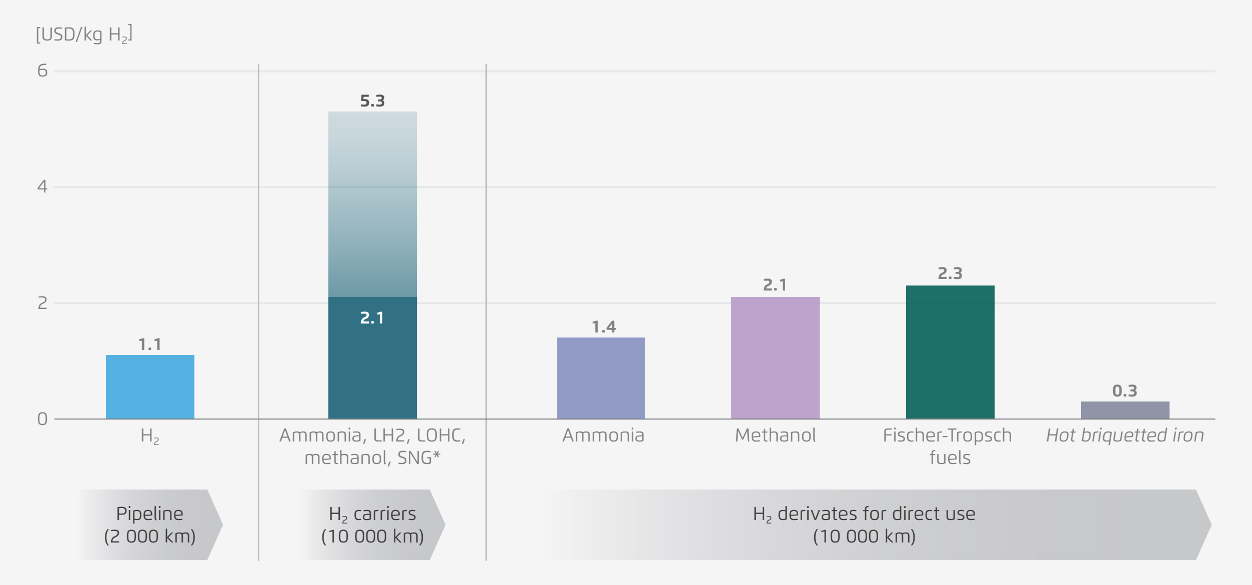
10. Brazil can play an important role in the global trade of PtX products, ensuring the competitiveness of its exports to European and Asian-Pacific markets

How can Brazil jump into the low-emission hydrogen trade?

The hydrogen trade is beginning to take shape, driven by the ambition of countries around the world to achieve net-zero emissions by mid-century. Regions such as Europe and East Asia are positioning themselves as potential low-emission hydrogen importers, as their limited domestic energy resources and high energy demand will not allow them to meet their own hydrogen needs in the industrial, transport and power sectors. On the other hand, many countries in the Global South have vast renewable energy resources that can meet the demand of industrialised countries. This new trade dynamic has the potential to change the landscape of energy geopolitics, with a greater diversity of countries participating in the sector, thereby creating a more inclusive political landscape for the energy transition (IRENA, 2022).

Against this backdrop, Latin America is projected to be the leader in low-emission hydrogen exports by 2030, with Argentina, Brazil and Chile as the main contributors. Their combined export capacity is expected to exceed 3 Mt H_2/year equivalent (IEA, 2022a). Brazil is a very attractive country for hydrogen exports given the competitive cost of renewable hydrogen, the diversity of energy resources, the dynamic renewable energy market and the low carbon electricity grid, among other factors. However, because Brazil's potential export market is overseas, the hydrogen trade is technically and economically complex. Pipelines are most cost-effective for distances under 5 000 kilometres, with retrofitted pipelines being more affordable than new ones. Shipping becomes viable for distances over 8 000 kilometres, though pure hydrogen then has to compete for shipping capacity with other green molecules such as ammonia and methanol. For distances between 5 000 and 8 000 kilometres, transport options vary depending on the product and delivery location (IEA,

Hydrogen transport costs to Germany 2030 → Fig. 15



Based on Agora Industry and TU Hamburg (2023). Note: *with a nearly closed carbon loop.

2022a). Therefore, hydrogen derivatives or PtX products may be the most cost-effective way for Brazil to trade hydrogen with overseas markets.

Figure 15 shows an example of the estimated costs of transport to Germany in 2030, from markets at different distances. For distances above 10 000 kilometres, as is the case for Brazil, transporting PtX products – i.e. hydrogen derivates for direct use – is much cheaper than using hydrogen carriers that need to be re-converted to hydrogen at the receiving port. Hot briquetted iron has the cheapest transport costs, followed by ammonia, methanol and hydrogen-based fuels (Agora Industry and TU Hamburg , 2023).

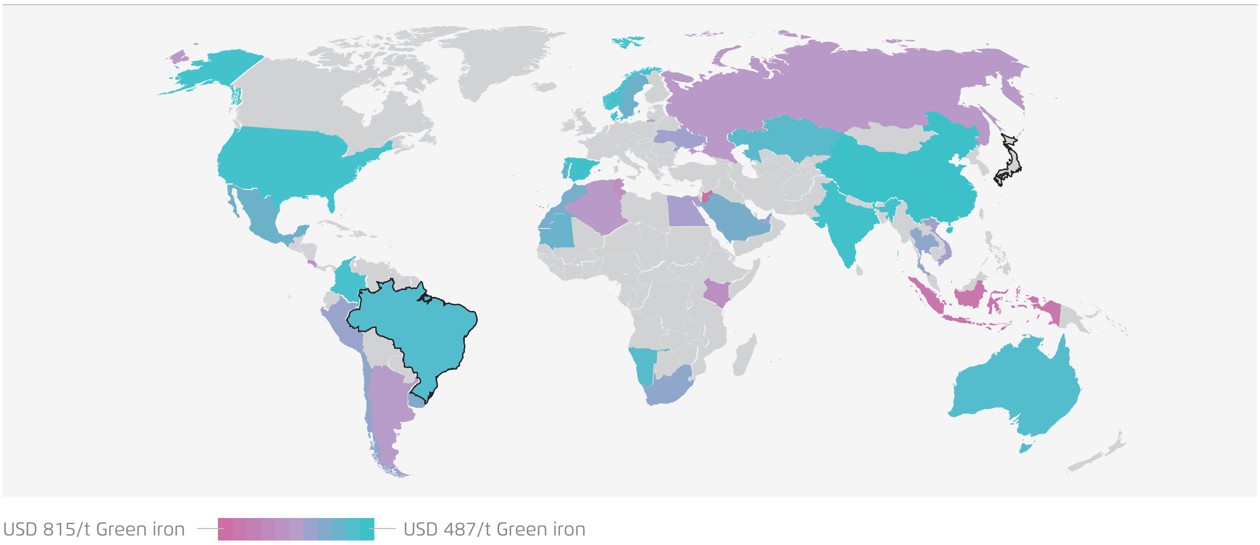
Trade in value-added products such as PtX can bring greater benefits to the country, such as low-carbon industrial development, increased investment and job creation. For example, as discussed in Insight 7, Brazil's iron ore resources put the country in a position to attract foreign investment in the production and trade of green iron, creating jobs and contributing to the decarbonisation of the steel sector. Therefore, developing trade in PtX products in Brazil can bring better benefits to the country. However, the terms of trade need to be carefully negotiated to ensure strategic partnerships with conditions that are equally beneficial to importers and exporters, so that the socio-economic benefits of this activity can have a clear positive impact in the country.

Brazil has a very positive advantage in trading PtX products

Brazil's unique conditions position it as one of the top potential exporters of PtX products to the European and Asian markets, despite the long trade distance. Figure 16 shows estimates of the cost of exporting green iron from Brazil to Japan by 2030. At around USD 528 per tonne, Brazil is more competitive than other countries in Asia, Latin America and North Africa. Similar estimates for the export of other PtX products to Japan in 2030 show competitive values of USD 128 per tonne for green ammonia, USD 138 per tonne for green methanol and USD 139 per tonne for Fischer-Tropsch fuels (Oeko-Institut, Agora Energiewende & Agora Industry, 2023).

For Brazil, the European market appears to be a more attractive export market than East Asia in terms of logistics and distance. By comparison with

Total costs of exporting green iron to Japan, 2030 → Fig. 16



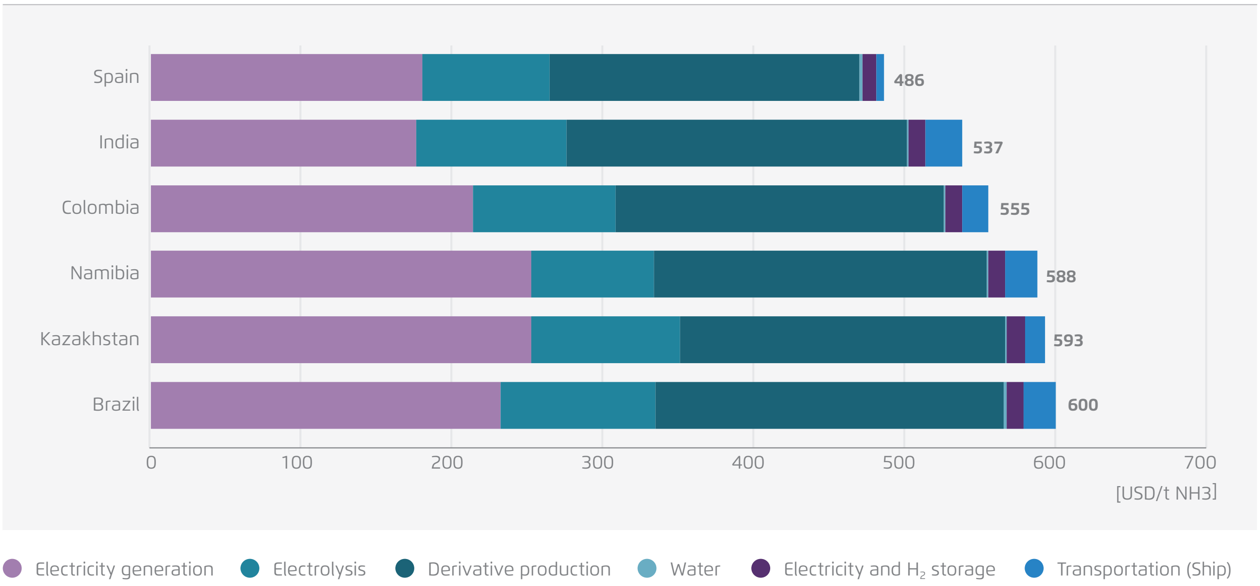
Created with PtX Business Opportunity Analyzer v1.0.9 (Oeko-Institut, Agora Energiewende & Agora Industry, 2023), using default parameter settings. This map is provided for illustration purposes only. Boundaries shown on this map do not imply any endorsement or acceptance by the tool developers.

other potential exporters of green ammonia to the Netherlands, Brazil shows competitive advantages, though also other aspects that need to be improved for the country to become even more competitive than other potential competitors. Figure 17 shows the cost breakdown for ammonia exports to the Dutch market from selected countries in 2030 with the total cost of delivered ammonia ranging from USD 486 to USD 600 per tonne of ammonia. Electricity generation and derivatives production account for the largest share of the costs of exporting ammonia from Brazil to the Netherlands, each accounting for around 38% of the total cost, followed by electrolysis (17%) and transport (3.5%). Electricity generation in Brazil is quite competitive, being almost 10% cheaper than in Namibia. In terms of transport costs, Brazil is clearly at a disadvantage compared to other countries closer to the Netherlands, such as Spain, where transport costs are around four times lower than in Brazil. However, this does not make the country uncompetitive, as it has the potential to further develop its renewable energy market to achieve even more competitive power generation costs.

In assessing its position in the international market, Brazil will need to evaluate its hydrogen production capacity and balance it prospectively with other producers in other regions, such as in the Middle East, North Africa, Central Asia and Latin America. By doing so, the country will be able to constantly review its competitiveness and adjust its plans with a view to increasingly strengthening its role in the global hydrogen market.

Brazil could also explore the potential offered by trading PtX products at a regional level to better position itself in intercontinental markets. Partnerships with other Latin American countries could be explored to take advantage of existing electricity and gas infrastructure and produce more PtX products, potentially developing a dynamic regional market in the long term. For example, the regional production of green fertiliser could help Brazil reduce its dependence on more volatile markets.

Cost breakdown of exporting ammonia to the Netherlands, 2030 → Fig. 17



Agora Energiewende and Öko-Institut (2023)

Brazilian port infrastructure needs to be prepared to export renewable hydrogen and PtX products

Current long-term planning studies for the Brazilian port sector do not take into account the potential trade in hydrogen and PtX[28]. Unlike the initial efforts of the PNH2 programme and the pioneering studies by EPE, this issue has not been officially documented[29] by the national port planning authorities (MT, 2021).

Brazil's port infrastructure has been built to meet the high-volume needs of mineral and agricultural commodities and the country's export profile. From January to June 2023, Brazil exported almost 415 million tonnes of products. Just ten products accounted for more than 95% of exports by weight, with around 60% being mineral commodities, 30% agricultural commodities and around 10% containerised cargo (ANTAQ, 2023).

The Brazilian coastline is home to several public and private ports of varying sizes and capacities. The most important (in terms of volume and financial resources traded) are located in the Southeast and South regions of the country. Regionally, the Southeast (50%) and Northeast (25%) account for 75% of the export volume by weight, followed by the South and North, both with 12%, and the Central-West with just 1% (ANTAQ, 2023).

There are a number of initiatives at port level in the country, such as the aforementioned port of Pecém. For example, the Porto do Açu in Rio de Janeiro, which aims to become a future hub for energy transition, and the ports in the Northeast region (Suape in Pernambuco and Salvador in Bahia), which are seeking strategic partnerships for hydrogen and PtX exports. At the same time, the port of Rio Grande in Rio Grande do Sul has good infrastructure and industrial centres in the surrounding area. However, there is no clear coordination between these initiatives, which could otherwise help to complement efforts and channel investments more efficiently to develop the infrastructure required for potential trade in PtX products.

28 However, initiatives to discuss these topics are already underway. See at: (ANTAQ, 2022).

29 National Logistics Plan (NLP) is the main long-term planning instrument for the sector in Brazil.

11. Hydrogen industry needs to be competitive and set low-emission hydrogen standards in line with global trade requirements

Brazil has already taken a first step in developing a hydrogen certification in the country

Brazil has recently taken an important step towards developing a hydrogen economy by publishing its first hydrogen certification scheme (CCEE, 2023a). The first version of the new certification system, developed by the Brazilian Chamber of Electric Energy Commercialisation (CCEE), defines standards for hydrogen generated by electrolysis. It also includes specifications for the method of measuring emissions associated with its production (see Infobox 5). So far, as previously mentioned in the other insights, Brazil has shown interest in becoming a major player in the hydrogen economy. Since 2002, it has launched several R&D programmes (see Insight 12), such as the Science, Technology and Innovation Programme for the Hydrogen Economy (ProH2), included hydrogen in its National Energy Plan 2050, and is currently developing a National Hydrogen Plan (PNH2). However, the development of a hydrogen market in Brazil still faces several challenges that have yet to be addressed (EPE, 2021). By creating certification standards that provide clarity for investors and project developers, Brazil is addressing one of the key challenges in promoting hydrogen production (PwC Brazil, 2022).

Towards a carbon footprint for hydrogen

Internationally, there has been widespread discussion about the standards for hydrogen production, in particular the criteria that determine the sustainability of hydrogen production. To date, the discussion has focused on the type of feedstock (renewable energy, natural gas, coal etc.) and the technology used to produce it (electrolysis, steam methane reforming, pyrolysis etc.). The hydrogen produced is assigned a colour according to these criteria (Infobox 2). While no global definition of "green" hydrogen yet exists, there has recently been growing international support for a differentiation system based on the carbon footprint associated with its production (IEA, 2023e) A life cycle assessment has been described as a more appropriate method of determining the emissions threshold of hydrogen because, rather than linking certification to the feedstock and technology used to produce hydrogen, it focuses on accounting for carbon emissions along the entire hydrogen production chain, including those emissions resulting from feedstock extraction, leakage during production and carbon storage. This approach could potentially capture the true emissions reduction potential of the hydrogen produced by a given technology pathway.

Although Brazil has been openly supporting a carbon footprint-based taxonomy (EPE, 2021), the first version of the certification standard only recognises electrolysis as a 100% sustainable production method (see Infobox 5).

The importance of coordination between importers and exporters

The creation of standards is undoubtedly an important step forward for sustainable hydrogen production; if Brazil is to establish itself as a key player in this sector, however, a broader regulatory framework is needed that not only aligns with international regulations and standards, but also includes PtX products such as ammonia. In 2023, for example, the EU extended its regulatory framework by setting clear requirements for the production of renewable fuels of non-biological origin, i.e. renewable hydrogen and its derivatives[30]. The EU has adopted two new laws to complement the Renewable Energy Directive (RED), setting out rules for sourcing the renewable electricity used in the production of renewable fuels of non-biological origin (RFNBO) on the basis of principles such as "additionality",

30 RFNBOs are liquid and gaseous fuels whose energy content is derived from renewable sources other than biomass.

"geographical correlation" or "temporal correlation" and by defining a methodology for calculating life-cycle greenhouse gas emissions for RFNBOs[31]. This is also intended to pave the way for international trade in these products, of which Brazil could become one of the largest producing countries. However, this regulation may not fully reflect the reality in Brazil, which could hinder trade in PtX products. The diversity of energy resources, including biomass, as well as certain specificities of the Brazilian grid due to the country's vast territory, such as the division of sub-markets and the operational process, may not meet some of the specifications of the "additionality", "geographical correlation" and "temporal correlation" criteria. Consequently, Brazil may decide not only to establish its own regulations covering different carbon content ranges, but also to campaign internationally for certification models that are being widely discussed by potential importers and exporters of hydrogen and PtX products. Technology-neutral certification may also be more in line with Brazil's view, especially when considering renewable pathways beyond solar and wind. However, the boundaries of the life-cycle assessment need to be clearly defined internationally for all hydrogen production pathways in order to ensure the sustainability of hydrogen globally, thereby enriching and strengthening the international market.

The United States, on the other hand, has already set standards for state subsidies for "clean" hydrogen in its recent Inflation Reduction Act (IRA). These are based on the lifecycle greenhouse gas emission rate, which in the case of clean hydrogen must not exceed four kilograms of CO_2 per kilogram of hydrogen produced. Such standards have been shown to have a clear positive impact on encouraging investment in and development of green technologies (WEF, 2023).

Hydrogen standards are being developed around the world, demonstrating the need for them in the development of a hydrogen economy, but also highlighting the importance of international alignment on compatible standards. This was an important issue at the recent G20 summit in Delhi, India. Brazil, along with the world's 19 other major economies, committed at the summit to promoting investment, mobilising finance and developing infrastructure to enhance the production, use and global trade of hydrogen produced by zero- or low-emission technologies and its derivatives. To this end, the signatories developed five "High Level Voluntary Principles on Hydrogen", the first of which is to "encourage cooperation in the development of national standards and work towards a globally harmonised approach to the certification of hydrogen produced from zero- or low-emission technologies and its derivatives, such as ammonia" (G20, 2023). In signing this declaration, Brazil has committed to contributing to the construction of the global trade requirements while giving due consideration to social aspects.

In addition, Brazil participated in the International Hydrogen Trade Forum (IHTF), which was established in July as an evolution of the International Hydrogen Trade Working Group that emerged from the Clean Energy Ministerial[32] (CEM) Hydrogen Initiative. This forum brings together coordinators from countries involved in the import and export of hydrogen. Brazil has been invited to co-host the export segment[33]. This means that it will have the opportunity from July 2024 to set the group's agenda for the following year. Brazil is expected to address issues related to foreign direct investment and the export of green products, including but not limited to commodities. Discussions will also include a proposal for the mutual recognition of hydrogen certification schemes, potentially enabling countries to acknowledge each other's national certifications. At the same time, there are ongoing

31 "Additionality" in renewable hydrogen production requires the use of new renewable generation, encouraging the creation of new capacity. "Temporal correlation" determines when renewable electricity is available, thus avoiding the use of grid electricity during periods of low renewable generation. "Geographical correlation" aims to ensure that hydrogen production is geographically close to the renewable energy source, preventing the worsening of electric grid bottlenecks and long-distance transfers via renewable energy credits Taken together, these rules aim to prevent the use of fossil-fuel based grid electricity for green hydrogen production.

32 In 2024, Brazil will host the fifteenth edition of the Clean Energy Ministerial (CEM15), https://www.cleanenergyministerial.org/cem14-and-cem15-hosts-announced-at-gceaf/

33 Subject to approval by the CEM.

discussions within Brazil on hydrogen-related legislative projects, with an emphasis on sector incentives and their impact on consumer tariffs.

Moreover, as the third largest economy in the Global South and the host of the upcoming G20 and COP30 summits, Brazil has the opportunity to position itself as an outspoken leader for social justice and a just energy transition in the international debate on sustainable production standards, building on its active participation in various platforms such as the G20, the COP, the International Standards Organisation (ISO) and the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE).

Infobox 5: The first hydrogen certification in Brazil

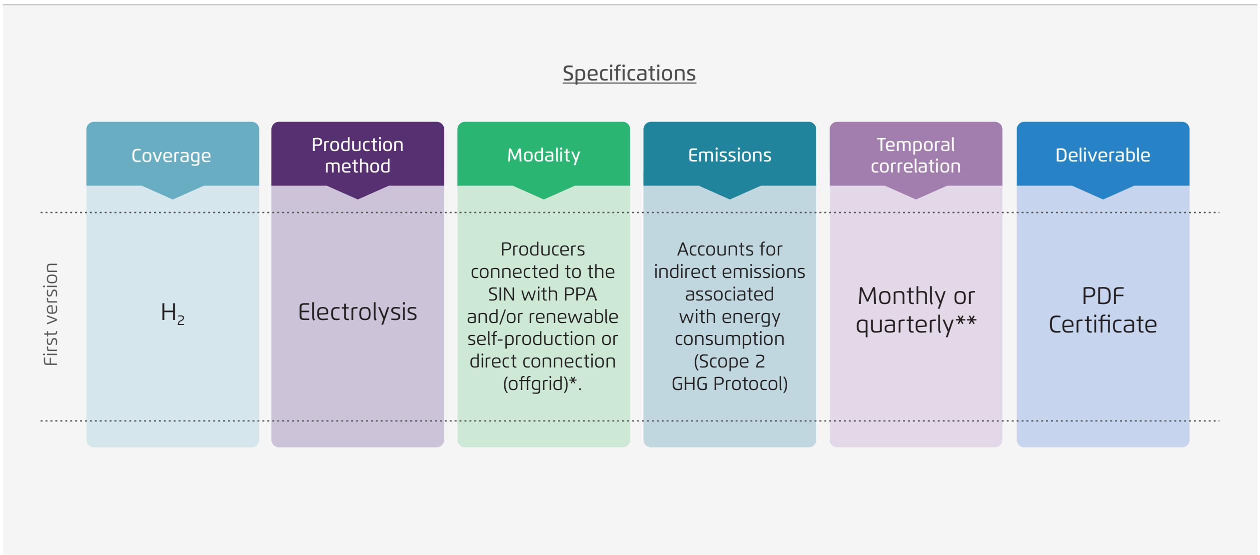
The Brazilian organisation CCEE - a market operator for energy contracts - published the first version of sustainable hydrogen certification at the end of last year. This first version has been developed in line with the latest rules complementing the EU's Renewable Energy Directive (RED II/III).

The new standard includes specifications for the feedstock and the technology used to produce it, as well as the method for measuring the emissions associated with its production.

Initially, the product will be certified free of charge by the Chamber of Commerce and the document will have two types of classification, one for 100% renewable inputs coming from wind, photovoltaic or hydroelectric power, and another for partially renewable inputs, complemented by another source and coming from thermoelectric projects.

Specifications for the first version of hydrogen certification in Brazil

→ Fig. 18



Based on CCEE (2023a). Note: *Hydrogen that is being produced in a production plant connected to the National Interconnected System (SIN) with PPA and/or renewable self-production or produced with a direct connection to a renewable generation plant (off-grid). **Temporal correlation: the quantification and evaluation of the energy used and the hydrogen produced will be assessed in a monthly or quarterly.

12. Enhancing international cooperation and promoting R&D&I will be a key aspect for the development of the hydrogen economy in Brazil

Brazil has a strong tradition of R&D&I in hydrogen and can use this to reduce its technological dependence

Hydrogen will play a crucial role in the decarbonisation of applications that truly need hydrogen to become climate-neutral in the coming years and decades. However, a coordinated effort is needed globally to increase investment in R&D&I with a view to accelerating technological progress and achieving commercial deployment by the mid-to-late 2020s. This will require significant financial commitments both from governments and the private sector (IEA-IRENA-UN, 2023). Brazil has been promoting research into hydrogen technologies since the 1970s and the oil crisis (Silva & N.P. Neves, 1992). Various universities, companies and government agencies have been involved, with projects reaching the prototype stage – and some even the commercialisation stage. However, interest in these technologies has wavered, leading to periods of research suspension, the demobilisation of technical and scientific teams, and the closure of university laboratories and corporate innovation departments (Santos, 2008).

Nonetheless, the global interest in hydrogen has sparked several R&D projects in the country, some of which are described in Infobox 6 below. For example, pilot and demonstration projects have led to innovative developments in hydrogen storage and production, as well as the design of a new hydrogen storage tank. However, Brazil has not yet produced homegrown companies capable of consolidating a national hydrogen economy. The only national company capable of manufacturing PEM electrolysers in Brazil has been taken over by a foreign company (Hytron, 2020). In fact, the introduction of hydrogen in Brazil is dependent on the import of practically all the components of the hydrogen production chain.

Even in biomass, Brazil's flagship energy sector, the country does not produce all the necessary equipment such as reformers and reactors (especially those requiring catalysts). Only simpler processes, such as some types of biodigester equipment, are produced locally. This is the result of previous international partnerships with the developed countries of the Global North; though these may have produced quick results they have led to few gains because they were based on asymmetrical agreements in which Brazil became more of an importer of technologies, patents and products than a developer (Buainain & Souza, 2019).

Given the challenges of downscaling large projects or upscaling laboratory experience, Brazil's significant expertise in intermediate-scale chemical engineering uniquely positions it as a hub for research and development. However, this development of new technologies at the local level should take into account the social considerations discussed earlier in Insight 8 to allow technology and innovation to create opportunities for upstream and downstream industries to emerge and harness job potential.

Brazil, based on its past ambitions, could develop its own national clean technology capacity, including electrolysers, batteries, electric vehicles, solar panels and offshore wind turbines. The country could also use its extensive knowledge and expertise in the field of bioenergy as a synergy to develop certain PtX products such as e-fuels and e-methanol (more information in insight 6).

Large projects coupled with innovation could thus have a significant impact in terms of stimulating innovation in the Brazilian hydrogen sector. While there are some successful R&D projects, however, there is a need for better coordination between universities and research institutes. In addition to tackling the fragmentation of research, the resources allocated to hydrogen technology R&D could be enhanced in the context of current Brazilian R&D programmes.

Infobox 6: Further development of the R&D&I initiatives in Brazil

The Brazilian energy market has the potential to benefit hugely from locally developed and implemented projects, in terms of both technological advancements and capacity building. Thanks to the government's regulatory framework and investment in national research, development and innovation (R&D&I), various hydrogen-related companies and projects have emerged, putting the country in the race for hydrogen technologies and local know-how. A few examples of hydrogen and PtX applications in various sectors are given below.

In 2016, the National Electric Energy Agency – ANEEL launched a call for proposals as part of the Strategic Project: *Technical and Commercial Arrangements for the Insertion of Energy Storage Systems into the Brazilian Electricity Sector*, aiming to encourage Brazilian power companies to prepare for the use of energy storage systems in terms of technologies and capacity building as part of the National Interconnected System (SIN) (ANEEL, 2017). As a result, 23 projects were considered suitable, of which three involved the storage of electricity in the form of hydrogen, proposed among other things by the *Companhia Energética de São Paulo* (CESP) and *Furnas Centrais Elétricas* (FURNAS). The two companies are planning to integrate solar PV systems into the existing hydroelectric plants of *Porto Primavera* and *Itumbiara*. PEM and alkaline electrolysers, storage tanks and fuel cells are added to the power production plants to store and reconvert electricity into hydrogen. The stored electricity is then fed into the grid to rebalance the power market. To compare the technology with conventional solutions, electrochemical battery storage systems were added to both projects (Furtado Júnior, 2021).

Another successful innovation project was initiated by the University of Campinas (UNICAMP) in the state of Sao Paulo. Researchers at the Hydrogen Laboratory turned three decades of work, which had initially been based on ethanol reformation technologies, into large-scale application products (IEA Bioenergy, 2023). Hytron, the company which resulted from the research project, has since developed a broad portfolio of hydrogen technologies, ranging from electrolysers and gas purification and fuel reforming systems to hydrogen refuelling stations. As such, they are able to serve customers in the industrial and transportation sectors, as well as the energy distribution and storage sectors, providing Brazil with a showcase for its innovative capabilities and the robustness of its national supply chains.

In August 2023, as part of the Triennial Work Plan 2023–2025 of the PNH2, the Ministry of Mines and Energy (MME) announced that investment in research and development of low-carbon hydrogen would be increased to over USD 40 million per year, a seven-fold increase compared to the funding in 2020 (MME, 2023a). In the meantime, various research projects have emerged, including the inauguration of the Hydrogen and Advanced Fuels Laboratory (H2CA) to launch the country's first pilot plant for producing Sustainable Aviation Fuels (SAFs). Located at the National Industrial Learning Service of Rio Grande do Norte (SENAI-RN), it forms part of H2Brazil, a Brazilian-German cooperation programme. As soon as the first conclusive results relating to the produced SAF are available, a certification process by the National Agency of Petroleum, Natural Gas, and Biofuels (ANP) is planned (MME, 2023b)

Another promising research initiative is the launch of the first green hydrogen laboratory at the Photovoltaic Laboratory of the Federal University of Santa Catarina (UFSC) with an endowment of 14 million reals (approximatively USD 2.9 million) and a production capacity of 4.1 m^3 of green hydrogen or one kilogram per hour of ammonia (MME, 2023c). The project is also part of the H2Brazil project and is supported by various ministries in the context of the hydrogen-ramp up and the development of the PNH2. All these projects will create important knowledge for the actors involved, promote the technological development of national industries and train a large number of technicians, specialists and researchers in the hydrogen innovation sector.

Regional cooperation can play a key role in addressing several aspects of hydrogen deployment

The Southern Cone countries of Latin America have great potential for hydrogen and PtX exports. Working together on the basis of a common vision can strengthen international trade talks and certification discussions. This could be integrated into the EU-Mercosur trade agreement negotiations. A regional bloc with aligned objectives would add weight to negotiations on export conditions, sustainability criteria and other key elements of the hydrogen market.

In addition to developing national technology capacity, Brazil could seek to collaborate with other countries in Latin America such as Chile and Uruguay, which have ongoing hydrogen research programmes and pilot projects under construction with approved funding. This could help guide Brazil's policy design in R&D&I and provide valuable information on the hurdles and successes of similar neighbours in the political and economic spheres. In addition, Brazil's integration into Latin American organisations (OLADE - Latin American Energy Organisation, Mercosur etc.) and the so-called BRICS (Brazil, China, India, Russia and South Africa) offers the possibility of symmetrical cooperation in the field of R&D&I, resulting in balanced agreements in terms of ownership and added value.

In this context, Brazil could play a leading role in developing international partnerships that lead to the establishment of local factories, the use of national parts and materials, and the employment of local labour. In addition, development partnerships supported by government programmes could be sought wherever possible, leading to new processes and innovations that could generate patents and advance national industries.

Brazil's current political momentum, as the incoming president of the G20 and host of COP30, puts the country in a good position to take the lead in promoting regional cooperation and the Latin American voice with the countries of the Global North. This could also serve to protect important issues in the region, avoiding extractive activities and fostering social equity, biodiversity, indigenous communities and economic development, among others. Regional positioning on such key issues could avoid competition between Latin American countries and reduce the risk of lax commitments being made with the sole aim of capturing the market faster than other countries.

Brazil could reindustrialise parts of its economy and lead global decarbonisation efforts

As the geopolitics of energy supply and demand evolve with global decarbonisation efforts, Brazil is likely to become an important partner in new international trading relationships, particularly for those regions with high energy needs and limited renewable resources. Europe for example, which is one of the world's most ambitious regions with respect to climate change, having set itself the target of carbon neutrality by 2050, is currently facing energy security challenges. As a result, the EU is looking for reliable trading partners (friendshoring) to reduce its dependence on China and diversify imports from major energy exporters such as Russia or the United States. Conversely, many countries in the Global South, including Brazil, are interested in win-win partnerships with the Global North, provided that the cooperation ensures value creation and equitable socio-economic benefits on both sides.

Brazil could become an attractive exporter of hydrogen derivatives or intermediates to intercontinental markets, given its significant renewable energy potential. Indeed, as the industrialised regions of the world decarbonise their economies, a new attractive and dynamic green market for renewable hydrogen and its derivatives is emerging. To kick-start the hydrogen and PtX market, countries have established financing mechanisms, such as H2Global in Germany or the planned EU Hydrogen Bank, to bridge the current cost gap between fossil and renewable hydrogen. By using these instruments, Brazil could position itself as a frontrunner in the international development of the hydrogen economy. A new comparative trade advantage could also see certain energy-intensive markets and low-carbon technologies relocating to Brazil, which in turn could help the country accelerate its "neo-industrialisation" plans. Brazil will have the opportunity to locally produce and export manufactured goods such as green fertilisers and green steel, while developing its hydrogen and PtX production capacity. Exports could also bring in valuable knowledge and capital to boost regional value creation. Brazil has the opportunity to become a leader in the hydrogen sector by working with neighbouring countries to share expertise and develop technologies and projects on a bi-national or regional scale.

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About Agora Industry
Agora Industry develops scientifically sound and politically feasible concepts for successful pathways to a climate-neutral industry – in Germany, Europe and internationally. The organisation which is part of the Agora Think Tanks works independently of economic and partisan interests. Its only commitment is to climate action.

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