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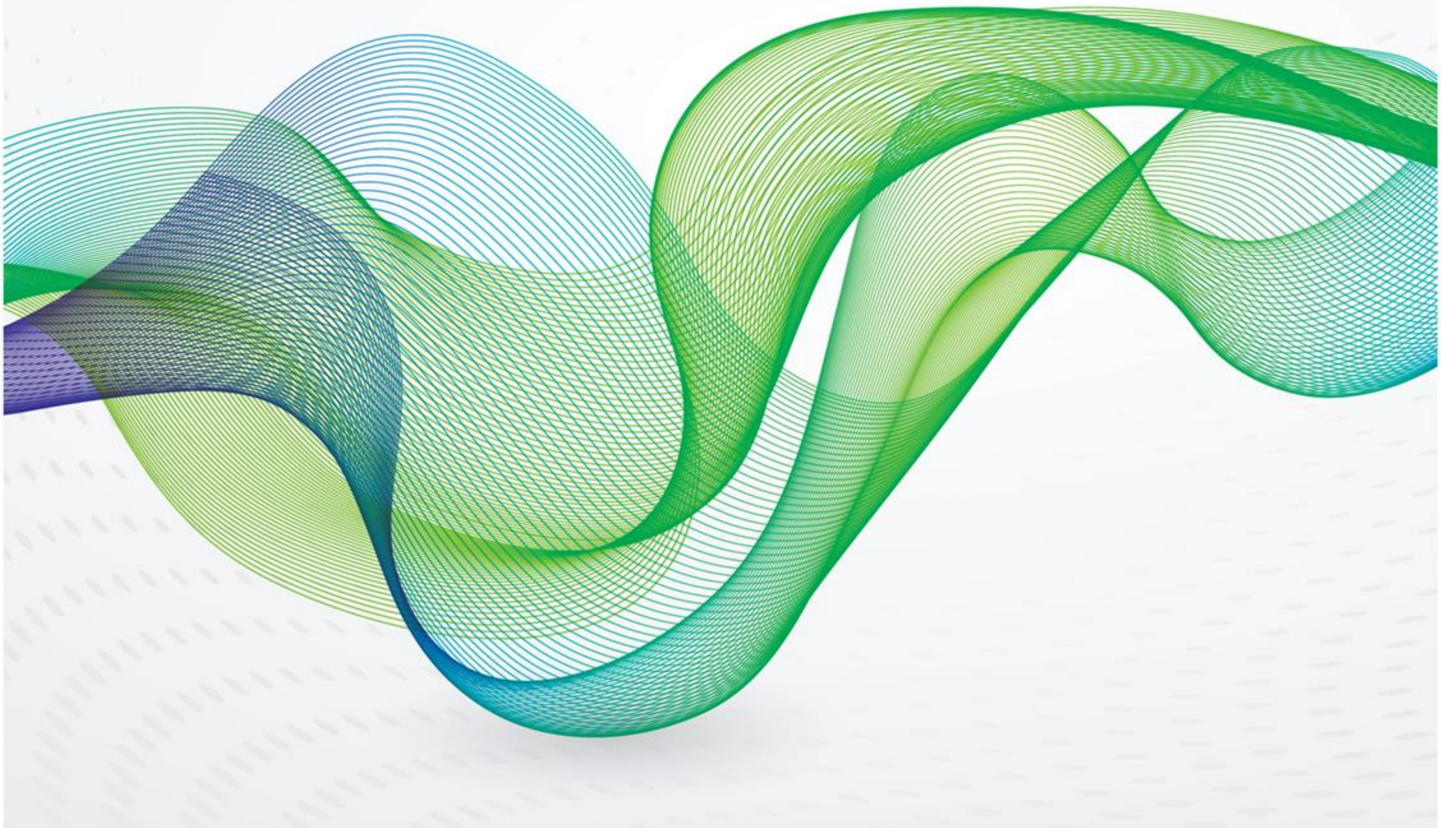
Hydrogen for the ‘low hanging fruits’ of South America: Decarbonising hard-to-abate sectors in Brazil, Argentina, Colombia, and Chile



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Abstract

Hydrogen produced with minimal or no carbon emissions is often expected to become an important tool for meeting climate objectives and decarbonising national economies that currently mostly rely on fossil fuels. Despite initial expectations, it seems unlikely that clean hydrogen will be used by all industries that require decarbonization. However, many researchers, policymakers, and energy practitioners anticipate that some hard-to-abate sectors, such as producers of oil and gas/petrochemicals, nitrogen fertilizers, steel, and electricity, and heavy-duty and long-distance land transport, will be among the first to adopt this substance, paving the way for others. Hence, they are often referred to as the 'low hanging fruits' since their transition to hydrogen is anticipated to be more feasible and often less complex compared with other industries. While considerable attention has been given to the role of clean hydrogen in the decarbonization efforts across Europe, Japan, South Korea, and the United States, the potential role of this substance in South America – a continent largely associated with significant potential for the cost-competitive production of decarbonised hydrogen – has not received substantial attention. Furthermore, besides favourable geographical and geological conditions that could enable the countries of the region to develop the manufacturing of clean hydrogen and its derivatives for export, South American nations also face challenges posed by hard-to-abate sectors that could potentially use hydrogen to decarbonise their operations. Therefore, this paper focuses on Brazil, Argentina, Colombia, and Chile – the four largest economies of the continent with ambitious plans to develop national hydrogen sectors – and analyzes the opportunities and challenges posed by clean, domestically sourced hydrogen for the decarbonization of their 'low hanging fruits'. It then compares and contrasts the key findings and finally concludes by applying the main points to similar industries worldwide.

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Introduction

Being currently viewed as a potential solution to some of the most crucial challenges of decarbonization, hydrogen (H_2) produced without the direct release of carbon emissions into the atmosphere appears to be the focus of many national strategies aiming to reach climate objectives by the middle of this century (IEA, 2022). In this respect, coupling technologies such as renewable power and the electrolysis of water, as well as steam methane reforming (SMR) and carbon capture and storage (CCS), are gaining the greatest attention from scholars, businesses, and governments in the context of securing the highest chances for spurring and accelerating the rapid ramp-up and development of clean H_2 on a large-scale (ibid). While the use of renewables-based green hydrogen is commonly considered the ultimate goal of the emerging H_2 economies in many countries, potentially cheaper and more abundant blue hydrogen, which combines SMR and CCS, is often perceived as a crucial transition substitute or even an 'enabler' of green H_2 by many energy researchers and practitioners (Dickel, 2020 and Cheng and Lee, 2022).

At the same time, despite the initial enthusiasm and hopes that this substance may replace many – if not most – of the fuels and energy sources contributing to carbon emissions (Hydrogen Council, 2017 and McKinsey & Company, 2017), the current debate has incorporated more realism into the discussion since it originated (Lambert, 2023). In particular, although the range of potential applications for clean H_2 can in theory be very broad, techno-economic, infrastructure, policy, social and other challenges related to its production, storage, and delivery often seem to be blocking the introduction of hydrogen into many sectors. In practice, in many cases the direct use of electricity or other low-carbon alternatives often seem to be more advantageous for such niches as residential heating or personal land transport (Financial Times, 2023 and MIT, 2023). In these circumstances, many experts agree that hard-to-abate industries should become the first off-takers of clean hydrogen[1], as H_2 is currently viewed as the only feasible solution to help these sectors reach net-zero carbon emissions. Here, oil refining, the production of fertilizers and steel, long-duration storage of electrical power, and long-distance, heavy-duty land transport are portrayed as no-regret options in most discussions that aim to identify the least risky initial applications for clean hydrogen (Nault, 2022).

Although climate change and decarbonization are challenges of global importance and concern, the interest in incorporating clean hydrogen into national economies also varies significantly from region to region. Specifically, at the moment, the greatest attention towards the development of this new energy and sustainability vector seems to come from countries located in Europe (encompassing the EU, Norway, the UK, among others.), North America (the USA and Canada), and East Asia (Japan and South Korea) (Lambert, 2020). At the same time, having recognized the impossibility of generating the required amounts of clean hydrogen domestically and therefore agreeing on the need for its large-scale imports to meet their national decarbonization goals, the countries of the EU together with Japan and South Korea are currently actively exploring opportunities for securing stable supplies of this fuel for the years to come (Ansari and Pepe, 2023 and Reuters, 2023). In this context, countries that have significant potential for the production of low-carbon hydrogen have been approached on many continents.

With its abundant hydrocarbon deposits and impressive potential for the development of CCS and renewable energy, South America presents as a continent where clean hydrogen – green and blue – could soon turn into an important sector capable of not only addressing some of the crucial decarbonization challenges, but also simultaneously generating significant revenues for nation's budgets. Having realised this, many South American countries have published their national hydrogen strategies in pursuit of harvesting this potential and securing leadership in supplying clean H_2 to countries anticipated as becoming the world's largest users of this fuel, such as Germany or Japan. (CSIS, 2022 and European Commission, 2023). While the potential for exports appears to be the driving force behind most of these efforts, the national economies of South America may also take

[1] In general, hard-to-abate sectors are estimated to be responsible for about 30 per cent of the world's greenhouse gas emissions (Siemens Energy, 2022).

advantage of their clean hydrogen potential to decarbonize their own industries. This is so not only because of the countries' declared commitments to meeting climate goals by mid-century, but also because the techno-economic feasibility of the largescale transportation of hydrogen over long distances is yet to be fully explored and appreciated, which makes the use of H_2 close to its production site a much more economically attractive undertaking from, among others, the financial and infrastructure standpoints, at least for now (Patonia et al, 2023).

Currently, South America's richest and most diversified economies also happen to be the continent's greatest emitters of carbon dioxide (CO_2) (Asturias-Schaub and Gil-Alana, 2023). This should be of no surprise because these countries possess industries and sectors which operate using on large amounts of fossil fuels and are hard to be converted to electricity: for example, steelmaking, oil refining or the production of fertilizers (ibid). In this context, the domestic use of locally-generated clean hydrogen by these economies is often considered to be one of the most logically well-grounded and reasonable steps towards reaching net-zero carbon by mid-century (IDB, 2023). It is also often considered to be the most rational one, as these sectors are often perceived to be among the 'low hanging fruits' for the direct application of clean H_2 – namely, the areas where applying clean hydrogen will presumably be most efficient (Magnus Commodities, 2021, BCG, 2022, and Hydrogen Insight, 2023).

This paper therefore focuses on the four biggest economies of South America: Brazil, Argentina, Colombia, and Chile (Figure 1 and Figure 2). These are the countries with significant annual volumes of carbon emissions that are generated primarily by the hard-to-abate sectors (Asturias-Schaub and Gil-Alana, 2023). These countries also appear to be among the continent's most active explorers of their own clean hydrogen potential, as each of them has a set of strategic documents on the development of national H_2 industries. In addition, with Brazil being the largest economy in Latin America and Chile being the regional pioneer by developing its own National Strategy for Green Hydrogen in 2020, the four countries also happen to be regional champions in actively incorporating the clean hydrogen vector into their policies and regulations on economic development (IDB, 2023 and International Monetary Fund, 2023b).

Figure 1: Top 10 economies in South America by estimated GDP (nominal) in 2022 (in $billion)

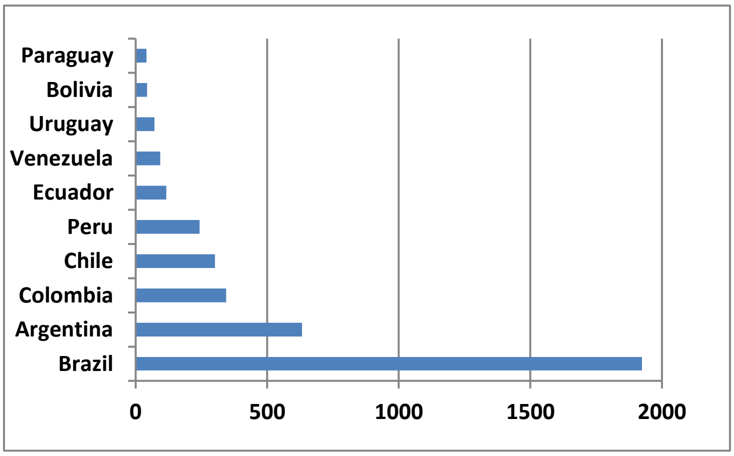
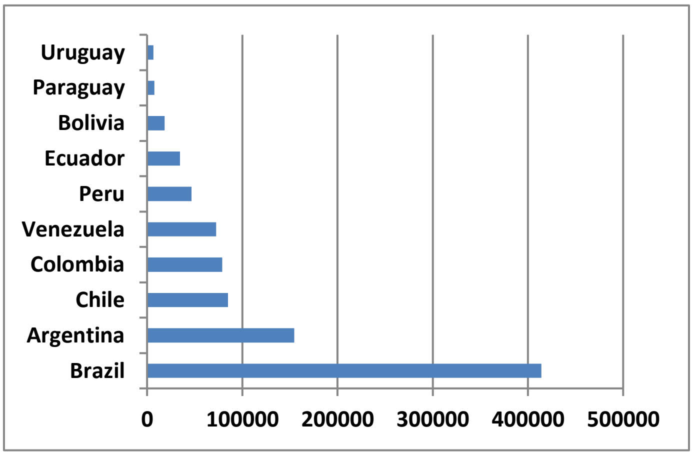


Figure 2: Top 10 emitters in South America by volume in 2021 (in thousand tonnes of released CO_2)



Source: Adapted from International Monetary Fund (2023b) and World Bank (2023).

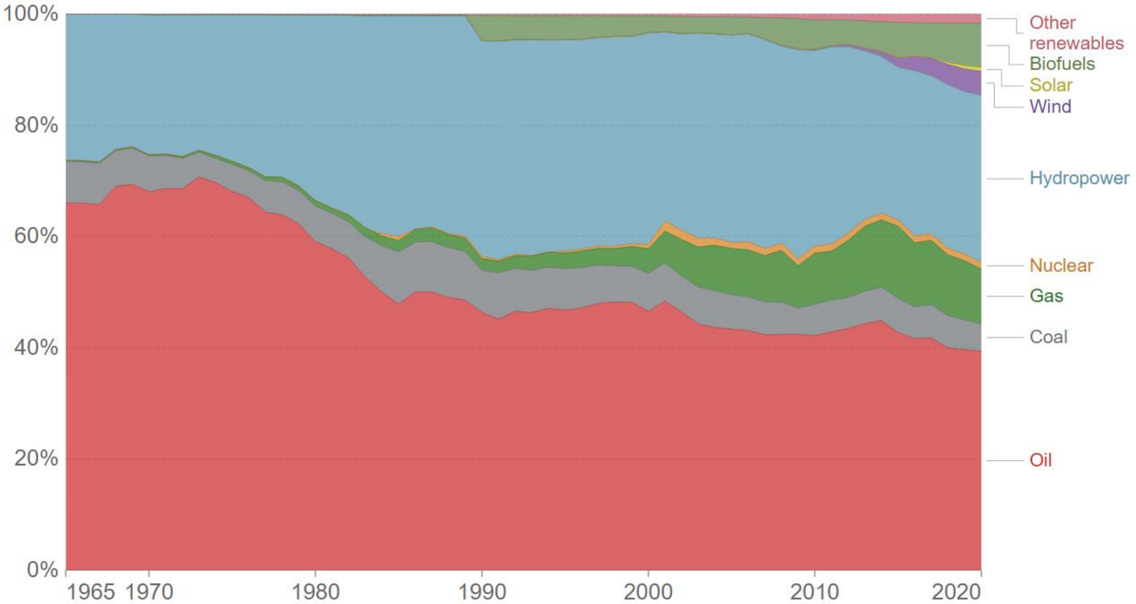
In contrast to a significant number of research and policy papers dedicated primarily to the evaluation of the potential of South American countries for exporting clean hydrogen to Europe and Asia, this piece aims to explore the domestic applicability of locally-sourced clean H_2. Focusing on oil refining and petrochemicals, the production of fertilizers and chemicals, steelmaking, the power sector and transport, it aims to identify what areas and niches in these hard-to-abate sectors offer the greatest scope for using domestically-generated clean hydrogen, green and/or blue. It then views the key measures and policies that are needed to facilitate the application of this clean H_2 in these countries. Finally, it outlines the key constraints and opportunities for the domestic application of locally-produced clean hydrogen in the four countries.

The outline of the paper is as follows. Sections 1-4 provide a country-by-country overview of the key sectors where hydrogen is expected to have the highest chances to be applied first. Specifically, following the nations' economic significance (here, nominal GDP), Section 1 will be dedicated to Brazil, Section 2 will cover Argentina, Section 3 will focus on Colombia, and Section 4 will conclude with Chile. The paper will then go to Section 5, which will provide a detailed comparison of the analysed countries highlighting the key findings of the analysis. It will summarize the main takeaways in the conclusion, which will provide final remarks and answer the question of whether the evaluated hard-to-abate industries, where locally-sourced clean H_2 is supposed to be applied first really appear to be the so-called 'low hanging fruits' for the use of clean hydrogen.

1. Brazil

Being Latin America's biggest economy and world's 12th largest economy in general, Brazil boasts one of the most environmentally sustainable energy matrices of all the South American countries (International Monetary Fund, 2024). In fact, almost half of Brazil's overall energy consumption comes from renewable sources (Figure 3), which contributed to an impressive 93 per cent of the electricity generated in 2023 (EPBR, 2024). With such a significant share of renewables, in November 2023 the country has updated its nationally determined contributions, committing to a net greenhouse gas (GHG) emissions limit of 1.32 gigatonnes of CO_2 equivalent ($GtCO_2e$) by 2025 (a 48.4 per cent reduction below 2005 levels) and, by 2030, to a net GHG emissions limit of 1.20 $GtCO_2e$ (53.1 per cent below 2005 levels) (Climate Action Tracker, 2023).

Figure 3: Energy consumption by source, Brazil[2]



Source: Adapted from Ritchie and Roser (2022).

With overall understanding of the limits of electrification and the significance of hard-to-abate sectors for the national economy, Brazil is also actively exploring low-carbon hydrogen solutions to decarbonize the heavily emitting sectors of its economy, and to establish and maintain a stable revenue stream through exports. While not potentially excluding natural gas- and CCS-derived blue hydrogen, the nation is expecting to focus primarily on green H_2 production due to its substantial capacity for renewable power generation. It is therefore estimated that, drawing upon its extensive and diversified renewables, Brazil has the potential to annually produce up to 120 million tonnes of green hydrogen by mid-century (Gomes et al, 2021).

[2] For the figure 'other renewables' include geothermal, biomass and waste energy.

At the same time, although since 2013 there have been tens of H_2-related research initiatives initiated and funded mostly by the National Fund for Scientific and Technological Development (FNDCT) and the electricity and oil and gas regulators ANEEL and ANP, respectively, the overwhelming majority of them have not transformed into large-scale commercial projects due to the high cost of the produced hydrogen, which made it less competitive than other alternative fuels (German-Brazilian Energy Partnership, 2021) (see Table 1). As in many other countries, a lack of clarity on projected demand as well as a lack of enabling regulatory frameworks are hurdles to implementing large-scale H_2 projects. These may also be the key reasons why, with 42 officially registered green hydrogen projects in 2021, most still are in the memorandum of understanding (MOU) phase and only a few small-scale pilot plants are already in operation or under construction (ibid).

Table 1: Summary of current main green hydrogen projects in Brazil

Project	Sponsor	Green hydrogen Capacity (in t/year)[3]	Electricity source	H_2 utilization
Suape Green H2 (Dec 2022)	White Martins (Linde)	156	Solar PV (up to 1.6 MW)	Food, chemicals, petrochemicals
Bahia Green NH3	Unigel Ferilizers	10,000 (H_2) 60,000 (NH_3)	Wind and PPAs	Fertilizers
Pecem H2 Verde (Dec 2022)	EDP	295	Solar PV (3 MWp)	To be determined
Itumbiara (2021)	Furnas	1.5	Solar PV (1 MW)	Seasonal storage
USP H2 for buses (2H2024)	University of São Paulo, Shell, Toyota, Hytron	40	Ethanol	University buses
Santa Catarina NH3 project	Federal University of Santa Cantarina	3.2 (H_2) 1.8 (NH_3)	Ammonia	Coffee plantation

Source : Adapted from EPBR (2023) and Federal Government of Brazil (2022).

When it comes to large-scale decarbonized hydrogen production projects, they are primarily supposed to focus on the generation of green hydrogen that will then be dedicated for export (ibid). Estimated to deliver around 4.5 million tonnes per year (mtpa), these projects[4] might require approximately 30 gigawatts (GW)[5] of electrolyzer capacity and investments in excess of $30 billion, but have not yet moved beyond the MOU and pre-FEED stage either[6] (EPBR, 2023 and Federal Government of Brazil, 2022).

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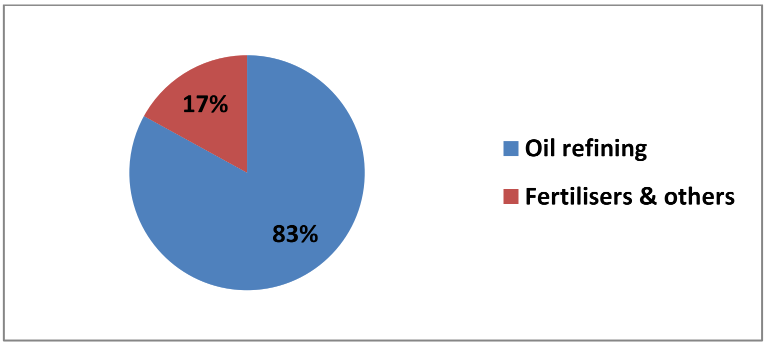
[3] t/year = tonnes per year.
[4] While some of them aim to use the generated hydrogen to produce ammonia (around 8 mtpa), others are still undefined (EPBR, 2023 and Federal Government of Brazil, 2022).
[5] 1 gigawatt (GW) = 1,000,000 kW = 1,000,000,000 W.
[6] As of July 2023, more than 40 MOUs have been signed between port operators in the states of Ceara, Pernambuco and Rio de Janeiro and international developers (for example, Fortescue, Hydro Havrand, ENGIE, EDF, ENEL, AES, among others.) (ibid). For FEED see page 8.

1.1 Key industries and areas for Brazil's domestic hydrogen use: Where is hydrogen expected to be used first?

In addition to possessing a clear interest in creating an export-oriented hydrogen production sector, Brazil could also aim to generate clean hydrogen to cover its existing and future domestic demand. This is so because, like many other world's biggest economies, Brazil has a substantial number of industries with carbon emissions that are hard to abate. In fact, by 2040, the potential domestic demand for green hydrogen is estimated to be in the range of 7.2-9.0 million tonnes (McKinsey & Company, 2021). There is no updated information on hydrogen consumption in Brazil, because most of the hydrogen is produced and consumed within the boundaries of Petrobras' refineries, and fertilizer plants producing hydrogen from natural gas were idle for many years due to very high gas prices and competition with low-cost imported urea (Figure 4). In 2019 the consumption of grey hydrogen – that is, derived from hydrocarbons – in refineries was 400 kt/year with another 130 kt from natural gas to fertilizer plants(IEA, 2022).

Figure 4: Domestic hydrogen consumption in Brazil by sector (in 2021)



Source: Adapted from IEA (2022).

In this context, the most obvious and immediate local application for clean hydrogen is the substitution of grey hydrogen currently consumed by refineries, fertilizer plants and niche industrial applications. This is so because, with ambitious plans to boost its clean hydrogen production in the foreseeable future, Brazil is still generating most of its H_2 in a very conventional way from fossil fuels.

Oil refining/petrochemicals

At the moment, Petrobras, the national oil company, is responsible for around 95 per cent of the total domestic hydrogen supply, which is covered mainly through steam reforming of natural gas and is subsequently used in refineries and fertilizer plants (German-Brazilian Energy Partnership, 2021). The remaining 5 per cent comes from industrial gas companies such as Linde, Air Products, Air Liquide, and Messer, and is utilised for smaller industrial applications (ibid). In total, in 2018-2019, around 530,000 tonnes[7] of grey hydrogen were produced in Brazil on an annual basis (ibid). In these circumstances, substituting most of the grey H_2 that is currently being generated – mainly by Petrobras – with locally produced clean hydrogen may seem to be the most reasonable next step towards reducing the nation's carbon emissions.

Nevertheless, in the short to medium term it seems unlikely that Petrobras, the main company operating the nation's refineries and its main producer of hydrocarbons, would replace natural gas with clean H_2 in their refineries. This is so because they have access to their own production of natural gas and refinery gas and currently do not have immediate plans to replace natural gas in their refineries with green hydrogen, unless it is cost competitive, according to a discussion panel organised in November 2023 by the São Paulo Federation of Industries[8]. On the other hand, in

[7] kt = kilotonne = 1,000 tonnes.

[8] Petrobras is committed to reduce emissions in its refineries from 37 kg of CO_2 equivalent per complexity weighted tonne (kg CO_2-e/CWT) in 2022 to 30 kg of kg CO_2-e/CWT by 2030 through processing improvements and energy efficiencies (Petrobras, 2024).

theory, if the right incentives and policies encouraging the use of clean hydrogen are in place, it may still be possible for this and other oil companies present in the country to pilot partial substitution of their natural gas-derived H_2 for refining with clean (primarily renewables-based green) hydrogen generated on site, just like it is currently being done by Shell at the REFHYNE project in Germany (REFHYNE, 2022). In practice, however, these incentives are yet to be introduced and implemented.

In this context, at the moment, there appears to be two key industrial sectors where the use of domestically produced green hydrogen could be prioritized, in light of strategic considerations, the potential implementation of stimulating policies, and the importance of such sectors to the Brazilian economy. These are the fertilizer and the steel sectors. Here, it should be noted that, in addition to strategic considerations, fertilizer and steel plants consume large amounts of energy which would allow for the co-location of dedicated electrolyzers in the industrial facilities, thus dispensing the transportation of hydrogen by pipelines and ships, provided that these sites have access to water and renewable energy. As a result, the introduction of locally-sourced, clean H_2 into these industries may potentially be associated with lower infrastructure development costs.

Fertilizers/chemicals

Being the world's fourth largest consumer of nitrogen fertilizers[9], Brazil covers most of its demand (up to 76 per cent) through imports primarily from Russia, China, Qatar and Algeria (Colussi, Schnitkey, and Zulauf, 2022). For instance, in 2023, the country imported 7.31 million tonnes[10] of urea (compared to 8.8 million tonnes in 2018[11]) and produced domestically only about 1.1 million tonnes of urea and around 0.4 million tonnes of ammonium nitrate (Farm News, 2023). This actually signifies that the potential perspective for the local generation of clean hydrogen and ammonia (NH_3) that could then be used for the production of fertilizers appears to be very significant. At the same time, given the small share of the existing domestic production, the saturation of the national nitrogen fertilizer market with local products derived from domestically-synthesised clean H_2 will require significant investment.

Table 2: The volumes of green hydrogen and renewable energy necessary to meet the goals of the National Fertilizer Plan[12]

Urea production (mtpa)	Green hydrogen production (ktpa)	Electrolyzer capacity (GW)	Renewable energy (GW at 35% load factor)
1.1 (current)	120	0.7	1.3
1.9 (2030)	210	1.2	2.3
2.3 (2040)	260	1.5	2.8
2.8 (2050)	320	1.6	3.5
8.6 (maximum potential)	1,000	4.9	10.5

Source: Author's estimate based upon electrolyzer efficiency of 64% till 2040 and 76% onwards.

[9] Unlike two other most important types of fertilizers – phosphorous (P) and potassium (K) – nitrogen (N) fertilizers are synthesised from ammonia (NH_3) through the Haber-Bosch process, which combines hydrogen most commonly supplied by natural gas via steam methane reforming and nitrogen that is derived from the air (Samuel et al). Nitrogen is an essential nutrient for plant growth, and nitrogen fertilizers play a crucial role in increasing agricultural productivity by providing plants with this element for their growth and development (ibid).
[10] mt = megatonne = 1,000 kt = 1,000,000 tonnes.
[11] The reduction in demand was caused by the steep price increase in the wake of the Russian invasion of Ukraine.
[12] These goals can potentially allow Brazil to become self-sufficient in ammonia/urea.

Previously, Petrobras was the largest ammonia and urea producer in Brazil, but decided to shut down or lease their old fertilizer plants to concentrate on more lucrative oil and gas activities. There are currently three industrial units operating in Brazil: a) two plants in Bahia and Sergipe, leased by Unigel from Petrobras, with the capacity to produce 0.93 mtpa of ammonia, 1.125 mtpa of urea and 0.32 mtpa of ammonium sulphate; b) one plant in São Paulo, owned by Yara, with the capacity to produce 0.2 million tonnes of ammonia and 0.5 million tonnes of ammonium nitrate (Secretaria Especial de Assuntos Estratégicos, 2021). Interestingly, there are two more facilities that could have potentially contributed to the production of fertilizers in the country, but they are not operating at the moment. Specifically, a plant in Parana State (Fosfertil), with the capacity to produce 0.44 mtpa of ammonia and 0.63 mtpa of urea, was mothballed and put up for sale by Petrobras (ibid). Another one, in Mato Grosso do Sul state, slated to produce 1.3 mtpa mtpa mtpa mtpa of urea and 0.8 mtpa of ammonia had its construction suspended by Petrobras a few years ago (ibid).

In fact, this actually does not align with the 2022 Brazilian National Fertilizer Plan that set up specific goals to increase Brazil's production capacity for nitrogenous fertilizers to 1.9 mtpa by 2030, 2.3 mtpa by 2040, and 2.8 mtpa by 2050 (Secretaria Especial de Assuntos Estratégicos, 2021). To achieve these ambitious goals and reduce imports to 60 per cent of demand, the government will seek to attract at least two new fertilizer producers by 2030 and another four producers by 2050 (ibid). In general, in order to become self-sufficient and no longer need any imported nitrogen fertilizers by mid-century, Brazil would need to significantly increase its installed production capacity to at least 8.6 mtpa (ibid). If this goal is to be achieved solely by means of decarbonized production of hydrogen and ammonia, the national generation of these products needs to be rapidly accelerated (Table 2).

In addition, the first industrial scale project for the production of green hydrogen and green ammonia in Brazil was kick-started by Unigel only in 2021 (Unigel, 2023). This project consists of three phases with the first one slated for 2024 aiming to annually produce 10 thousand tonnes of green hydrogen and 60 thousand tonnes of green ammonia (ibid). Phase two, in turn, originally slated for 2025 is expected to generate 40 thousand tonnes per annum (ktpa) of green H_2 and 220 ktpa of green ammonia (ibid). Finally, phase three is estimated to produce 100 ktpa of green hydrogen and 600 ktpa of green ammonia (ibid). While the project looks very ambitious and promising, the company managed to commission only three 20 MW electrolyzers, supplied by ThyssenKrupp, for phase one (Thyssenkrupp, 2022). In February 2024, Unigel filed for extra judicial recovery with its creditors and the status of the green hydrogen project is unclear (DATAGRO, 2024).

When it comes to using green ammonia as the feedstock for the urea plant, the resulting fertilizer would only be able to qualify as 'green' provided the source of green carbon could be secured to produce urea. In these circumstances, in December 2023, Yara announced that they will be purchasing biomethane (which already contains carbon), instead of hydrogen, to produce 'greener' ammonia, starting from the second quarter of 2024 (InfoMoney, 2023). However, the volume of biomethane (20,000 m^3/day), is equivalent to only three per cent of the company's typical consumption of natural gas (ibid). Just like many other projects, this actually signals that, although the potential for decarbonization of Brazil's fertilizers through locally-sourced clean H_2 is immense, the economic reality of cheaper imports coupled with the insufficient scale-up of production facilities, as well as a lack of more significant supporting policies, makes its realization a pretty challenging task.

At the same time, there is a proposed large-scale project which could turn out to be a breakthrough if implemented. In particular, Atlas Agro is planning to build a green fertilizer project in the vicinity of the agricultural hubs in Minas Gerais. Instead of producing urea, the $850-million Uberaba initiative will annually generate 500,000 tonnes of green ammonium nitrate and potentially calcium ammonium nitrate (Atlas Agro, 2024). The company is planning for FEED[13] in the first half of 2024, with construction starting in 2025 and commissioning in 2028 (ibid). This project is expected to consume

[13] Front-End Engineering Design (FEED) is a design approach utilised to manage project expenses and thoroughly plan a project before a fixed bid quote is submitted (Blackridge, 2024).

3.5 TWh per annum of renewable energy and the cost of the manufactured fertilizers is expected to allow them to compete with the imported ones[14] (ibid).

Steel

Brazil is the world's ninth largest steel manufacturer with an installed capacity of 51 mtpa spread across 31 production plants (Instituto Aço Brasil, 2022). In 2022, the country produced 34.1 million tonnes of steel and 31.5 million tonnes of iron-related products and exported 11.1 million tonnes of iron and steel products (ibid). The largest importers of Brazil's steel and iron products are the USA, Latin American countries (Argentina, Uruguay, Paraguay, and Mexico), and the UAE (Logcomex, 2023). Although until recently Europe did not feature as a significant destination for Brazil's steel, in 2022 there was a 830-per cent increase in the country's exports to the continent due to the curtailment of Russian steel supplies in the wake of the invasion of Ukraine (CNN, 2022). Therefore if Brazil continues to increase its steel exports to the European Union (EU), it will need to comply with Europe's Carbon Border Adjustment Mechanism (CBAM) which specifically targets the iron and steel sectors. Therefore, the development of domestic green hydrogen-to-steel sector may become an imperative if the supply to Europe's markets is to cointue.

In general, at the moment, the Brazilian steel sector has a good track record on emissions when compared with its foreign peers. In particular, in 2020, it emitted 1.72 tonnes of CO_2 per tonne of steel on average (Instituto Aço Brasil, 2022), below the global average level of 1.89, although the sector is still heavily dependent on fossil fuels (ibid). Since approximately 25 per cent of Brazil's steel is produced via the Electric Air Furnace (EAF) process, it is potentially possible to use green hydrogen in place of natural gas for the Direct Reduction of Iron (DRI), in addition to producing Hot Briquetted Iron (HBI) to feed both EAF and blast furnaces (BF)[15]. The use of decarbonized hydrogen can also help to reduce coal injection in BF. In this connection, assuming a gradual conversion of the industry over the next two decades, the required production of green hydrogen could range from 0.12 mtpa by 2030 to 0.6 mtpa by 2040 (Table 3). In this case, setting the whole Brazilian steelmaking industry into the green steel track would require in excess of 2 mtpa of green hydrogen and around 26 GW of renewable energy supply (ibid).

Table 3: Brazil: potential consumption of green hydrogen in the steel sector

H_2-based DRI steel (mtpa)	H_2 input (mtpa)	Electrolyzer capacity (GW)	Renewable Energy (GW, 35% load factor)
2.0	0.12-0.14	0.725-0.9	1.3-1.6
8.4 (2040)	0.5 -0.6	3	6.5
34.1 (max potential)	2.04-2.39	12	26

Source: Author's estimates based upon estimated electrolyzer efficiency of 64% till 2040 and 76% afterwards.

In addition to the above figures, if Brazilian mining giant Vale decides to produce 6 mtpa of HBI within the country (both for domestic and export markets), an additional input of 0.4-0.5 mtpa of green hydrogen would be required in the long run, which will lead to the total requirement of 0.9-1.1 mtpa by

[14] Potentially due to lower logistical costs of reaching hinterland farmers.

[15] In general, clean hydrogen can be used to decarbonize steel production in the two main processes of the Direct Reduction of Iron Ore (DRI), with its production either feeding an Electric Air Furnace (EAF) or is used to produce Hot Briquetted Iron (HBI) (Sane et al, 2021). This process involves using green hydrogen as a reducing agent – instead of natural gas - converting iron ore into a sponge iron product, bypassing the traditional blast furnace route that relies on coke or coal (ibid). Here, hydrogen reacts with iron ore to remove oxygen, resulting in the production of high quality iron without carbon emissions (ibid). HBI can be transported long distances and can feed EAFs or conventional Blast Furnaces (BF)/Basic Oxygen Furnaces (BOF) (ibid).
In addition to being used for DRI, hydrogen can also be injected into BFs and BOFs, which are traditionally powered by coke or coal, as a supplementary reducing agent. This approach, known as hydrogen injection, can help lower GHG emissions. At the same time, in BFs or BOFs, it is not possible to replace all the coke with hydrogen due to the endothermic reaction, which causes a drop in temperature, among other technical issues (Carbon Neutral Steel, 2022).

2040 (Vale, 2022). If this happens, according to Midrex, a provider of DRI plants capable of running with a range of hydrogen feedstock, in order to be able to compete with natural gas at 4 $per Metric Million British Thermal Unit (MMBtu)[16], green hydrogen prices should not exceed 0.5 $ /kg (Midrex, 2022). Here, based on the rule of thumb of $1.1 billion CAPEX per 1 million tonnes of EAF/DRI steel capacity, it would be necessary to invest $36 billion to switch the current steel production of 34.1 million tonnes per year to clean hydrogen (Roland Berger, 2022)[17].

Summarising the requirements for Brazil's two key sectors that could potentially be decarbonized with domestically generated clean hydrogen and derivatives, it should be noted that the combined production of the mentioned amounts of steel and nitrogen fertilizers (here, urea) would require substantial growth in the country's renewable energy and electrolyzer capacities. In particular, by 2040 only, the joint manufacturing of 8.4 mtpa of DRI/EAF steel, 6 mtpa of HBI and 2.3 mtpa of urea would require 1.3 mtpa of green hydrogen, 7.2 GW of electrolyzer capacity, and 14 GW of renewable energy capacity. Here, while the renewable energy requirements needed to cover these demand levels could potentially be met internally (given Brazil's immense renewable energy potential), the nation will still need to rapidly increase its electrolyzer capacity, which will most likely have to be done initially through imports, since there are no domestic manufacturing plants.

This is so because the country's wind and solar potential is technically estimated to be 1,500 GW and 28,500 GW, respectively (ABEEolica, 2023). In December 2023, Brazil's installed electricity capacity was 216.8 GW, of which 190.5 GW was wind, solar, hydro, biomass and small/micro decentralized generation (ONS, 2024). By 2031, the nation's total installed capacity in the National Integrated System (SIN) is expected to reach 260 GW, of which 218 GW will be renewable energy (ibid), and by 2050 renewable energy capacity might reach from 304 GW to 418 GW, depending on the scenarios presented (EPE, 2023 and ABSOLAR, 2016).

Energy/power sector

Taking into account Brazil's large hydroelectric electricity capacity, which can be used to modulate the intermittency of solar and wind power, and the fact that most of the electricity production is already decarbonized, there are currently no announced plans to produce hydrogen for power generation.

Transport

Heavy-duty and long-distance land transportation has also been regarded as a very important market for the use of hydrogen in Brazil. However, there are many logistical challenges posed by the very size of the country, the area of which is larger than that of Western Europe. In particular, the country's natural gas pipeline system that could potentially be repurposed and used for delivering hydrogen for refuelling stations is concentrated mostly in coastal areas, and stretches to only around 9,400 km (Transporte Moderno, 2023). In addition, the nation's lorry and bus fleet is very numerous (with about 2.16 million lorries and 690,000 buses), which means that the development of a well-functioning refuelling infrastructure system for such a great number of transport units scattered across so vast a territory will be extremely challenging (ibid).

1.2 Key measures and policies needed to facilitate domestic use of locally produced hydrogen in Brazil: What should be done to make it happen?

In April 2021, the Federal Government of Brazil launched the National Hydrogen Program (PNH2) aiming to provide strategic guidelines for the harmonization of low-carbon hydrogen with other energy sources (Federal Government of Brazil, 2022). One of the key elements of the PNH2 is to increase annual investment in research and development (R&D) and pilot projects to R$200 million ($40 million) by 2025, and to consolidate the creation of a low-carbon H_2 hub by 2035 (ibid). While these provisions are important, industry players tend to complain about the focus on pilot projects which often tend to never reach maturity, instead of promoting large-scale projects[18]. Therefore, from a pure

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[16] MMBtu is a unit traditionally used to measure the heat content or energy value of a fuel source (Adani Gas, 2023), being widely associated globally with the energy measurement of natural gas.

[17] These figures do not include the CAPEX related to the supply of green hydrogen and renewable energy.

[18] As discussed at FIESP's seminar on Green Hydrogen, on the 27 November, 2023 in São Paulo.

business and industry perspective, incentives for large-scale projects that would focus on R&D of the supply chain for clean hydrogen would be of particular practical use.

Another important legal milestone is the Decree 11,075, of 19 May, 2022, which creates a regulated carbon market in Brazil, with the focus on export credits, especially for countries and companies that need to compensate emissions to meet their carbon neutrality commitments (President of the Republic, 2022). While the implementation of this decree would provide a strong, encouraging signal for many to a lot of decarbonization incentives and projects, it is yet to enter into force. This is similar to another potentially important document, Bill (PL) 725/2022, which is currently being discussed at the Brazilian Congress and is supposed to establish goals for the injection of hydrogen into the natural gas pipeline system, with a target of 5 per cent blending by 2032 and 10 per cent by 2050 (Federal Senate, 2022). Although the mentioned legislation could spur the development of Brazil's domestic clean H_2, uncertainty about their future binding nature is currently hampering the progress of the country's hydrogen sector.

In response to these deficiencies and criticisms, and aiming to give additional impetus to potential local producers and off-takers of clean H_2, in November 2023 the Chamber of Representatives voted for the adoption of the Low-carbon Hydrogen (LCH) Bill. The bill aims to define low carbon hydrogen with a maximum of 4 kg of CO_2 per kg of H_2, create a steering committee formed by ministries and regulators, establish what projects will benefit from tax credits and subsidies, and indicate the process for authorization and certification of LCH (Senate, 2023). However, even though this document represents a more concrete step forward, it still needs to be voted for by the Senate to enter into force, followed by infra-legal regulation.

Overall, the steel industry in Brazil supports the adoption of the national regulatory frameworks, such as payment for services (PSA) and a voluntary carbon market integrated with the compulsory market (Instituto Aço Brasil, 2022). It is also advocating for tax breaks, levies, subsidies, and financing to ensure cheaper green electricity and government support to CAPEX requirements (ibid). However, in order to foster the transition to green steel, it is important to implement green steel standards and encourage purchase mechanisms such as government procurement quotas and corporate buyers' clubs. The Brazilian government should therefore negotiate with steel importing countries a mechanism supporting a kick-off auction to buy green steel.

When it comes to fertilizers, some progress has been already done as well. For instance, the federal government has reached an agreement with the federal states allowing for tax parity for domestically produced and imported fertilizer (Secretaria Especial de Assuntos Estratégicos, 2021). Nevertheless, this might not be enough to foster domestic fertilizer production if it is not accompanied by tax breaks and incentives, for example, a special incentive regime for the development of a fertilizer industry infrastructure (REIF), with a validity period of at least five years (ibid).

That is why, in order to further stimulate the generation and use of Brazil's own clean hydrogen, some key measures must be implemented to support the creation of a favourable ecosystem. These measures should include, among others, the development, approval and implementation of the legal framework, regulation and incentives for hydrogen, in the wake of the enactment of the Low-carbon Hydrogen Bill, no later than 2025. Additionally, infrastructure debentures for hydrogen projects should be issued, and blended finance instruments to channel resources from other multilateral banks and the domestic capital market should be created[19]. Finally, the government should introduce a renewable certificate mechanism, similar to the one being implemented for biofuels, in which biofuel producers can issue credits of decarbonization based on energy and environmental efficiency scores.

1.3 Key constraints and opportunities for Brazil's domestic hydrogen use: What is preventing it from happening?

Despite the impressive potential of renewable energy resources which could be used for the production of clean hydrogen and its derivatives, there are key constraints, impacting not only the steel and fertilizer sectors but also other domestic applications of H_2. Here, one of the key barriers

[19] Additional sources of funding could be created by the National Bank for Economic and Social Development (BNDES) and the Financiadora of Studies and Projects (FINEP).

relates to Brazil having a limited infrastructure of natural gas pipelines that could be used for the delivery of hydrogen by land. In fact, historically, they evolved primarily along the coastal areas and the transportation and distribution grids constitute only 9,400 and 37,000 km, respectively (Transporte Moderno, 2023). In these circumstances, it would be logistically complicated to produce hydrogen in centrally located hubs and then transport it as a gaseous fuel to industrial plants, refuelling stations, and so forth in the interior of the country, even if the whole natural gas pipeline infrastructure were to be repurposed, in addition to technical constraints.

Geographically speaking, most of the nation's solar and wind energy is currently generated in the northeast of the country, respectively 42 and 92 per cent (Chicano, 2022). At the same time, most of the potential domestic demand for green hydrogen would be located either in the southeast or mid-west, which are respectively the largest industrial and agricultural regions in Brazil. That is why large flows of renewable energy from the northeast to the southeast and mid-west will face some serious bottlenecks in transmission infrastructure connecting potential supply with demand, and will require substantial investment.

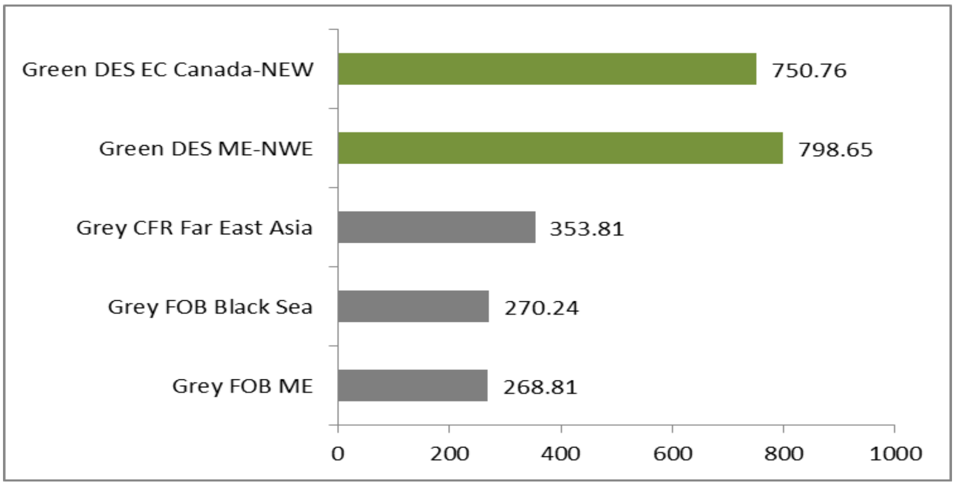
In addition, despite the significant number of research projects and initiatives around clean hydrogen, there is no widespread experience in the production or use of clean H_2. More generally, there is a lack of a developed ecosystem of equipment suppliers, technological partners, investors, skilled human resources and, more importantly, off-takers. In fact, the existing market is also quite small to foster a clean hydrogen economy, based upon conversion from grey hydrogen (400-530 ktpa). Besides, at the moment, most of the grey hydrogen is consumed by refineries owned and operated by Petrobras and the company does not have any stated plans to convert their refining park to green H_2. Here, taking into account the prices estimated for green hydrogen (3.67-5.19 $/kg) (Ministry of Mines and Energy, 2021), there is a need for government incentives similar to those in Chile, the USA and Europe to be introduced to stimulate its production and use in the domestic market.

The infant stage of the certification for the clean hydrogen supply chain and for the product itself is also very likely to slow down the development of both domestic and export projects. While the Brazilian Association of Technical Standards (ABNT) issued a few standards, and several others are currently being discussed within the working group of the Special Study Commission on Hydrogen Technologies – ABNT/CeE-067 (Energy Partnership, 2021), only the Brazilian Chamber for Energy Trading (CCEE) started working on the matter of green hydrogen certification in 2022, and produced a draft document to certify H_2 production from a pilot project (CCEE, 2022). Although these efforts are extremely important, they still seem to be insufficient for the adjustment of the country's entire economy to domestically-manufactured clean hydrogen.

Most notably, there is currently no line of sight about firm demand to underpin long-term contracts and to support the development of large-scale clean H_2 initiatives, bearing in mind that the first projects will have higher costs due to the learning curve faced. In addition, carbon markets are very nascent in Brazil and internal carbon prices are deemed necessary for clean hydrogen to compete with other fuels. In these circumstances, there is a need to provide low cost financing and incentives to allow for the implementation of hydrogen-pioneering projects to guarantee the payment of a green premium, taking into account that the first harvests of projects will be more expensive than the alternatives and will tend to decline as the technology matures.

When it comes specifically to the domestic production of clean fertilizers in Brazil, one major constraint to the industry is the high cost of manufacturing green H_2 and significantly lower cost of grey hydrogen production in countries which benefit from low gas prices, which has a direct impact on the cost of ammonia synthesis that uses hydrogen as a feedstock. In particular, at the moment, the Levelised Cost of Ammonia (LCOA) from green hydrogen is estimated to be two to five times that of ammonia produced through grey hydrogen, using cheap natural gas from Russia, the US and Middle East, where grey hydrogen can be produced at around $1/kg (S&P Global, 2024). According to industry sources, in July 2023, grey ammonia was traded internationally at $271/tonne FOB Black Sea whereas green ammonia DES prices in Europe ranged from $751 to 799/tonne (Figure 5) (ibid). In order to compete with Black Sea and Middle East supplies to Brazil, green ammonia prices should not exceed $260-280/tonne FOB.

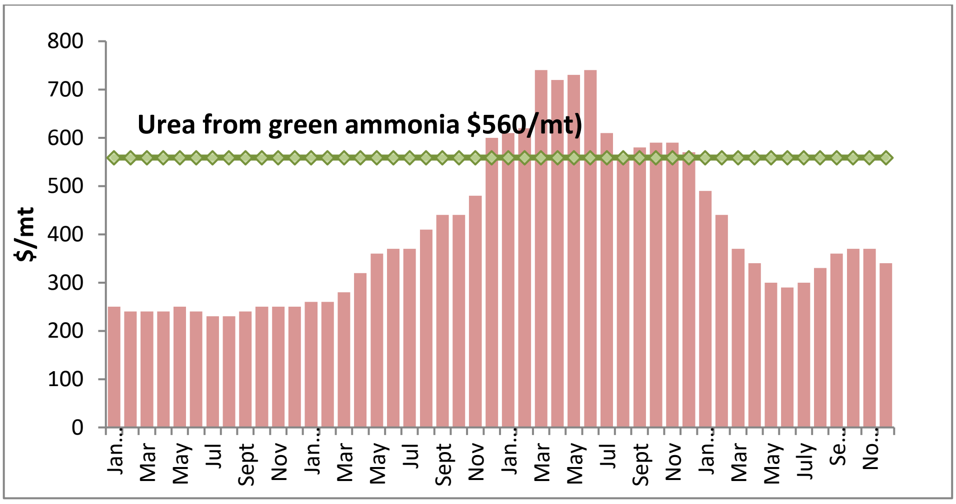
Figure 5: International prices of grey and green ammonia, July 2023 ($/mt)



Source: S&P Global (2024).

In 2023, Brazil's export of agricultural commodities reached $81.5 billion[20]. Such a massive scale of the country's agriculture business requires large amounts of fertilizers and since the Russian invasion of Ukraine, the sector has suffered from volatile fertilizer prices. After a peak of $740/tonne in June 2022, prices for imported urea dropped to $340/tonne in December 2023 (Figure 6). If the estimated costs of urea produced from green ammonia synthesised in Brazil are around $560/tonne (and for green ammonia being around $750/ tonne), importing urea at $300-400/ tonne appears to be a lot more attractive economically for the agriculture sector.

Figure 6: Price of imported grey urea FOB Brazil vs. 2023 estimated green urea price



Source: Author's estimate for green urea, based on green ammonia price of $750/tonne and green hydrogen at $2.6/kg.

Although this difference in costs could potentially be leveraged through the imposition of carbon prices for the fertilizer sector, their application in Brazil is likely to be challenging. This is so mainly because this would result inititally in higher prices for food and agricultural commodities, which is likely to result in social unrest and reduced competiveness in the export markets.

At the moment, the interstate tax on goods and services (ICMS) disparity between national and imported fertilizers is identified as one of the main obstacles to domestic production. In fact, the ICMS

[20] Presentation to FIESP: Balanca Comercial Brasileira 2023, MDIC, Brazil

penalizes domestic fertilizer producers, because the tax does not apply to imported fertilizers, nor which are subject to import taxes (Couto, 2023). Although the government is slowly increasing the ICMS on imported fertilizer up to 4 per cent in 2025, this is not enough to make domestically produced fertilizer prices competitive, in particular if green hydrogen is used as a feedstock.

The existing fertilizer plants, including the one whose construction was halted by Petrobras, were designed to steam reform natural gas; therefore converting them to green hydrogen requires scrapping the reforming plant and replacing it with electrolyzers, with considerable investment costs. Even if that was possible, hydrogen costs would then have to drop to $1-1.5/kg to successfully compete with imported fertilizer from the Baltic Sea, which makes the entire undertaking very challenging[21]. Additionally, in order to qualify as a 'green fertilizer' the urea manufactured from green ammonia will need to be coupled to new, sustainable sources of green CO_2, such as biomass or biogas.

At the same time, high natural gas prices at the city gate ($11.2-13.3/MMBtu) and to industrial consumers ($18.9-22.1/MMBtu) have been deterring the production of nitrogen fertilizers in Brazil using methane reforming processes (Federal Government of Brazil, 2023). These high gas prices are also a deterrent for the production of blue hydrogen. In these circumstances, if less price-volatile green hydrogen could be produced at $1-1.5/kg (versus the current estimates of $2.67-5.19/kg), this might encourage the revival of existing plants and investment in new facilities. With this in mind, new fertilizer plants could then be located in the Brazilian hinterlands, as in closer to the agricultural regions, to reduce transportation costs while bringing fertilizers close to their end-users. Although the National Fertilizers Plan focuses on measures to primarily increase competitive gas supplies to foster domestic production of fertilizers (ibid), the reality is that it makes more economic sense to import cheaper fertilizers from low gas-cost producers than to produce it locally either with domestic natural gas or green hydrogen.

The introduction of green hydrogen and the decarbonization of the whole steelmaking industry in Brazil require different production chains with CAPEX needs of $30-50 billion (based on Midrex, 2022). In this context, due to the high estimated costs associated with the adjustments, one might come up with other alternative routes for the decarbonization of the country's steel sector. For instance, substituting charcoal for coal has been discussed. This, however, might not be feasible on a large scale for blast furnaces due to technical issues since, in fact, charcoal is friable, easily pulverized, and creates the risk of obstruction (Fastmarkets, 2022). It might be also difficult to secure enough plots of land for reforestation with eucalyptus, which is the raw material for charcoal (ibid). While the industry is also considering the use of biomethane, the supply of this fuel might not be available on a large scale either.

More generally, there is a lack of policy and regulatory incentives to promote global green steel standards to enable fairer competition among steel-making countries. This poses a particular challenge, given that the sector is highly sensitive to prices. For instance, in 2023, Brazil's steelmakers suffered from higher imports of cheap Chinese steel, which forced one of the largest producers, Usiminas, to temporarily shut down one of their three blast furnaces, and Aperam, another player, to postpone their expansion investment schedules for 2024-2025 (Terra, 2023). In these circumstances, transitioning to more expensive clean hydrogen[22] without any sound policy support from the government will ultimately result in more expensive and thus less competitive products.

Bearing in mind industries' pledge to reach net zero carbon by 2050, there is an opportunity to do it gradually in order to phase investment and costs. The first step here would be to gradually reduce the carbon intensity of the BF/BOF process, by injecting a mix of hydrogen and DRI/HBI into the blast furnace, which will reduce the intake of coke. It is also possible to reduce the carbon intensity of the EAF by combining scrap and DRI/HBI, produced initially with natural gas and then hydrogen; and finally, at the end of the useful life of the blast furnaces, transition to carbon-neutral EAF production

[21] This does not take into account the CAPEX to install new electrolyzers.

[22] The reduction of the iron ore with hydrogen is an endothermic process, whereas reduction by use of coal/coke is exothermic (Capper, 2021). This implies that decarbonized heat must be continuously supplied from an external source during the ore reduction process, with higher electricity demand and higher energy costs (ibid).

using a mix of scrap and hydrogen-based DRI. Unfortunately, this is unlikely be achieved in the short term due to high costs and the lack of availability of affordable hydrogen.

DRI–EAF production plants require higher-quality iron ore than BF–BOF plants, because insufficiently dense iron ore can create acidic slag which can corrode the electric arc furnace and, in the longer term, lead to decreasing yields (Shell, 2022). Therefore, the consensus among industry players is that just 30 per cent of global iron ore supply is currently suitable for DRI–EAF plants and only 3 per cent of seaborne supplies have iron content above 66 per cent (Institute for Energy Economics and Financial Analysis, 2022). Brazil is well positioned to supply such plants through the mine province in Carajas, north Brazil, with 67 per cent iron content (Vale, 2023).

EAF-based steel production requires a continuous and steady supply of electricity (350 and 600 kWh/t) (Capper, 2021). Since DRI and HBI are solid products the supply of intermittent renewable electricity should either be coupled with power storage systems or with solid product stockpiling if the producer is not able to access green PPA's. In any case, here, with its large hydro resources base, Brazil appears to have significant advantages.

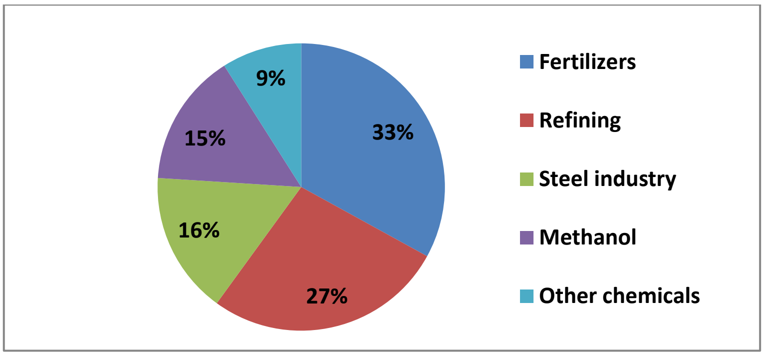
At the same time, the imposition of CBAM by the EU might lead to increased production costs for Brazilian steel companies if they are required to either purchase emissions allowances or pay the carbon tax. These additional costs could dent the profitability of Brazilian steel exports to the EU, potentially leading to reduced trade volumes or increased prices for European consumers. For conventional BF–BOF, by 2050 the carbon price is expected to represent almost 70 per cent of costs, based on an estimated carbon price of 320 euros per tonne (Shell, 2022). If the steel industry in Brazil could access low cost green hydrogen, this would be a competitive advantage to export green steel, if compared to steel export countries heavily dependent on coal/coke.

In conclusion, green hydrogen could become an important feedstock for the production of green steel for exports, in particular to Europe, but not necessarily in the production of fertilizers, unless the costs of nitrogen-based fertilizers becomes very competitive with cheaper gas-based imported fertilizers.

2. Argentina

As mentioned in the National Strategy for the Advancement of the Hydrogen Economy that was unveiled in September 2023, Argentina currently manufactures 0.4 Mtpa of conventional hydrogen for internal use, predominantly in the form of natural gas-derived grey H_2 (Secretaría de Asuntos Estratégicos, 2023). This quantity accounts for around 9 per cent of the entire Latin American and approximately 0.4 per cent of the global demand (ibid). A substantial portion, nearly 60 per cent, of this domestic consumption is earmarked for applications in fertilizers (~0.13 mtpa), specifically ammonia synthesis and urea production, as well as in the refining sector (~0.11 mtpa), primarily for hydrodesulphurization of fuels (Figure 7). Additionally, grey hydrogen currently finds applications in other important sectors of the Argentinean economy such as methanol production (approximately 15 per cent or ~0.06 mtpa), the steel industry (around 16 per cent and ~0.06 mtpa), and the manufacturing of various chemicals (9 per cent and ~0.04 mtpa) (ibid).

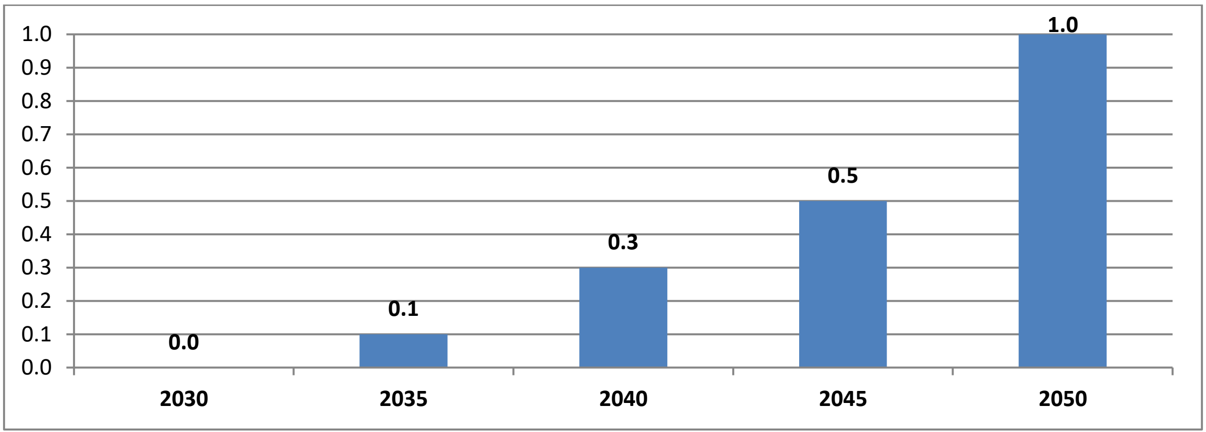
Figure 7: Domestic hydrogen consumption in Argentina by sector (in 2023)



Source: Secretaria de Assuntos Estratégicos (2023).

While consuming significant amounts of grey hydrogen, Argentina has quite an ambitious target to rapidly build up its clean H_2 production from scratch so that its capacity by mid-century reaches 5 mtpa (Secretaría de Asuntos Estratégicos, 2023). Achieving this level of output by means of scaling up green hydrogen production necessitates the installation of at least 30 GW of electrolyzers alongside 55 GW of renewables (mostly wind and solar photovoltaic [PV] energy), in addition to the existing 16.4 GW (including 4.9 GW from wind and solar PV) (ibid). It is however expected that almost 80 per cent of all this clean hydrogen, equivalent to 4 mtpa, will be dedicated for exports (ibid). Starting from 2030 the domestic consumption of low-emission hydrogen is anticipated to experience consistent growth, projected to reach 100 ktpa by 2035, 500 ktpa by 2045, and 1 mtpa by 2050 (Figure 8). Here, at least some segment of this demand is expected to be met through the local production of blue H_2 via SMR and CCS, which is supposed to bolster the conditions for large-scale developments capable of competitively participating in export markets.

Figure 8: A projection of Argentina's domestic clean hydrogen consumption to 2050 (mtpa)



Source: Adapted from Secretaria de Assuntos Estratégicos (2023).

2.1 Key industries and areas for Argentina's domestic hydrogen use: Where is hydrogen expected to be used first?

Concerning the prospective trajectory of domestic hydrogen consumption within Argentina, locally-source clean H_2 is expected to be primarily dedicated to hard-to-abate sectors, such as oil refining, the chemical industry, and the manufacturing of fertilizers and steel (Secretaría de Asuntos Estratégicos, 2023). Additionally, there is an expectation that some share of this supply will be taken by emerging applications, notably the utilization of synthetic fuels – specifically, sustainable aviation fuels (SAF) and methanol – as well as applications for gas blending, heavy-duty and long-distance transportation and other industries undergoing decarbonization. Furthermore, the incorporation of green hydrogen into the energy system could potentially enable the integration of renewables into power grids, as load flexibility and long-term and seasonal storage could then be enabled. At the same time, given the limitations related to budget constraints, the most important sectors for Argentina's economy – fertilizers, steelmaking, and oil refining – are assumed to become the 'lowest hanging fruits' where domestically produced hydrogen will be applied first.

Oil refining/petrochemicals

In Argentina, there are nine refineries collectively capable of processing almost 700 thousand barrels of crude oil per day[23] (Secretaría de Energía, 2024). Among these, the most prominent facilities include La Plata and Lujan de Cuyo owned by YPF, Dock Sud owned by Shell/Raizen, and Campana owned by Axion Energy. Over the past decade, Argentina's Secretariat of Energy has consistently urged these and all other companies engaged in refining to adhere to stricter regulations regarding

[23] Among these, the most prominent facilities include La Plata (YPF), Lujan de Cuyo (YPF), Dock Sud (Shell/Raizen), and Campana (Axion Energy) (Secretaría de Energía, 2024).

cleaner fuels and specifically to reduce the maximum sulfur content in gasoline and diesel oil. Although some deadlines have been subject to postponement, Axion Energy completed the modernization of its Campana refinery in 2021, while YPF is actively implementing its investment plan on developing hydrotreating and desulphursulphersulpherization units alongside blending facilities by 2026 (CAF, 2023). It is projected that by this time, over 70 per cent of YPF's fuel stock will comply with ultra-low sulfur content standards[24] (CAF, 2023).

Since all critical units within these refineries, such as hydrotreating, desulphurization, isomerization, catalytic cracking, and catalytic reforming, heavily rely on grey hydrogen, there is significant potential for the introduction of clean H_2 into Argentina’s refining sector. Here, while the implementation of renewables-based green hydrogen is likely to be viewed as the ultimate decarbonization goal, initial advancements are more likely to focus on blue hydrogen instead. This is so because integrating CCS technologies into Argentina’s existing refining processes that are all based on relatively low-cost and abundant local natural gas, will have fewer techno-economic challenges and therefore will be of a lesser financial burden.

Beyond the scope of conventional oil refining, Argentina possesses substantial potential in synthesizing fuels through the utilization of domestically-produced clean hydrogen. The National Strategy for the Development of the Hydrogen Economy emphasises that ‘the production of synthetic fuels like methanol, sustainable aviation fuel (SAF), and hydrogenated vegetable oil (HVO) will necessitate low-emission hydrogen to decarbonise the maritime and aeronautical transport sectors’[25] (Secretaría de Asuntos Estratégicos, 2023). Overall, in 2022, the consumption of aviation fuels in Argentina (based on fossil fuels) reached 1.43 million m^3, with YPF, Pan American Energy and Shell/Raizen being the largest producers (Secretaría de Energía, 2024). Under existing conditions, the estimated domestic demand for HVO within Argentina's market stands at roughly 4,600 thousand tonnes of oil equivalent per year (ktoe/year), which includes the current import demand for diesel oil and its supplementary usage for power generation (Secretaría de Energía, 2023). When it comes to SAF, the potential domestic production could reach 466 ktoe/year, while the demand for domestic flights reaches 560 ktoe/year (Secretaría de Energía, 2024). Collectively, at current levels, the anticipated need for hydrogen for both these applications stands at about 162 ktpa H_2, which consists of 120 ktpa of hydrogen for HVO and 42 ktpa for SAF (Caratori, 2024).

For Intermediate Fuel Oil (IFO)) residual marine fuel blends, Argentina’s market totalled 1.22 million tonnes in 2022, led by Shell/Raizen, trailed by Trafigura, Pan American Energy, and YPF as key stakeholders (Secretaría de Energía, 2024). Approximating marine fuel consumption using a 70-30 blend known as ‘Mezclas IFO’, Argentina's demand in 2022, encompassing bunker fuels, reached 1,213 ktoe (Secretaría de Energía, 2024). For context, this energy content equates to around 2,500 kt of methanol used as a reference fuel (Secretaría de Energía, 2016). Factoring in hydrogen requirements ranging between 0.1175 and 0.1875 H_2/kg of methanol, this signifies an annual need between 300 and 480 kt of H_2 for all IFO sales in Argentina, with an estimated 195 kt of H_2/year that would cover about half of the demand, primarily oriented towards waterway applications (ibid).

Fertilizers/chemicals

The fertilizers market in Argentina reached its peak at 5.7 million tonnes in 2021, exhibiting a compound annual growth rate (CAGR)[26] of 4.4 per cent from 2011 to 2021 (Fertilizar Asociación Civil, 2023). However, a significant downturn of minus 16 per cent occurred the following year, resulting in a decrease to the level of 4.8 mtpa (Fertilizar Asociación Civil, 2023). This decline was attributed to severe droughts in Argentina in 2022 and 2023, and a concurrent surge in international prices (Infocampo, 2024).

[24] In 2023, YPF secured a $375-million loan from CAF to support its modernization efforts (CAF, 2023).

[25] It further notes a supplementary application for road transport, primarily focusing on heavy vehicles powered by hydrogen fuel cells.

[26] Compound annual growth rate (CAGR) relates to the geometric progression ratio that provides a constant rate of return over the time period (Anson, Fabozzi, and Jones, 2010).

Overall, only 30 per cent of the national fertilizer market is sustained by domestic production, with the remaining 70 per cent reliant on imports (Agora, 2023). Here, although not all fertilizers require the direct use of hydrogen in their production process, nitrogen fertilizers – the main type of fertilizers that need hydrogen hydrogen in their synthesis – account for 56 per cent of the total Argentinean market (Table 4). In these circumstances, enhancing Argentina's indigenous production of clean hydrogen and its derivatives, such as ammonia, presents an opportunity to address a considerable disparity in the supply of this most popular fertilizer type in the future. With this in mind, in 2023, Profertil (JV Nutrien and YPF) – the country's main producer of fertilizers with the current industrial capacity of 1.4 mtpa of granulated urea and 0.8 mtpa of ammonia – set a goal to duplicate its installed capacity, which should include, among others, the production of green ammonia and the installation of CCS in the existing facilities (Profertil, 2023).

Table 4: Fertilizer market in Argentina (in 2022)

Type	Main fertilizers	Consumption (mtpa)	Share (%)
Nitrogen	Urea, UAN, Calcareous Ammonium Nitrate	3.20	56
Phosphorus	MAP, DAP, SPS, SPT Ca, MAP 15 & S	2.08	37
Sulphur	Ammonium sulphate, TSA	0.20	4
Potassium	Potassium chloride, Potassium nitrate, Potassium sulphate, TSK	0.07	1
Other	-	0.13	2
Total	-	5.68	100

Source: Adapted from Fertilizar Asociacion Civil (2023).

Steel

In 2022, the apparent consumption of steel in Argentina stood at the level of 5.1 Mt with a steady CAGR of 0.2 per cent between 2013 and 2022 (Cámara Argentina del Acero, 2023). Here, the domestic production accounts for 91 per cent of the overall market share, positioning Argentina as the 32nd largest steel producer globally[27]. Presently, the country operates four active steel plants, collectively capable of producing 5 mtpa[28] (Cámara Argentina del Acero, 2023). Since these facilities use natural gas for the production process, apart from applying hydrogen for the direct reduction of iron (DRI)[29], green hydrogen could potentially substitute methane itself to help the Argentinean steelmaking sector decarbonise. On the other hand, introducing CCS into the gas-based production process may appear to be a more promising alternative.

The demand for steel in Argentina is primarily influenced by the construction, automotive, agricultural, and energy sectors, with a noteworthy potential for export, particularly within the automotive industry to markets such as Brazil. In this regard, the projected potential market for 'green steel' in the country is generally estimated by evaluating the existing capacity and technological infrastructure of the four operational steel plants, which is expected to be around 3.5 mtpa (Bertero, 2023). Here, given that approximately 55 kilograms of H_2 is required to produce one tonne of green steel, the annual demand for green hydrogen could amount to approximately 190 kt. However, it seems unlikely that, without clear incentives from the demand side, the conversion of Argentina's steelmaking process to the use of green hydrogen will take place, as it will significantly increase the ultimate costs of the product. In these circumstances, without government subsidies covering the difference or securing a stable

[27] Here, the key industrial players include Ternium Siderar, Tenaris Siderca, Acindar, Sipar Gerdau, Acerbrag and Acero Zapla.
[28] Among these, three plants utilise EAF technology, contributing to approximately half of the country's total steel production. The remaining 50 per cent is manufactured in a single plant using BOF technology, operational since before 1974 (Bertero, 2023).
[29] DRI is a process used to convert iron oxides, typically in the form of iron ore pellets or lump ore, into metallic iron without melting it. Using hydrogen as the reducing gas produces no greenhouse gases (International Iron Metallics Association, 2019).

demand from the off-taker of these steel products that will be willing to pay the green premium, it will hardly be possible.

Energy/power sector

According to the Working Group II contribution to the sixth assessment report of IPCC on adaptation, vulnerability and damage, El Niño-Southern Oscillation (ENSO) is and will continue to be the dominant mode of inter-annual variability in climate change scenarios (IPCC, 2022). Moreover, the report highlights that it is very likely that rainfall variability related to ENSO will be enhanced significantly by the second half of this century in those scenarios (Representative Concentration Pathways, or RCPs) with a higher concentration of GHG, increasing the frequency of these cycles and rainfall variability (IPCC, 2022).

The risk of increasing inter-annual variance of rainfall and, in consequence, water availability for hydropower poses challenges for power generation during years of low-hydraulicity (World Bank, 2023b) which can be managed through better integration and long-term storage, a role for which hydrogen could be competitive in the medium- to long-term.

Transport

Hydrogen faces stong competition as a standalone fuel for road transport in gas-abundant Argentina. Over recent decades several governments have promoted the idea of blue corridors, consisting of micro-LNG fueling stations for long-haul transport (Energía online, 2020) and compressed natural gas is currently one of the lowest-cost fuels for light transport (ENARGAS, 2024). In this line, hydrotreated vegetable oil (HVO) and green diesel as a co-product from hydroprocessed esters and fatty acids (or HEFA) SAF production could gain increasing competitive advantages, leveraged by the country's agricultural powerhouse. For instance, Argentina is the main global exporter of soybean oil, reaching 4.87 million tonnes (Our World in Data, 2023) a key raw material for the production of SAF via HEFA, and the fourth-largest global exporter of biodiesel.

The potential market for aviation bunkering fuel currently represents 466 ktoe/year, while the demand for domestic flights is 560 ktoe/year (Secretaría de Energía, 2023), implying potential H_2 requirements which at current levels would be equivalent to 42 kt hydrogen/year for SAF (Caratori, 2024). Such demand constitutes a relevant market that should grow in a context of economic normalization. The availability of large quantities soybean oil at competitive prices and the lower comparative costs of HEFA pathways compared with other SAF alternatives turns HEFA SAF into the potentially lowest hanging fruit for hydrogen derivatives production in Argentina.

2.2 Key measures and policies needed to facilitate domestic use of locally produced hydrogen in Argentina

As evident, while numerous sectors and niche industries in Argentina exhibit potential for the widespread adoption of locally produced, decarbonized hydrogen, their implementation should be fostered and facilitated by supportive policies and regulations. In principle, the formulation and introduction of these mechanisms could promote the uptake of Argentina's clean hydrogen not only by hard-to-abate sectors but by other related industries as well. At the same time, before it could take place, policies should address some of the country's key specific domains.

First and foremost, Argentina should have a sound regulatory framework overseeing operations at each stage and element of the clean hydrogen value chain. With this in mind, in May 2023, the Argentine Energy Secretariat unveiled plans for a comprehensive encompassing renewables-based green hydrogen, nuclear-derived pink hydrogen, and blue hydrogen produced via SMR with CCS (Secretaría de Energía, 2023b). This bill aims to establish fiscal stability for three decades, along with tax benefits, certification of origin, and the integration of local value chains. Additionally, a roadmap for the certification of origin of green and low-emission hydrogen is expected to be created by the National Institute of Industrial Technology, or INTI (INTI, 2021). However, with a new administration taking office in December 2023, uncertainties surround the continuity of current and future incentive mechanisms for specific technologies amidst the imminent energy sector deregulation.

Apart from a well-functioning regulatory framework supporting the operations of the Argentinean clean hydrogen value chain, an efficient value chain involving local suppliers of goods and services should be created. Currently, efforts are being applied to enhance or establish capabilities across sectors that could engage competitively in local clean H_2 development, such as those of wind towers, equipment for energy conversion and control, electrolyzer components and balance of plant, power electronics, storage and transportation infrastructure for hydrogen, operational practices for hydrogen plants, predictive maintenance, logistics, and traceability (CONICET, 2020).

Like in most other countries that aim to expand their national hydrogen production, renewable and electrolyzer capacities of Argentina should be substantially augmented. In pursuit of national decarbonized hydrogen targets by 2050, plans call for the addition of 30 GW of electrolyzers and an additional 55GW of renewables (Secretaría de Asuntos Estratégicos, 2023). It is projected that investments totalling around $90 billion by 2050 will be necessary to meet the established production objectives (Secretaría de Asuntos Estratégicos, 2023).

At the same time, even when the production facilities for clean hydrogen are ready for operations at full scale, implementing H_2 solutions in any of the mentioned sectors will be impossible without a proper deployment of the relevant hydrogen (or potentially adjustable natural gas) infrastructure. In this connection, the National Strategy for the Development of the Hydrogen Economy of Argentina delineates six priority vectors necessitating the establishment of production facilities near hubs, the adaptation of corridors linking production sites and demand, the renovation and expansion of port infrastructure, the construction of storage and dispatch sites for hydrogen and its derivatives, identification of storage locations for carbon dioxide, and the formulation of energy transportation networks (Secretaría de Asuntos Estratégicos, 2023). Of significance is the declared strategic need to renew and enhance at least nine ports across five provinces, involving capacity expansions, dredging, and infrastructure enhancements (ibid). This, however, will most likely also contribute to the solidification of the hydrogen export potential (ibid).

Overall, like most other hydrogen enthusiasts, Argentina requires a thorough territorial planning for the build-up of its hydrogen economy. Here, a strategic approach should be prioritized so that it aligns with commercial-scale production projects or hubs that are located near available natural resources. These resources encompass renewable energy potential, sustainable carbon sources, transmission capacity, carbon dioxide storage conditions, and local demand centres.

More importantly, perhaps, the industrial end-users (off-takers) could be incentivised to convert to this locally produced, clean H_2 from their initial energy sources and feedstock, as the conversion itself will most likely not only have significant technical challenges but also substantial costs. In this respect, incentives may include tax benefits for industrial sectors utilizing decarbonized hydrogen as well as hydrogen blending in natural gas distribution networks in connection with book-and-claim mechanisms for industrial end-use sectors. In addition, the Argentine government should consider including HEFA and Fischer–Tropsch SAF in aviation, particularly as a bunkering fuel for international aviation, integrating hydrotreated vegetable oil (HVO) in road transport and agriculture machinery, and setting methanol targets for bunkering fuels in shipping, among other initiatives.

Ideally, this should be done alongside the all-encompassing phase out of inefficient fossil fuel subsidies and the establishment of carbon pricing mechanisms. Argentina’s carbon tax for liquid fossil fuels has lagged during recent years and currently stands below $1/tonne of carbon dioxide CO_2 for liquid fossil fuels – well below the original $10 /tonne of carbon dioxide tax set by design during the 2017 tax reform – while natural gas faces no carbon taxes and is heavily subsidized (República Argentina, 2017; World Bank, 2023c). By phasing out fossil fuel subsidies which do not address energy poverty and simultaneously implementing economy-wide or energy sector-wide carbon pricing mechanisms, Argentina can facilitate an environment conducive for accelerating the development and adoption of clean hydrogen and other sustainable energy sources. This strategy aligns economic incentives with environmental goals, fostering a transition to a more sustainable energy sector.

More broadly, since many of the technologies critical for the development of the national hydrogen economy in Argentina are currently imported and will most likely continue to be imported at least in the near-term, domestic research and human capital development should go hand in hand with international collaboration and expertise engagement. Here, fostering international partnerships and alliances with countries and leading companies proficient in the clean H_2 sector seems to be an imperative[30]. In addition, Argentina should continue elevating its own research and development capabilities, promoting innovation, and enhancing competitiveness in the production of electrolyzers[31]. Here, schemes advocating scholarships for professional training in higher education and tertiary careers pertinent to the clean hydrogen sector should be prioritised.

Finally, environmental and safety standards should be developed. More generally, these should ensure safety across the value chain as well as stakeholder engagement[32] through consultations within the national economy. They should also acknowledge the significant water requirements for the production of clean hydrogen and aim to strive for efficient water discharge mechanisms for desalination plants to mitigate potential water scarcity issues, among the key measures.

2.3 Key constraints and opportunities for Argentina's domestic hydrogen use: What is preventing it from happening?

Despite the fact that the prospects of using domestically generated clean hydrogen in hard-to-abate sectors of Argentina are promising, there are several constraints to the probability of success. In this context, a major general challenge related to the unstable economic situation in the country itself leads to such negative consequences as an increasing rate of inflation, fiscal and financial deficits, and a growing debt to GDP ratio. These factors, in turn, result in high country risk[33] and therefore high capital costs negatively impacting any large-scale investment in a clean hydrogen project.

Nevertheless, it is worth highlighting the paradoxical situation during the last three years, where, amidst prevailing capital controls and consequent surplus liquidity in specific markets, numerous renewable energy companies and projects have secured remarkably low interest rates for their recent debt issuances – rates that fall significantly below 10 per cent, for projects with a 70 per cent leverage (debt-to-capital ratio) (ByMA, 2024). In these complex circumstances, access to long-term financing (either international or local) of large-scale infrastructure projects that normally require multi-billion dollar investments is likely to be scarce, while low-carbon development projects might generally experience better conditions, both in terms of access and interest rates, than carbon-intensive projects in the context of transition risks (OECD, 2021).

Projects are also limited by the restrictions that the government imposed on the import of goods and services for capital and operational expenditures (Fitch Ratings, 2021). These restrictions generate additional costs and lead times. In addition, current limitations related to cross-border capital flows constrain the ability of investors to freely decide on the destination of their dividends (BCRA, 2021). Finally, Argentina's government also limits access to the foreign currency exchange market at the official rate (EY 2023). If the new government does not waive these limitations, it seems unlikely that the growth of the country's domestic clean hydrogen sector is going to be extremely rapid.

Conventional fuels like gasoline, diesel or natural gas as well as electricity are currently heavily subsidized (International Monetary Fund, 2023a). In Argentina, implicit subsidies (undercharging for environmental costs and forgone consumption tax revenues) relate to liquid fossil fuels, and explicit subsidies relate to natural gas and power generation (República Argentina, 2023c). In the conditions

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[30] One such example is the MOU signed between YPF, YPF Luz, and the Korean steel producer Posco in September 2023 that shares the intention of exploring and investigating the development of renewable energies and clean hydrogen (YPF Luz, 2023).

[31] Y-TEC and CONICET have been working since the beginning of 2023 on a Strategic Project for the Energy Transition titled 'National development of a high-power electrolyzer for the production of green hydrogen. A contribution to the steel industry decarbonization' with financing from FONARSEC - R&D&I Agency (República Argentina, 2022).

[32] Here, key stakeholders should include state entities, private sectors, financial institutions, scientific-technological sectors, local communities, minorities, indigenous groups, among others.

[33] For instance, in December 2023, Argentina's Emerging Markets Bond Index (EMBI) spread was second highest only to Venezuela among all the Latin American countries (Statista, 2023). EMBI country risk represents a set of bond indices that track the performance of sovereign debt issued by emerging market countries and refers to the level of risk associated with investing in the bonds issued by a specific with lower EMBI values typically suggesting lower perceived risk and higher values indicating higher perceived risk (Mari del Cristo and Gomez-Puig, 2017).

where both are applied, carbon pricing appears to be difficult. This also generates uncertainty on energy prices and therefore on future cash flows of decarbonized hydrogen projects.

In addition, taxation in Argentina appears to be pretty burdensome for companies (OECD, 2023), including to the specifics of local labour regulations. In fact, the total cost of labour for companies is loaded with extra taxes and costs (World Bank, 2023a). This results in uncompetitive conditions compared with other high-potential decarbonized hydrogen supplying countries.

Most (if not all) of these limitations and challenges will likely need to be revisited in the foreseeable future due to the reforms planned by the new government appointed at the end of December 2023. In fact, it is currently putting in place a completely different policy orientation to rapidly address many of the aforementioned restrictions (namely, import restrictions, energy subsidies, labour regulations, eliminate restrictions on cross-border capital flows and facilitate access to foreign currency exchange rate, among other issues) (Argentine Presidency, 2024). In addition, the new policy orientation, given high external indebtedness, fiscal and financial deficits and the growing debt-to-GDP ratio, the scarcity of fiscal resources to invest in large projects, as well as willingness to promote private investment, is expected to virtually cease exclusively public investment in projects, but rather enable private-public initiatives in priority and business opportunity areas (Argentine Presidency, 2024).

In general, within the emerging national hydrogen sector, it is expected that the new government will be able to leverage some of the key opportunities that Argentina has to offer. These could, for instance, relate to the immense potential capacities for the production of wind (both onshore and offshore) and solar power at very low cost. In particular, according to IEA estimates for the year 2030, the northwest of Argentina (with solar energy potential) and the south of Argentina (with wind energy potential) could become one of the world’s regions with the lowest production costs (IEA, 2023). Given that electricity constitutes around 73 per cent of the total cost of green H_2 (Patonia and Poudineh, 2022), this, in turn, could be used as a basis for the large-scale domestic production of extremely competitively priced green hydrogen. This optimism has most recently been shared by Fortescue, an Australian mining company that announced an investment of $8.4 billion into a 2.2 mtpa green hydrogen project to be located in Argentina’s province of Río Negro (Gobierno de Río Negro, 2022 and Diario Río Negro, 2024).

Apart from possessing significant green hydrogen potential, Argentina also has an opportunity for the development of natural gas and CCS-derived blue and nuclear-powered pink H_2. Specifically, blue hydrogen potential relies on the vast, unconventional shale gas resources in Vaca Muerta that could be complemented with CCS technology (Secretaría de Asuntos Estratégicos, 2023). Argentina’s nuclear tradition, in turn, and especially the CAREM project (a small modular reactor) could be applied to the production of pink H_2 (Secretaría de Asuntos Estratégicos, 2023). This potential for the development of different ‘colours’ of clean hydrogen[34] raises synergies related to the concepts of ‘flexibility’ and ‘optionality’, promoting infrastructure developments such as power transmission networks (linked to renewable energy), pipeline infrastructure (with duality or conversion of natural gas/hydrogen) and port infrastructure required for the export of H_2 and its derivatives (FTDT, 2024). However, for these synergies and potential to be successfully realised, the national government of Argentina as well as the provincial governments who, under the constitution, hold the original domain of natural resources, should start developing their respective national and provincial hydrogen development plans, which will enhance cooperation and dialogue among all the involved stakeholders. International collaboration for de-risking this emerging industry is crucial, and may take the form of long-term off-take agreements, direct foreign investment and financing mechanisms.

[34] The current trend in the sustainability assessment of hydrogen production has shifted beyond the previous ‘colour palette’ classification into a threshold-based assessment, including the mutual recognition of different national and regional certification schemes and the adoption of common standards for ‘low-carbon hydrogen’, which includes the recently launched ISO standard (TS 19870) specifies methodologies to determine the carbon footprint of a hydrogen product, in line with ISO 14067 (Secretaría de Asuntos Estratégicos, 2023).

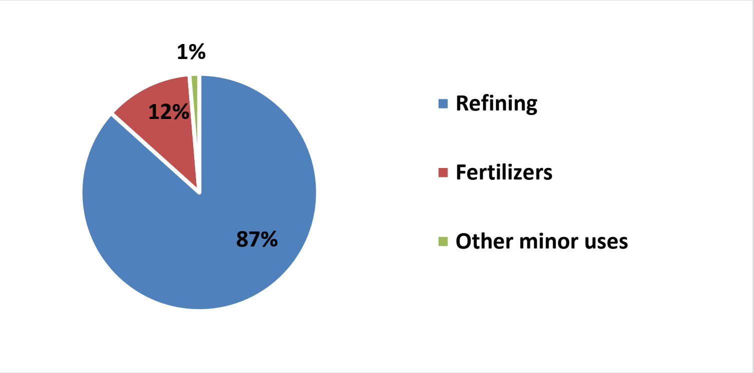
3. Colombia

Colombia has been internationally recognized as a promising producer and exporter of renewable and low-carbon hydrogen due to its abundant renewable resources, its strategic geographical location and the most recent efforts made by the government to establish a dynamic hydrogen ecosystem. The country's Hydrogen Roadmap, published in 2021, has set production targets for blue hydrogen (based on SMR with CCS) and green hydrogen (produced via water electrolysis by renewable power) up to 2050 (Ministerio de Energía, 2021). The anticipated distribution of various types of hydrogen will be influenced by the evolving cost associated with each. As estimated by the government in the Hydrogen Roadmap, green hydrogen based on wind energy produced in La Guajira, in the north of the country, can become the most competitive means of production, optimistically reaching a levelised cost of production at as low as $1.7 /kg by 2030 and $1.1 /kg by 2050[35] (ibid). Similarly, a study by the Fraunhofer Institute for Solar Energy Systems – ISE (Fraunhofer ISE, 2023), states that an 'extremely favourable wind production costs can be reached in La Guajira region, in northern Colombia', with hydrogen and its derivatives (ammonia and methanol) being produced very cost-effectively such that they could potentially become some of the cheapest in the world, which will encourage their ultimate export to Germany[36].

3.1 Key industries and areas for Colombia's domestic hydrogen use: Where is hydrogen expected to be used first?

When it comes to the domestic consumption of hydrogen, at the moment, Colombia uses around 150 kt of H_2, mostly in the country's oil refineries, where hydrogen is produced from natural gas via SMR (Figure 9) (Ministerio de Energía, 2021). In addition to this, fertilizer production represents other relevant demand, of around 18 ktpa (ibid). The remaining applications of hydrogen such as those for margarine or glass manufacturing appear to be relatively insignificant in terms of quantities (ibid). Since Colombia does not produce enough hydrogen for all the hydrogen-containing products that it uses, a significant volume of H_2 derivatives such as ammonia, methanol and nitrogenous fertilizers is imported (ibid). Also, the national Roadmap states that low-emission hydrogen will begin to be used in refineries as a replacement for grey hydrogen. Some of this hydrogen will be blue, derived from the application of carbon capture and storage in natural gas steam reforming plants (ibid). In 2022, Ecopetrol, the national oil company, started low-carbon hydrogen production in its refinery in Cartagena with a pilot project of 50 kW of electrolysis (Ecopetrol, 2022).

Figure 9: Domestic hydrogen consumption in Colombia by sector (in 2023)



Source: Ministerio de Energía (2021).

[35] It is, however, still not entirely clear how realistic these estimates are, given that most of the green hydrogen projects are still at very early stages of development.
[36] In addition to the interest in blue and green hydrogen, most recently, the national government has been exploring opportunities for the extraction/production of naturally occurring hydrogen (often referred to as 'white' or 'gold'). These explorations are supposed to take advantage of the already developed oil and gas exploration infrastructure.

As estimated in the national Roadmap, in the future, the local consumption of hydrogen is expected to further grow to 790 ktpa by 2040, a more than five-fold increase compared with the current indicators (Ministerio de Energía, 2021). This objective will require the deployment of new applications for renewable hydrogen that will stimulate their consumption, such as the use of clean hydrogen in the transport sector and for domestic ammonia and fertilizer production in order to replace imports of the latter products (ibid). Also, the potential use of hydrogen for the development of synthetic fuels and the expected growth of the use of hydrogen derivatives (ammonia and methanol) in the maritime sector creates an opportunity for Colombia to become an international hub for bunkering in the medium to long term, considering its favourable location close to sea trade routes (ibid).

Oil refining/petrochemicals

Colombia's distinctive geographic location, coupled with its proximity to important maritime routes, provides great access to major trading pathways and export markets. These favourable conditions not only facilitate engagement in maritime-based hydrogen trade with other countries within the Latin-American and Caribbean regions and other regions, but also open opportunities for bunkering at Colombian ports, thanks to their proximity to the Panama Canal (Global Maritime Forum, 2023). Given the country's robust port infrastructure along both the Atlantic and Pacific coasts, with the capacity to efficiently handle substantial quantities of liquid fuels, chemicals, and other pertinent products, there exists a compelling potential to establish low-carbon bunkering services or ship-loading facilities for hydrogen and green derivatives.

Presently, Colombia's ports do not offer bunkering services. However, the particularly low levelised cost of hydrogen (LCOH) achievable in certain areas, coupled with the strategic positioning of the primary maritime terminals, suggests that Colombia could play a significant role in advancing the decarbonization of maritime transport in the medium term. This aligns with anticipated international regulations and mandatory quotas set to come into effect in the coming years[37].

Regarding the local demand for low-carbon bunkering, there is a substantial opportunity to offer such services for domestic maritime and inland waterway transportation in the medium and long term. Presently, there are 75 liquid fuel stations catering to waterway transport and four for maritime transport across the country (MME, 2022). This, combined with the government's commitment to enhancing this mode of transport and leveraging the country's extensive river system, presents an opportunity not only to capitalize on the international market but also to address local demand for low-carbon fuels.

Regarding refineries, as previously mentioned, Ecopetrol has already initiated efforts toward the production of low-carbon hydrogen. Presently, the oil company is actively involved in two additional hydrogen pilot projects, both with a primary focus on clean mobility. Collectively, across these three active projects, Ecopetrol achieves a daily production of 100 kg of hydrogen. These endeavours form a pivotal part of the first horizon, spanning from 2022 to 2030 of its Hydrogen Strategic Plan launched in 2022. The plan's initial phase prioritizes the 'sustainable expansion of their own operations through the development of industrial-scale projects, road mobility, and the construction of key capabilities to optimize production costs.' As part of its Strategy, Ecopetrol has set the target of producing one million tonnes of low-carbon hydrogen by 2040, estimating that 60 per cent of this production will be used in its own operations, natural gas blending, sustainable mobility, and new low-emission products at national level and the remaining 40 per cent will be for export (Ecopetrol, 2022). As part of this target is the development of green hydrogen, blue hydrogen, and white hydrogen. Ecopetrol expects that low-carbon hydrogen contributes between 9 and 11 per cent to the goal of reducing 50 per cent

[37] For instance, the FuelEU Maritime Initiative from the European Council, aims to put maritime transport on the trajectory of the EU's climate targets, ensuring that the GHG intensity of fuels used by the shipping sector will gradually decrease over time, by 2 per cent in 2025, rising to 6 per cent in 2030 and up to 80 per cent by 2050. Also, the International Maritime Organization (IMO), in the most recent version of its GHG emissions strategy, targets emissions from international shipping to reach net-zero by or around 2050, including the adoption of zero or near-zero GHG emission technologies, fuels and/or energy sources to represent at least 5 per cent, striving for 10 per cent of the energy used by international shipping by 2030 (IEA, 2023).

of scope 1, 2, and 3 emissions by 2050, with an average annual investment close to $$140 million by 2040 (Ecopetrol, 2022).

Fertilizers/chemicals

Historically, Colombia has seen a notably low level of domestic fertilizer production. In 2023, nearly 95 per cent of national demand was met through imports from Venezuela, Trinidad and Tobago, and Russia, with the latter being the major source of urea and other nitrogen fertilizers (CONPES, 2023). This reliance on imports is primarily due to Colombia’s limited installed capacity to produce essential feedstock such as nitrogen, potassium, and phosphorus (ibid).

Despite this, the fertilizer industry is the second largest consumer of hydrogen in Colombia, after oil refining (Ministerio de Energía, 2021). A key player in the market, Yara, consumes around 18 ktpa of hydrogen in its Cartagena plant (Yara International, 2020). In total, Yara produces around 620 ktpa of fertilizers in its Cartagena and Yotoco plants (ibid). Considering the substantial reliance on imported fertilizers, Colombia has an opportunity to bolster domestic production using its clean hydrogen potential. This development could mark a significant step towards emerging as a relevant exporter of hydrogen derivatives and products like green ammonia and green fertilizers to meet both local and international demand.

Here, given the developed refining sectors, blue hydrogen could play a role in building the Colombian fertilizer sector from scratch, considering the vast agricultural potential of the country. However, relying on green hydrogen may be more promising in the long-term because of the greater sustainability of its production process. In Colombia, the development of blue hydrogen is primarily undertaken by oil and gas firms, with a keen awareness of the constraints posed by limited and decreasing natural gas reserves. This development is further challenged by the fact that opting for coal gasification would entail significantly higher expenses due to the increased need for CCS technologies. Consequently, it is anticipated that the interest in green versus blue ammonia will align closely with the prevailing interest in green and blue hydrogen. In this respect, the utilization of green ammonia in nitrogen fertilizers holds the potential to significantly mitigate the GHG emissions associated with agriculture. This approach not only supports the production of environmentally friendly agricultural products, but also fosters the growth of the national industry. Additionally, it proves advantageous by reducing the current reliance on imports, enhancing independence from international suppliers, and mitigating exposure to price and availability bottlenecks during geopolitical crises. Indirectly, such initiatives may also play a role in bolstering food security within the country.

Steel

Colombia boasts six steelmaking plants and 12 hot rolling mills dedicated to the production of long steel, collectively possessing an installed capacity of 2.6 million tons (ANDI, 2023). Five of the seel mills produce 100 per cent of the long steel products manufactured in the country. The predominant method employed for steel production involves EAFs, with recycled and reclaimed scrap metal as the primary inputs. Consequently, the practice of steelmaking through DRI remains virtually non-existent in Colombia (ibid). Given the current industrial landscape, the integration of hydrogen as an alternative for the country's steel industry would necessitate a substantial technological transformation, a prospect not anticipated in the short or medium term.

Energy/power sector

According to the National Hydrogen Roadmap, the integration of hydrogen into the country's power generation is anticipated to materialize after 2035. The national strategy envisions hydrogen as a flexible, seasonal storage solution, aligning with the widespread deployment of Non-Conventional Renewable Energy Sources (Ministerio de Energía, 2021). This involves its subsequent application in combined cycle plants fuelled by hydrogen or fuel cells (ibid). Projections indicate that by 2040, the power sector could require approximately 30 kt of low-emission hydrogen, constituting roughly 4 per cent of the hydrogen demand outlined in the strategy for that timeframe (ibid). Colombia's electricity system, predominantly driven by hydroelectric generation, complements with other renewables like solar and wind and is able to cover baseload requirements with renewable energy for the greater part of each year. Consequently, the necessity for utilizing hydrogen for energy storage is limited, given the favourable dynamics within the existing power infrastructure.

Nevertheless, hydrogen for energy storage could be developed as a solution for islands and isolated regions. These areas, which are beyond the reach of the National Electric System due to geographical constraints, rely on off-grid solutions and microgrids predominantly fuelled by diesel generators to meet their electricity demand. In this context, hybrid hydrogen/battery microgrids fueled by renewable energy, could emerge as potential alternatives to decarbonize these isolated energy systems, offering a sustainable and environmentally friendly solution to address the challenges associated with remote power generation.

Transport

In Colombia, approximately 95 per cent of cargo transportation relies on road networks due to the limited availability of alternative modes such as railways (ANDI, 2023). Additionally, the freight fleet is notably old and should be renewed (ibid). Both aspects, together with the fact that the transport sector accounts for around 12 per cent of the nation's GHG emissions, with trucks and buses responsible for half of these emissions, present prime opportunities for the integration of low-emission technologies in the near to medium term. The country's reliance on trucks for long-distance hauling, with the average freight transport route being 350 km, makes the adoption of fuel cell technologies particularly advantageous over battery electric vehicles (ibid).

According to the National Hydrogen Roadmap, the transport sector can become a key driver behind the exponential growth in demand for hydrogen, accounting for 64 per cent of the total hydrogen demand in 2050[38] (Ministerio de Energía, 2021). The document also estimates that between 1,000 and 1,500 fuel cell heavy-duty vehicles would be deployed by 2030 nationwide, focusing on infrastructure development across the main freight corridors[39] (ibid). Table 5 shows the estimated demand for low-carbon hydrogen and derivatives in the transport sector according to the National Hydrogen Roadmap.

Table 5: Hydrogen and derivatives demand for transport sector in Colombia

Time horizon	Hydrogen demand (ktpa)	Electrolyzer capacity (GW)[40]
2030	7.2	0.04
2040	371	2.1
2050	1,184	5.7

Source: Adapted from Ministerio de Energía (2021).

Out of the 28 hydrogen projects under development in Colombia, including seven in testing phases, four appear to be in the mobility sector (La República, 2023). Here, it is worth mentioning the development of the first fuel cell passenger bus pilot project in the country, located in Bogotá, which was funded by the national government via FENOGE (National Fund for Renewable Energies Promotion) and Ecopetrol (Ecopetrol, 2022). Notably, the vehicle was completely assembled locally and has a range of 459 km. In addition to the ongoing projects, a noteworthy initiative from the private sector, notably spearheaded by key energy companies such as Ecopetrol, involves the initial phase of delineating potential hydrogen corridors within the country. These endeavours also encompass proposing financing schemes aimed at advancing the technological capabilities of heavy-duty vehicles in the region (Portafolio, 2023).

[38] This, obviously, depends on the general trends and developments in the field of road transport, as much of the land transportation is currently being converted to electric battery solutions, rather than hydrogen.
[39] The freight fleet size in Colombia is estimated to be 390,600 units, where around 240,000 units corresponds to Heavy Duty vehicles (Ministerio de Energía, 2021). Therefore, the National Roadmap target of 1,000–1,500 fuel cell heavy-duty vehicles represent around 0.5 per cent of the current Heavy Duty Fleet.
[40] Source: Author's estimate based upon electrolyzer efficiency of 64 per cent till 2040 and 76 per cent onwards.

3.2 Key measures and policies needed to facilitate domestic use of locally produced hydrogen in Colombia: What should be done to make it happen?

Colombia distinguishes itself as one of the key and most prominent nations in South America actively implementing initiatives to foster the creation of the national hydrogen ecosystem and assert its significance in the global hydrogen market. This is particularly evident in the regulatory and policy measures instituted in recent years. As previously mentioned, the Energy and Mining Ministry unveiled the National Hydrogen Roadmap in 2021, outlining specific targets for hydrogen production and demand by 2030 and 2050 (Ministerio de Energía, 2021). In alignment with this vision, the government has identified four critical fronts of action that must be pursued to ensure the ongoing progress of the hydrogen market in the country: i) legal and regulatory framework; ii) market development instruments; iii) infrastructure development; and iv) technology development and industry (ibid).

When it comes to the legal and regulatory environment, in recent years, the government has implemented a set of policies and regulations that, while still open to improvement, have laid the groundwork to develop a vibrant hydrogen economy. Notably, financial incentives acknowledging hydrogen as an energy carrier have been incorporated into the existing regulatory framework, particularly through the enactment of Law 2099 in 2021. This legislation categorizes green and blue hydrogen as non-conventional energy sources eligible for fiscal benefits, including exemptions from customs duties, value-added taxes, accelerated depreciation, and a 50% income tax deduction on investments (ibid). Furthermore, FENOGE, which supports and finances projects and programs related to renewable energy, is also available to fund initiatives associated with green and blue hydrogen (ibid). Over the past year, the fund has effectively allocated resources from international banks and development institutions to finance prefeasibility analyses and market studies for various green hydrogen projects covering the complete value chain: hydrogen production from renewable energy, including biomass; hydrogen transport and conditioning; and the final application of hydrogen and its derivatives in different sectors.

At the same time, although the existing regulation represents a significant step towards supporting the development of hydrogen projects in Colombia, there is still a long way to go before the first volumes of locally sourced clean hydrogen are used by Colombian hard-to-abate sectors. As it stands, the key areas requiring further attention include demand-side incentives, the establishment of low-carbon hydrogen taxonomy, implementation of guarantees of origin, and clarification of specific environmental permitting procedures that align with the pivotal role of hydrogen as an energy carrier. Additionally, there is a need for the adoption of regulation that covers the entire power-to-X value chain, such as incentives for equipment and services related to low-carbon ammonia, methanol or e-fuels. Furthermore, potential revisions of technical standards associated with hydrogen and the electricity system may be necessary to ensure the smooth integration of decarbonized molecules within the existing energy system.

Apart from this, while initial actions have been taken to support the development of the hydrogen market in Colombia, there are key aspects that still need to be further developed. For instance, significant progress includes the establishment of sectorial associations such as the Colombian Hydrogen Association and the Hydrogen and Energy Efficiency Chamber, having in total more than 80 affiliated companies from a wide range of industries that includes technology providers, energy utilities, academia, and key players from the chemical and oil and gas industries (ANDI, 2023). Both entities aim to promote the development of hydrogen and its derivatives and are a meeting point for industries and relevant actors, for knowledge sharing and networking.

Despite this progress, other key elements, such as the development of innovative financing mechanism for low-carbon hydrogen projects and the definition of hydrogen hubs across the country, are yet to be implemented. However, in case of the former, currently the Ministry of Mines and Energy, together with the EU and the Colombian Hydrogen Association are working on structuring a financing facility for large-scale hydrogen and power-to-X projects in Colombia and expect to present preliminary results during Q2 2024 (Ministerio de Energía, 2021). When it comes to the latter, a recently published study from the German Agency for International Cooperation (GIZ) mapped several potential power-to-X hubs to be developed in the country, taking into consideration aspects such as renewable energy availability, local demand, infrastructure, and social and environmental aspects, among others (H2LAC, 2023).

At the moment, one of the main challenges for the development of projects in the country is the lack of current and short-term upcoming demand for hydrogen and its low-carbon derivatives. As mentioned before, more than 98 per cent of the country's need for hydrogen comes from two off-takers: Ecopetrol and Yara (ibid and Ecopetrol, 2023). Although Ecopetrol is working on replacing part of its grey hydrogen consumption with clean hydrogen, there is no regulatory requirement in this regard (La República, 2023). Accordingly, a significant effort is required to stimulate further local demand for renewable H_2, considering not only the substitution of the prevalent industrial-use grey hydrogen but also its use in new innovative applications. A pivotal tool in achieving this goal can be the implementation of a carbon price that accurately reflects the externalities associated with fossil fuel use. In pursuit of this objective, an emissions market designed as tradable emission quotas is currently in the preparatory phase under the auspices of the Ministry of Environment and Sustainable Development (H2LAC, 2023).

Apart from legislation and regulations, the successful establishment and enhancement of infrastructure play a crucial role in advancing the hydrogen market. Adaptations may not only be necessary for the electrical infrastructure but also for port facilities, aiming at providing bunkering services. As previously noted, most of the country's ports boast well-established infrastructure geared towards importing and exporting fossil fuels (ibid). This presents a promising opportunity for repurposing and modifying the existing infrastructure for the transportation and storage of hydrogen and its derivatives, including methanol, ammonia, and e-fuels. Particularly noteworthy are ports along the Atlantic Ocean, such as Zona Portuaria de Cartagena and Puerto Brisa, which feature the most advanced and dynamic terminals in the nation (ibid). These ports possess extensive experience in handling liquid fuels and are strategically situated in proximity to regions abundant in renewable resources.

Furthermore, the development of new infrastructure is essential to integrate hydrogen into the transport sector. A major challenge in this endeavour is the insufficient number of hydrogen refuelling stations (HRS) under development, which hinders the widespread acceptance of hydrogen as a zero-emission fuel for road transport (ibid). Additionally, the lack of fuel cell vehicles compounds this issue, discouraging investments in the necessary infrastructure (ibid). Recognizing these intertwined challenges, the National Hydrogen Roadmap underscores the importance of having a synchronized deployment of infrastructure in line with the expected adoption of fuel cell vehicles. The national government plans to deploy at least 20 HRS of public access for every 100 fuel cell vehicles, leveraging the current fuel stations network, mainly those located in corridors with high transit of freight vehicles and long-distance intercity buses (Ministerio de Energía, 2021). However, progress in this area has so far been slow.

Finally, while Colombia boasts a generally low water stress index, certain regions, such as La Guajira, face challenges due to insufficient water accessibility, which impacts both industrial processes and local communities (H2LAC, 2023). Despite the abundance of renewable resources in these areas, the lack of adequate water infrastructure can be considered as a constraint (New Climate Institute, 2023). In addressing this issue, the implementation of renewable hydrogen production projects could present a dual opportunity. Specifically, by integrating desalination facilities within these projects, there is the potential not only to advance the production of renewable hydrogen but also to enhance water access and infrastructure for local communities. Given the above, the infrastructure development for the green hydrogen economy not only represents a unique opportunity for Colombia to showcase globally the viability of an effective and equitable energy transition, but also has the potential to yield substantial benefits in economic, environmental, and social terms for the country.

The Colombian government aims to actively engage in the hydrogen economy not merely as a consumer of foreign technology for project development, but also as an integral part of R&D and the value chain for equipment manufacturing. To achieve this, the National Hydrogen Roadmap considers a number of actions including the development of a regulatory sandbox to reduce uncertainties, develop training and educational programs for technical and professional personnel and promoting industrial capacities with an emphasis on R&D (Ministerio de Energía, 2021).

Nevertheless, progress in these areas has so far been modest. While a few pilot projects are currently in operation phase, they have been developed within the existing, and somewhat limited, permitting and regulatory framework. The lack of clear rules in terms of specific sandbox regulation for hydrogen projects has been described as a barrier for project development by some stakeholders (La República, 2023). Similarly, while several professional courses and continuing education programs exist about hydrogen and power-to-X, and some universities have included classes related to this field in this post graduate programs, there is still a shortage of professionals and experts, especially in activities related to operations and maintenance. This skill gap is seen as a major barrier to the development of renewable hydrogen projects in the country by several key actors. Finally, there has been minimal to no progress in R&D activities.

3.3 Key constraints and opportunities for Colombia's domestic hydrogen use: What is preventing it from happening?

Colombia can be marked out as having significant potential for the development of renewable energy, which could position the country as an important participant in the global low-carbon hydrogen ecosystem, particularly in terms of its production capabilities and export potential. Transitioning to a hydrogen-driven economy has the potential to yield extensive benefits to the population, manifesting in areas such as job creation, water and energy access, and the alleviation of poverty and inequity. This could support a just and sustainable energy transition within the country. However, to realize these benefits fully, it is necessary to overcome existing challenges, in order to leverage opportunities and capitalize on the current window of opportunity presented by low-carbon hydrogen for the country.

In recent years, the country has demonstrated a proactive approach in rapidly developing its regulatory framework and hydrogen ecosystem. The institutions' foresight in recognizing advantages such as a favourable geographical location, abundant renewable resources, and robust infrastructure creates opportunities for accelerated growth in the green hydrogen sector. Combined, this puts Colombia in a valuable position compared with other countries in the region, that, despite enjoying similar advantages of favorable geographical conditions, still in the main need to develop or strengthen their regulatory frameworks to facilitate the development of the power-to-X value chain.

The country's significant renewable resources, if harnessed efficiently, provide a valuable opportunity for the development of green hydrogen production. Colombia has potential in both solar and wind energy resources, most of them still untapped and located in the northern regions of the country. Concurrently, there is the proactive exploration of producing low-carbon hydrogen using alternative resources, such as small hydroelectric plants, leveraging the abundant availability of this resource across the country. Additionally, Colombia is delving into the prospect of generating low-carbon methanol and urea from agricultural crop waste, especially in regions with robust agriculture development (Ministerio de Energía, 2021). The combination of these initiatives, coupled with the country's relativity high water availability, creates highly promising conditions for the production and export of hydrogen.

At the same time, despite Colombia's significant potential vis-à-vis hydrogen, some aspects need to be tackled to leverage that potential. Most notably, there are no current incentives or clear market signals for the development of strong hydrogen and power-to-X initiatives, which hinders the growth of the clean hydrogen sector, possibly to the extent that it comes to depend solely on international market demand, where Colombia would be competing with other regional green hydrogen producers, such as Chile or Brazil, who may be advancing faster in this regard.

In addition, resistance from some local communities to large-scale projects introduces an added layer of complexity, demanding meticulous attention and thoughtful engagement in the planning and execution of low-carbon hydrogen projects. This challenge is particularly pronounced in regions like La Guajira, where renewable energy projects have encountered such obstacles. An example of this is the Enel Green Power's Windpeshi wind project which was indefinitely paused due to construction delays arising from challenges from neighbouring communities (Enel, 2019).

La Guajira region has a historical backdrop of community resistance to energy projects, primarily rooted in issues such as inequality, inadequate government presence, and a pervasive incidence of multidimensional poverty (New Climate Institute, 2023). In this regard, it is imperative to prioritize a fair energy transition that thoroughly considers the well-being and development of all the communities involved. This highlights the critical importance of such considerations in the development of hydrogen projects within the country.

On the other hand, delays in environmental licensing and permit processes by regional entities have affected several renewable energy projects in recent years, such that in October 2023 EDF Renewables announced the cancellation of a 50 MW solar PV plant, primarily attributed to the failure to obtain environmental permits within the anticipated timelines (El Tiempo, 2023). Therefore, both social and environmental components of project development jointly impact Colombia's renewable energy sector, promoting an environment of uncertainty affecting companies and potential investors and negatively impacting their willingness to invest in projects, including those involved with hydrogen.

Furthermore, as mentioned previously, the limited development of infrastructure could be one of the main barriers for the progress of a fully integrated hydrogen economy in the country. An efficient strategy to overcome these challenges, while limiting early-stage investments, involves retrofitting and upgrading existing infrastructure, particularly from established industries such as oil and gas or the maritime transport industries. As an example, current port facilities that are predominantly designed for fossil fuel exports and imports would require modifications to handle ammonia and other hydrogen derivatives, either for bunkering services or for exporting power-to-X products. However, a full integration of the hydrogen ecosystem, allowing for long-distance transport between supply and demand using dedicated pipelines, or enabling the large-scale adoption of fuel cell mobility by the development of an overarching network of HRS, would require heavy investments in new infrastructure. Undertaking such endeavors can demand substantial resources, a coordinated execution between public and private players, and public willingness to achieve implementation within a reasonable and adequate timeframe.

In conclusion, Colombia has taken significant strides toward the establishment of a low-carbon hydrogen economy, setting ambitious targets in production, consumption, and prominent participation in the international market. Although there are many challenges to be addressed, and progress has stalled in the last year, the country is currently acknowledged as a key exporter and regional leader alongside Chile and Brazil. An important consideration in Colombia's journey towards a dynamic hydrogen economy is achieving a balance between its export-oriented focus and the local benefits that it can generate. Ensuring that initiatives geared towards exports are complemented by local value creation and sustainable development is essential for the successful implementation of clean hydrogen projects.

4. Chile

According to the National Green Hydrogen Strategy, in contrast to other South American countries that apply a broader scope of possible hydrogen production with input from sources including biomass and natural gas, Chile is focussing solely on producing renewable green hydrogen, which in the local context will mainly refer to solar and wind energy (Chilean Ministry of Energy, 2020). As estimated by the Ministry of Energy, with over 2,071 GW of solar PV and over 79 GW of onshore wind capacity that could be developed in the future (Chilean Ministry of Energy, 2021), the nation's renewable energy potential exceeds the domestic demand by far, being from 70 to 85 times higher than current needs (Chilean Ministry of Energy, 2024a). In the opinion of the IEA (2019), the high quality and availability of primary renewable energy sources together with expected decreases in solar and wind technology costs position Chile's northern and southern regions as among the world's most attractive renewable hydrogen production areas, with the expected LCOH by 2030 to be between $2.5 and $3.5/kg[41] (IEA, 2019).

The best solar energy resources are in Chile's northern regions, specifically close to the Atacama Desert with some of the world's highest solar irradiation levels, guaranteeing capacity factors of over

[41] Here, just as in the case of Colombia, it should be noted that although production costs are likely to be low, it is unclear what the realistic numbers would be, since most of the projects at the moment are in the very early stages of development.

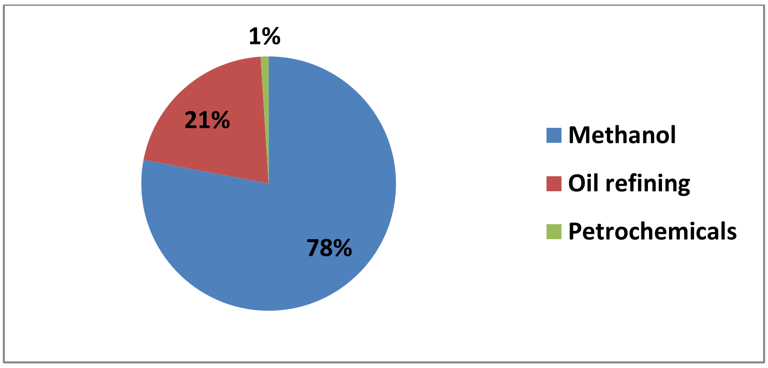
30 per cent for solar PV plants (Chilean Ministry of Energy, 2014). In addition, the country, which extends for over 4,000 km from north to south, has highly suitable conditions to develop onshore wind energy. In particular, in the Magallanes region of Chilean Patagonia, the capacity factors for onshore wind are estimated to be as high as 60 per cent (Chilean Ministry of Energy, 2021).

4.1 Key industries and areas for Chile's domestic hydrogen use: Where is hydrogen expected to be used first?

One of the key targets of Chile's National Hydrogen Strategy is to position the country among the top three global exporters of hydrogen and derivatives by 2030 (Chilean Ministry of Energy, 2020). At the same time, hydrogen is also expected to be responsible for a quarter of all reductions in domestic carbon emissions by mid-century, which aligns with Chile's target to achieve carbon neutrality (Chilean Ministry of Energy, 2020). That is why the build-up of domestic clean hydrogen production can contribute not only to the development of hydrogen exports but also to the overall decarbonization of the nation.

Nowadays, the domestic demand for hydrogen is spread among specific sectors, encompassing oil refining, petrochemicals and methanol production (Figure 10).

Figure 10: Domestic hydrogen consumption in Chile by sector (in 2023)



Source: Adapted from HINICIO (2024).

Oil refining/petrochemicals

With three operating refineries and one methanol production plant, Chile possesses an important area where domestically produced renewable hydrogen could be utilized. The demand for grey hydrogen within Chile is predominantly driven by Methanex, a methanol producer, and is concentrated in the Magallanes region, which accounts for 78 per cent of the total national demand. Currently, both the refining sector and methanol production generate around 265 kt of grey hydrogen from natural gas that is imported from Argentina (Internal data from Hinicio, 2021). Hence, replacing at least part of this locally produced and consumed grey H_2 with renewable hydrogen is crucial to foster decarbonization and spur growth in domestic demand for clean hydrogen[42].

Moreover, significant potential exists for expanded applications, particularly in key sectors such as energy, steel production, and transportation. As demand continues to grow in these areas, locally-generated renewable hydrogen presents a promising opportunity to address these needs effectively.

Fertilizers/chemicals

At the moment, more than 70 per cent of the hydrogen projects that are developed in Chile are focused on the use of hydrogen as a feedstock for the production of derivatives (GIZ, 2022). This is because most of these projects are dedicated to covering foreign hydrogen demand, thus focussing on energy carriers that are more easily transportable than liquefied hydrogen (mainly ammonia). At the same time, local applications of these locally-synthesized derivatives do exist as well.

[42] Another lesser-known chemical feedstock is hydrogen peroxide, broadly used in the Chilean pulp and paper sector, and that today is also produced using natural gas.

In particular, hydrogen is mainly intended to produce ammonia and then ammonium nitrate, which is then used as a feedstock to produce explosives for the mining sector and nitrogen fertilizers (GIZ, 2022). Nowadays, Chile is annually importing about 350 kt of conventionally synthesized grey ammonia to manufacture mining explosives. The same applies for the agricultural sector: almost all the country's demand for fertilizers is covered by imports (GIZ, 2022). That is why, in the future, locally produced renewable H_2 could be used to synthesize renewable ammonium nitrate for the domestic production and use of mining explosives and fertilizers, and to produce mining and agricultural goods with a lower carbon footprint by decreasing scope 3 emissions[43]. This will not only align with international commercial trends towards more sustainable products, but will also help Chile to become more self-reliant and less dependent on imports.

Steel

Chile also has its own iron mining sector and steelmaking industry. The main steelmaking company CAP Acero has already started the first pilot project in this field, partnering with the technology provider Paul Wurth (Chilean Ministry of Energy, 2023b).

Energy/ power

When it comes to Chile's power generation sector, clean hydrogen could find application there, too. In particular, there are two main applications of locally-produced green hydrogen in electricity production. Specifically, due to the extreme weather conditions in northern Chile, there is a significant difference in solar PV power generation between the summer and winter seasons (World Bank, 2021). This inherently leads to the curtailment of many PV assets, which currently represents one of the key problems of the national power market (Fraunhofer Chile, 2022). In these circumstances, seasonal storage (through power-to-H_2 process) together with the benefits of sector coupling (demand response) seem to be key to reducing the challenge of curtailing current and future PV facilities.

The second application arises from the fact that Chile has hundreds of isolated communities and islands, which are mostly powered by generators that run on diesel, liquefied petroleum gas (LPG) and/or natural gas (GIZ, 2018). Here, the most notable cases are the ones of the Easer Island, San Pedro de Atacama and the so called 'Sistemas Medianos' (Medium Sized Systems) in Patagonia (Chilean Ministry of Energy, 2019). While all these places represent world-renown ecotourism locations, today their power and heat demands are completely dependent on fossil fuels. In these circumstances, using power-to-X applications for storing renewable power could represent a more sustainable alternative to hydrocarbons for island and isolated communities. However, the necessary renewable GW, electrolysis capacity and associated costs have yet to be estimated for these regions. Nevertheless, ongoing studies in specific areas such as the Aysén region are addressing these crucial considerations.

Transport

Renewable hydrogen is currently being explored in Chile in different mobility applications, ranging from green shipping, aviation, and from heavy-duty trucks to forklifts. In particular, it is expected that for long-distance and heavy-duty transportation vehicles, mainly used within the country's vast mining industry, a combination or hybrid use of batteries and hydrogen fuel cells will be required (Internal data from Hinicio, 2023).

According to the Ministry of Energy (2020), out of the estimated contribution of approximately 25 per cent of domestically-produced renewable H_2 that would be needed to help decarbonize the national economy, around 70 per cent is expected to be dedicated to the heavy-duty transport sector (Ministry of Energy, 2020). This should be of no surprise, as Chile, with a well-developed mining sector, is one of the world's key producers of copper and lithium (Economic Commission for Latin America and the Caribbean, 2023b). Therefore, hydrogen for locomotives (for instance, to transport copper cathodes), for buses (like the transport of the labour force from the cities to the mines) and for shipping through

[43] Scope 3 emissions are the result of activities from assets not owned or controlled by the reporting organization, but that the organization indirectly affects in its value chain.

first-of-a-kind ‘green corridors’, are all potential local applications for renewable H_2 currently being analyzed in Northern Chile[44].

In Central Chile – the country’s most populated area – locally-generated hydrogen and derivatives are expected to be used in logistics and interurban transport (Internal data from Hinicio, 2023).This is driven by the fact that the country is over 4,000 km in length and does not have any major railways (neither for passengers nor for cargo). In this context, one of the first projects of delivering a fleet of over 100 fuel cell forklifts to a logistics centre outside Santiago has been already realized by the Engie-Walmart consortium (ENGIE, 2023); also, Anglo American is producing renewable hydrogen to move forklifts used within its mining divisions (Anglo American, 2021). Apart from this, a consortium of Anglo American, Andes Motor, Buses Hualpén, Copec Voltex and Linde are currently investing in a fleet of intercity fuel cell buses with capacity for 50 passengers and a range of 300 km[45].

Besides road and rail tansport, there are also emerging initiatives to study and explore potential H_2 applications for Sustainable Aviation Fuels (SAF): various actors from the public sector, with the support of the Interamerican Development Bank (IDB), in 2022 launched the Sustainable Aviation Fuels Working Group within the framework of the ‘Clean Flight’ Program. This group has been bringing together diverse industry stakeholders to discuss the development of SAF in Chile and globally.

Its primary objective is to draft a roadmap that sets out initial guidelines for Chile’s production of SAF, in response to the interest of different sectors in promoting the de-fossilization of Chilean aviation. The roadmap is expected to be launched during the first semester of 2024. To grasp the potential of SAF, according to data from the National Energy Commission (CNE), prior to the pandemic in 2019, approximately 1.6 million cubic metres (mcm) of conventional aviation jet fuel were sold (demanded) in Chile. Assuming that during this year 2024 air transport may recover and return to pre-pandemic annual growth rates, this total fuel consumption could double before 2035 (Chilean Minister of Energy, 2024d).

4.2 Key measures and policies needed to facilitate domestic use of locally produced hydrogen in Chile: What should be done to make it happen?

When considering renewable and low-carbon hydrogen market development policies in Chile, two main categories of measures can be found on a global level: those being referred to as ‘carrots’; and those referred to as ‘sticks’[46]. At the moment, Chile is focusing on ‘carrots’ and the national government has already launched many non-economic policy initiatives, while not enough economic measures of this kind have been defined so far (Chilean Ministry of Energy, 2024b). In particular, until now, the Chilean government has focused on outlining and communicating the country’s high potential and global competitiveness to produce renewable hydrogen, with a strong focus on attracting foreign investment, as seen with the signing of seven international collaboration agreements with H_2 importing markets, namely Singapore, South Korea, Belgium, Japan, Germany, and two MOUs with the Netherlands (Ministry of Energy, 2024c). The agreements with Singapore, South Korea and one of the two agreements with the Netherlands have already entered into force, while the remaining agreements have yet to do so (Ministry of Energy 2024c). Additionally, in 2021, the public

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[44] At the same time, it should also be noted that in land transport overall, direct electrification is also being actively explored as an alternative to fuel cells. Therefore it is still not completely clear which technological solution will become preferable.

[45]This is aligned with the country’s National E-mobility as well as Climate Change Strategies.

[46] ‘Carrot’ incentives represent instruments that make the production of renewable or low-carbon hydrogen more attractive, specifically in economic terms, by offering tax credits or subsidies targeting the production side. An example for this approach is the Inflation Reduction Act (IRA) which was published 2023 by the U.S. Government, but also financial support mechanisms based on the Contracts-for-Difference (CfD) model, like H2 Global.

‘Sticks’ incentives refer to policy measures that ‘punish’ the consumption of non-renewable/low-carbon products and goods, defining certain emission intensity thresholds, like the European Carbon Border Adjustment Mechanisms (CBAM); or obligatory targets for certain shares of renewable/low-carbon fuels in transport or industry, as those defined within the European Union’s Renewable Energy Directive (RED) II in context of the Renewable Fuels Non-Biological Origin (RFNBOs); thus targeting the demand side.

Agency for Productivity (CORFO), part of the Chilean Ministry of Economy, launched a subsidy mechanism for the acquisition of electrolyzers with a minimum capacity of 10 MW, which benefited six selected project developers (CORFO, 2021).

Apart from these incentives, some measures have been taken to stimulate the market. In particular, in 2023, CORFO issued a request for information that aimed to identify the companies interested in manufacturing and/or assembling electrolyzers and their components in Chile, to understand the conditions that they would require, and understand how different existing and potential future public instruments might or might not increase the interest and accelerate decisions (CORFO, 2023). While the deadline for submitting this information passed in June 2023, nine companies – including six foreign – expressed interest in entering the Chilean market (InvestChile, 2023). In the future, CORFO may call for a Request for Proposal (RFP) process, in which the previously suggested initiatives in the RFI stage[47] must be specified in greater detail (CORFO, 2023).

In addition, regulatory and legal frameworks that considers hydrogen as an energy carrier and revises safety guidelines for their inclusion in existing regulations have been initiated together with guidelines facilitating H_2 project development in Chile (SEC, 2021), leading to collaboration between all relevant institutions such as the ministries of energy, environment, economy, mining, finances, education, and health (ibid). The government also supported international collaboration with potential hydrogen importing nations through organizing international hydrogen conferences such as Hyvolution Chile of 2023 and H2 Summit Chile of 2023.

Apart from this, in 2023, the Ministry of Energy elaborated the National Hydrogen Action Plan (Chilean Ministry of Energy, 2024b). It is based on the nationwide public participation occurences and aims to update Chile’s 2020 National Hydrogen Strategy, specifically to define and prioritize initiatives and measures for the years 2023 to 2030 (ibid). The plan focuses on achieving the development of the country’s targeted renewable hydrogen market and is at the stage of public consultation (ibid). In parallel to this, the ministry also convened a Strategic Committee of 10 national experts from different economic sectors to define strategic guidelines for the materialization of Chile’s national hydrogen strategy (Chilean Ministry of Energy, 2023a). The outcome of their work was published openly and is seen as an important input for the National Hydrogen Action Plan (ibid).

Despite all these important initiatives, though, there is still a lot that could and should be done to further stimulate the build-up and development of Chile’s domestic hydrogen production and its subsequent use. For instance, the Chilean Energy Ministry should address the challenges of increases in grid transmission costs and transmission bottlenecks in several grid zones of the country that result from the limited grid capacity in some areas and regions (Chilean Hydrogen Association, 2022). Solving this is key to ensuring economically attractive and internationally competitive costs of one-grid renewable H_2 generation, as the overall cost of green hydrogen is mostly defined by the cost of electrical power[48].

This issue is also related to a more general one of the necessities to develop infrastructure for the use of locally-produced hydrogen. In fact, enabling infrastructure for power-to-X projects is very CAPEX-intensive. Building pipelines, water desalination plants and storage and transport facilities carry high capital risks and require certain coordination not just between project developers but also between the private and public sectors. Therefore, public institutions need detailed information about required capacities and project locations from project developers, among others, to be able to design good-fitting support mechanisms (for example, land concessions that may facilitate the use of a common, shared infrastructure to decrease investment risks). That is why, even with the government being supportive overall for domestic initiatives on hydrogen use, an efficient system of communication needs to be built between all the stakeholders.

[47] RFI stands for ‘request for information’ and is a preliminary document used by companies that do not understand the marketplace they are about to enter (Cobalt, 2023).
[48] Approximately 60 per cent of the levelised cost of hydrogen (LCOH) in Chile (Chilean Hydrogen Association, 2020).

At the same time, with this system in place, there will still be a definite need for specific incentives to stimulate local off-takers to use local renewable hydrogen instead of other conventional alternatives such as grey hydrogen, ammonia, or simply hydrocarbons such as natural gas, diesel or petrol. These incentives in various forms (such as tax exemptions for companies using local renewable H_2 in their industrial processes or transport, or obligations for public entities to apply certain amounts of green hydrogen to de-fossilise their operations[49]) should ultimately create stable demand for Chilean clean hydrogen. This demand, in turn, is key for the power-to-X business model and therefore is a necessity for all the memoranda of understanding to be transformed into final investment decisions.

In fact, some of these and other measures were preliminary outlined in the National Hydrogen Action Plan, which broadly defines eight action lines on supporting the development of the national hydrogen economy (Chilean Ministry of Energy, 2024b). These lines include: (i) market promotion measures; (ii) infrastructure development; (iii) information and education; (iv) permits; (v) sustainability in industries; (vi) geographical deployment; (vii) the development of human capital; and (viii) international positioning (ibid). Under these action lines, over 70 specific measures and initiatives were defined, and 30 prioritized together with the allocation of responsibilities among the key respective ministries (ibid). Some of these prioritised measures include the promotion of the development and local demand for SAF[50]; the creation of a fund for tax credits attributable to the first category tax for investments with a high multiplier effect, including the 'green' dimension; the development of a strategic proposal for a sustainability certification system for hydrogen, ammonia and synthetic fuels to meet target markets' requirements; the identification and implementation of measures to promote hydrogen and derivatives in the mining industry; the development of strategic port infrastructure masterplans for logistics and for public use; the integration of green hydrogen and derivatives' industry requirements into public infrastructure planning; and the promotion of regulations for seawater desalination (ibid).

4.3 Key constraints and opportunities for Chile's domestic hydrogen use: What is preventing it from happening?

The potential surplus of renewable energy, which exceeds by far current local demand, together with generally favourable market conditions and investment climate offer Chile a chance to become an important H_2 player not only in South America but also on the global stage. This has been recognized by the government and other public institutions as an important 'window of opportunity' (Chilean Ministry of Energy, 2022). In this connection, many initiatives such as those mentioned above have been realised, and over 60 power-to-X projects have been launched across the whole country since 2020 (Chilean Ministry of Energy, 2022). While most of the real projects still remain at the very initial development stages, export-oriented undertakings have the highest chances to be successfully accomplished. This is so because the overall target of the defined public measures is to turn Chile into an export economy of sustainably produced renewable hydrogen for import markets in Asia and Europe through developing a new economic sector with local value creation and participation by avoiding the kinds of social conflicts related to huge infrastructure projects seen in previous decades (Chilean Ministry of Energy, 2022).

On the other hand, as mentioned before, though being crucial to Chile's hydrogen strategy, the export of renewable hydrogen is not the only driver behind the national H_2 initiatives. As mentioned, renewable hydrogen is also expected to contribute to the country's decarbonization and by 2050 reaching carbon neutrality[51]. At the same time, taking full advantage of the existing 'window of opportunity' in a timely manner so that Chile's competitiveness is ensured while the economy is decarbonized is currently facing a number of challenges and constraints. A primary concern is the

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[49] In this context, the public mining company CODELCO as well as oil company ENAP can play an important role.

[50] This should be done in coordination with the National Agency for Sustainable Energy (ASE) and the Civil Aeronautics Board (JAC) to promote energy sustainability in aviation within the framework of the „Clean Flight Program' (Programa Vuelo Limpio), through the promotion and implementation of an own SAF Roadmap (Chilean Minister of Energy, 2024).

[51] This has been formalized in several strategic national planning instruments such as the long-term energy policy PELP; NDC; Climate Strategy.

lack or absence of a proper and aligned coordination of public and private actors working on specific projects in the most promising regions where the first hydrogen hubs are expected to be developed (Antofagasta and Magallanes) (LSBT, 2022). This coordination should be to smoothen, for example, issues relating to land use and territorial regulations (LSBT, 2022).

In addition, despite the relatively early initiation of clean hydrogen projects, critical infrastructure that is critical to develop Chile's clean H_2 projects is missing. As a result, in many cases, securing the required components for the wind parks that would then be generating renewable power for green hydrogen in such regions as Magallanes becomes challenging (LBST, 2022). Similarly, port infrastructure – that is supposed to not only provide the projects with required materials and equipment but also secure the national export of clean hydrogen and derivatives – is currently unable to match the required capacities (Cortés, 2023).

Here, part of the problem is the long duration of the permitting process that is supposed to enable the building of infrastructure – but is in fact postponing its commissioning in many cases, while other factors relate to more global challenges (Oxford Analytica, 2023). In particular, some of the most significant global constraints relate to the pervasive gaps in competitiveness between the 'green' products and 'business-as-usual' solutions, resulting in difficulties for securing long-term off-take agreements for the intended production quantities –the key aspect for a project developer to de-risk the business model. This is followed by other, closely related constraints, such as challenges in obtaining project finance, technical and logistical hurdles, uncertain willingness to pay for the final product (green hydrogen), unclearly defined sustainability criteria for the imported product by the importing countries, and the lack of a globally harmonised or mutually recognised product certification scheme to facilitate the global trade of hydrogen and derivatives (LBST & Hinicio, 2022).

Apart from this, it also appears to be a substantial challenge to ensure proper dissemination of information and knowledge about the potential benefits and impacts of a renewable hydrogen market. In a country whose society has been confronted with large infrastructure projects from the mining industry that have significant social, economic, and environmental impacts, an early integration of different communities across all the territories in the decision-making processes seems to be crucial. The optimal use of this leverage may determine the ultimate success of not only individual H_2 projects but also of the national hydrogen strategy in general. Having started its renewable hydrogen related activities as a frontrunner in South America, Chile has now also arrived as a first player at a decisive inflection point, where market's progress depends on the concrete materialization of the several crucial stimulation measures.

5. Summary, or key findings and other considerations

As seen, the four biggest economies of South America have significant potential for the build-up of their own clean hydrogen industries. Although, according to the strategic national documents of all these nations, the to-be-developed clean H_2 sectors are expected to serve primarily as a tool aimed to generate budget revenues through export to the world's biggest anticipated consumers of clean hydrogen such as Japan, South Korea or the EU, each of these countries recognises the important role that this new fuel could play in helping their own economies to reach net-zero carbon targets by mid-century. On the other hand, with diverse natural endowments and unique industrial specifics, Brazil, Argentina, Colombia, and Chile appear to have different perspectives on the creation of their national clean hydrogen sectors as well as the areas where locally-sourced clean H_2 could be applied.

In particular, while possessing significantly underused hydropower potential that could be further exploited for the power-to-X projects where alkaline electrolyzers[52] could be used for large-scale projects, Brazil is expecting most of its clean hydrogen to come from renewables[53] (Gomes et al,

[52] Representing the most mature electrolyzer technology, alkaline electrolyzers are currently the cheapest and most powerful ones (from 150 to 200 MW in capacity) and therefore could be used for the largest-scale power-to-X projects (Patonia and Poudineh, 2022). However, this type of electrolyzer is not particularly suitable for being coupled with intermittent renewables (such as wind or solar PV), as it prefers stable load (ibid).

[53] Environmenal permitting has been a key barrier to the development of additional hydropower plants

2021). At the same time, having significant hydrocarbon deposits and suitable conditions for the development of CCS initiatives, the country is not betting on blue hydrogen due to high gas prices and a lack of available of onshore gas, as most of the associated gas offshore is reinjected in the pre-salt fields to boost oil production (ibid). This position is similar to those of Argentina and Colombia which are also considering the development of both renewable and hydrocarbons-derived clean types of H_2 is very different from the position taken by Chile, whose immensely under-utilised wind and solar energy poetentical are driving the national hydrogen sector solely towards green H_2 and its derivatives (Secretaria Especial de Assuntos Estratégicos, 2023, Ministerio de Energía, 2021, and Chilean Ministry of Energy, 2020).

Similarly, while clean hydrogen sourced in these nations could be used in each of the five hard-to-abate sectors listed in this paper, the likelihood for its direct use in the foreseeable future varies across these industries and from country to country, especially given the lack of sound, long-term incentives for the key potential off-takers (Table 6). In particular, in the current conditions, Brazil has the highest potential demand for clean H_2 in its steel and fertilizer sectors, if hydrogen prices reach $1-1.5 /kg. Argentina, in turn, may do too and add oil refining to this set of industries, as it expects to become an aspiring producer of sustainable hydrogen-derived fuels for aviation and maritime transport. Similarly, being advantageously located close to the Panama Canal, Colombia may become a centre for the manufacturing of decarbonized bunker fuels while also trying to convert its abundant – but obsolete – intercity bus fleet from combustion engines to fuel cells, and significantly augment its use in the fertilizer and steel industries. Having a clear focus on the exploitation of its rich renewable energy potential, Chile, in turn, will most likely focus on the synthesis of chemicals used for the mining sector (ammonium nitrate for explosives), and the utilization of power-to-X track for the long-term and seasonal storage of electrical power, as well as building up its fuel cell-powered fleet of long-distance and heavy-duty vehicles used, among others, in the afore-mentioned mining industry.

- **Clean hydrogen is likely to be in competition with other decarbonization options, many of which may be easier and cheaper to apply**

Although the preferences and specific focus of each of these nations appears to be well-grounded and in consideration of their national and industry specifics, given current economic conditions, decarbonization trends and socio-political developments, the fate of many undertakings associated with the conversion of industrial processes, transportation, and energy storage from fossil fuels to locally-sourced clean H_2 may be less colourful than expected. In particular, there are several challenges and barriers hampering or inhibiting the direct use of domestically-generated clean hydrogen in all four countries. The first major barrier is the availability of other less complex decarbonization alternatives that could potentially be further explored. For instance, even though Brazil could utilise green hydrogen for long-term and seasonal energy storage, the further building up of its renewable potential may seem to be a more reasonable and cheaper solution, despite the challenges in obtaining environmental licenses and the fact that most of the remaining potential is located in the Amazonia. This is because, with a lower seasonal variability of output than wind and solar PV, hydropower plants generate relatively stable power loads that usually do not need energy storage applications as desperately as intermittent renewables (as is the case in Chile where *surplus* power output often has to be curtailed) (Assad and Rosen, 2021). In fact, when landscape elevations allow, countries may also use their water resources as a means of energy storage through applying pumped hydroelectric technologies (International Hydropower Association, 2023).

Table 6. Key characteristics of the main hard-to-abate sectors in Brazil, Argentina, Colombia, and Chile, their main stimuli and challenges for conversion to domestically-sourced clean hydrogen

Key characteristics	Country	Key sectors for domestic application of hydrogen					
		Hydrocarbon processing		Nitrogen fertilizers and components	Steelmaking	Energy and power sector	Transport
		Key refining products	Key (petro) chemicals				
Main targeted products and niches	**BRA**	• Petrol • Diesel • Kerosene • Fuel oil • Liquefied petroleum gas • Naphtha • Residual fuel oil • Bitumen, etc.	• Methanol • Olefins • Formaldehyde	• Ammonia • Urea • Ammonium nitrate • Ammonium sulphate • Calcium ammonium nitrate	• Semi-finished steel • Flat products • Long products • Specialty steel products (incl. stainless steel) • HBI and green pellets	• Hydrogen and derivatives for long-term and seasonal energy storage	• Long-distance vehicles • Heavy-duty vehicles/ mining trucks • Intercity buses
	ARG		• Methanol • SAF • HVO • IFO				
	COL		• Methanol • Olefins • Formaldehyde				
	CHL		• Ammonium nitrate[47] • Hydrogen peroxide • Methanol • SAF		• Flat products • Long products		
Main current feedstock/ energy source for the application of hydrogen	**BRA**	Oil	Oil and natural gas	Natural gas	Coal	Renewables (hydropower)	Petrol, diesel, ethanol
	ARG				Natural gas	Renewables (hydropower, wind & solar)	Petrol and diesel
	COL				Electricity		
	CHL			N/A for sodium nitrate & natural gas	Coal	Renewables (wind & solar)	
Expected H_2 'colour' for decarbonization	**BRA**	Primarily green but also blue					
	ARG	Both blue and green					
	COL						
	CHL	Green					
Main potential stimuli for conversion to clean H_2	**BRA**	• Utilization of domestic renewable energy/ green H_2 potential		• Reduction of imported fertilizers	• Introduction of carbon tax (CBAM) to imported steel in Europe	• Utilization of domestic renewable energy (surplus power)/ green H_2 potential	• Large distances between main cities
	ARG		• Global decarbonization of aviation	• Development of domestic fertilizer production/ reduction of imports of fertilizers	• Substitution of natural gas for decarbonization in DRI		
	COL		• Global decarbonization of maritime sector		• Utilization of domestic renewable energy/ green H_2 potential		• Old land transport fleet • Lack of railroad connection
	CHL	• Reduction of imports of natural gas				• Limited electricity transmission capacity • Utilization of domestic renewable energy (surplus power)/ green H_2 potential	• Utilization of domestic renewable energy/ green H_2 potential • Strong need for heavy-duty vehicles in mining
Current strength of the stimuli for conversion to clean H_2	**BRA**	*	*	**	**	*	**
	ARG	*	***	**	**	*	**
	COL	*	**	***	*	*	***
	CHL	**	**	**	**	***	***
Main challenges for conversion to domestically-sourced H_2	**BRA**	• Lack of regulatory and policy incentives/ high cost of clean H_2		• Cheap imported fertilizers	• High cost of clean hydrogen • Competition with cheap Chinese steel	• Abundant hydropower resources with limited need for storage	• Lack of incentives • Lack of infrastructure • Large territory • Large fleet
	ARG	• Lack of explicit carbon pricing mechanisms and existing explicit subsidies • No clear global incentives for decarbonization of refining and (petro)chemical sector		• Cheap imported fertilizers • Lack of incentives/ high cost of clean H_2	• No incentive to move from cheap natural gas	• Power generation mostly with stable load (fossil fuels and hydropower)	
	COL				• No incentive to move from cheap coal to more expensive clean H_2		• Insufficient financing
	CHL	• Cheap imports of oil and oil products		• Cheap imported natural gas • Cheap imported fertilizers • Lack of incentives	• Higher cost of green H_2 compared to alternatives	• Lack of infrastructure • High infrastructure/ investment costs	

Source: Adapted from Wisniak and Garces (2001), Secretaría de Energía (2016), República Argentina (2017), Trade Administration (2018), Chilean Ministry of Energy (2019), Chilean Ministry of Energy (2021), IEA (2021), Ministerio de Energía (2021), Ecopetrol (2022), Federal Government of Brazil (2022), Fraunhofer Chile (2022), GIZ (2022), CAF (2023), Chilean Ministry ofEnergy (2023a, 2023b), EPBR (2023), IEA (2023), Sumitomo Corporation (2023), Secretaría de Asuntos Estratégicos (2023), Transporte Moderno (2023), Caratori (2024), Chilean Ministry of Energy (2024a, 2024b, 2024c), and Secretaría de Energía (2024).

[54] Chile primarily produces sodium nitrate, a natural mineral, as a source of nitrogen fertilizer (Wisniak and Garces, 2001). The production of sodium nitrate does not typically involve the use of natural gas as a feedstock (ibid). Instead, sodium nitrate is mined directly from deposits in the Atacama Desert and processed for use as a fertilizer (ibid). In contrast to other countries, ammonium nitrate is then generated to manufacture explosives for the mining sector.

- **Adjusting existing production facilities and infrastructure to the use of clean hydrogen is likely to be challenging from a techno-economic perspective**

In many cases, the techno-economic burden associated with the adjustment of the key pieces of equipment and machinery will also most likely put the odds on the side of other alternative options (such as CCS). In these circumstances, even if replacing natural gas (or any other currently used conventional fuel or feedstock) with hydrogen may potentially be addressed from the technical point, the construction of new facilities tailored specifically for the use of clean hydrogen may ultimately become cheaper if the use of clean H_2 is a must. That is why focusing on the areas that are currently significantly covered by imports and therefore would require the build-up of domestic production facilities to substitute such foreign product may make more sense than converting the existing production facilities currently running on fossil fuels. This, for instance, could apply to the production of fertilizers and chemicals in all the listed South American countries, as the existing local fertilizer producers are incapable of covering domestic demand on their own. On the other hand, such industries with large capacities and broad international presence as, say, Brazil's steelmaking sector will most likely have no other choice except to adjust their operations to the new fuel.

- **At the moment, there is no clear market signal incentivising industries to start using clean hydrogen**

This adjustment to clean hydrogen, however, is unlikely to happen if the market does not send a clear signal. In fact, introducing a new and more expensive fuel into the existing production process in such circumstances of information asymmetry – when it is unclear whether customers will actually pay the 'green premium' – will most likely be perceived as very risky and therefore will not happen very fast. This seems at least in part the rationale behind ArcelorMittal's refusal to set a specific deadline for their initial plan to replace coal-fired blast furnaces in Bremen, Germany with a green hydrogen-powered DRI plant and electric arc furnaces, despite the company's pledges to significantly reduce their emissions and having secured EU funds of over €1.6 billion to build the decarbonization infrastructure (Hydrogen Insight, 2024a). Instead, having claimed that green hydrogen would be 'too expensive to use', and which would result in more expensive products, the company is currently considering importing DRI from other countries where green H_2 production would be cheaper (ibid).

- **Industries using clean hydrogen to manufacture low-carbon products for export may have a higher chance of being converted to the use of locally sourced clean hydrogen**

In these circumstances, industries that are oriented primarily to the manufacturing of export products may have a higher chance of being converted to locally-sourced clean hydrogen than the ones without aspirations to export. This will be so if the importing markets are under higher environmental bars that could not be met without converting to clean hydrogen. In this respect, as mentioned, the European CBAM could potentially stimulate the Brazilian steelmaking industry, whereas setting universally-applied clean decarbonization standards for maritime and aviation fuels could give impetus to refineries in Argentina and Colombia.

- **Lack of domestic policy support will hamper the conversion to clean hydrogen**

While the introduction of carbon taxes or the application of tools like CBAM could instigate South America's hard-to-abate businesses to start converting to clean hydrogen, the lack of efficient policy support within the respective countries may also be a reason why this conversion to domestically-produced clean H_2 may not take place as fast as might be expected. Here, the case of ExxonMobil threatening to scrap what would be the world's largest blue hydrogen project at the Baytown refinery in Texas, on the grounds it may not qualify for the proper tax credit, is one of the most telling (Hydrogen Insight, 2024b). In South America's circumstances when governments continue to subsidise oil and gas companies to do 'business as usual' without providing any clear and feasible incentives to generate clean H_2 and its derivatives, getting an external signal from potential far away markets to ramp-up the generation of clean fuels may not suffice to spur such initiatives, as the local production facilities may not be scalable to that extent. Without these proper support mechanisms, the overall costs of conversion or the introduction of the clean hydrogen segment into operations is likely to be an unbearable burden (Table 7).

Table 7: Current share of key hard-to-abate sectors in hydrogen demand and total current and expected domestic hydrogen demand in Brazil, Argentina, Colombia, and Chile

<table>
<tr><th rowspan="3">Key characteristics</th><th rowspan="3">Country</th><th rowspan="3">Reference year</th><th colspan="6">Key sectors for domestic use of hydrogen</th></tr>
<tr><th colspan="2">Hydrocarbon processing</th><th rowspan="2">Nitrogen fertilizers and components</th><th rowspan="2">Steelmaking</th><th rowspan="2">Energy and power sector</th><th rowspan="2">Transport</th></tr>
<tr><th>Key refining products</th><th>Key chemicals/ petrochemicals</th></tr>
<tr><td rowspan="4">Current share in hydrogen demand (%)</td><td>BRA</td><td rowspan="4">2023</td><td>83</td><td>N/A</td><td>17</td><td colspan="3">N/A</td></tr>
<tr><td>ARG</td><td>27</td><td>49</td><td>33</td><td>16</td><td colspan="2">N/A</td></tr>
<tr><td>COL</td><td>87</td><td>N/A</td><td>12</td><td>87</td><td>N/A</td><td>12</td></tr>
<tr><td>CHL</td><td>21</td><td>79</td><td colspan="4">N/A</td></tr>
<tr><td rowspan="8">Domestic hydrogen demand (ktpa)</td><td rowspan="2">BRA</td><td>2023</td><td colspan="2">420</td><td>130</td><td colspan="3">N/A</td></tr>
<tr><td>2050</td><td colspan="2">600</td><td>~1,000</td><td>2,040-2,390</td><td>N/A</td><td>TBD[55]</td></tr>
<tr><td rowspan="2">ARG</td><td>2023</td><td>110</td><td>100</td><td>130</td><td>60</td><td colspan="2">N/A</td></tr>
<tr><td>2050</td><td colspan="3">TBD</td><td>190</td><td colspan="2">TBD</td></tr>
<tr><td rowspan="2">COL[56]</td><td>2023</td><td colspan="2">130</td><td>18</td><td colspan="3">N/A</td></tr>
<tr><td>2050</td><td colspan="2">629</td><td>37</td><td>1,184</td><td>629</td><td>37</td></tr>
<tr><td rowspan="2">CHL</td><td>2023</td><td colspan="2">250</td><td>TBD</td><td colspan="3">N/A</td></tr>
<tr><td>2050</td><td colspan="6">TBD</td></tr>
</table>

Source: Adapted from Chilean Ministry of Energy (2019), Chilean Ministry of Energy (2021), IEA (2021), Ministerio de Energía (2021), Ecopetrol (2022), Federal Government of Brazil (2022), Fraunhofer Chile (2022), GIZ (2022), Chilean Ministry ofEnergy (2023a, 2023b), EPBR (2023), Sumitomo Corporation (2023), Secretaría de Asuntos Estratégicos (2023), Transporte Moderno (2023), Caratori (2024), Chilean Ministry of Energy (2024a, 2024b, 2024c), and Secretaría de Energía (2024).

- **When converting to clean hydrogen, decision makers should not focus on the LCOH but rather on all the relevant costs associated with the entire value chain**

In fact, approaching the challenge of decarbonizing the hard-to-abate sectors in Brazil, Argentina, Colombia, and Chile via domestically-sourced clean hydrogen only from the perspective of cheap hydrogen generation costs (LCOH) is likely to be misleading. Here, just like in the case of needing to adjust equipment for the replacement of conventional feedstock and fuels with clean H_2, one should also think about the entire value chain, including the infrastructure most likely required to deliver hydrogen from producers to consumers. While this may be less relevant to oil refining, steelmaking or fertilizer production if generating clean hydrogen is integrated into their operating processes, the development of hydrogen storage or transport facilities is likely to be required for using clean H_2 to preserve energy or propel heavy-duty or long-distance transport. For example in the case of Brazil that whose vast territory has not been adequately covered with a potentially convertible natural gas infrastructure, the construction of new storage sites and pipelines, as well as the conversion of millions of existing consumers, will most likely require large financial inputs.

- **Apart from techno-economic factors, social acceptance is likely to play an important role in the success of converting hard-to-abate sectors to clean hydrogen**

Finally, even if these efforts are applied and the required infrastructure is created, there will still be a risk of social discontent and public opposition to such projects. In fact, the first cases of protests against renewable power initiatives designed to spur the regional development of the clean hydrogen sector have already been noted in La Guajira, Colombia and Antofagasta, Chile (Renewables Now,

[55] All 'TBD' stand for cases when no public information is available.

[56] According to the Colombian Hydrogen Roadmap, the total domestic demand is estimated to reach 1,850 ktpa by 2050 (with 629 ktpa to be for the industrial sector only). In the industrial sector, the hydrogen demand is expected to be distributed evenly between the fertilizer, mining and steel sectors, while refining would remain the subsector with the highest demand (Ministerio de Energía, 2021).

2023 and Coalition for Human Rights in Development, 2024). While these instances may not prevent investors from finalizing the projects, in the absence of any clear domestic demand for clean H_2 nor any binding regulations forcing industries to use it, most clean hydrogen initiatives in South America meant to stimulate the consumption of this locally-sourced decarbonised fuel are likely to remain in their early development stages for a very long time. This is so also because the lucrative prospects of supplying locally-sourced clean H_2 to far away markets willing to pay more for the 'green premium' will most likely outweigh the risks and difficulties associated with its domestic use. At the moment, however, these markets are still yet to be created.

Conclusion

South America's four biggest economies envelop a diverse group of national industrial sectors that generate significant volumes of carbon emissions. While some of these industries could potentially be electrified, others appear to be the areas in which the carbon dioxide emissions are hard to eliminate. In this connection, just like in many other countries with substantial potential for the development of renewables-based as well as SMR and CCS-derived clean hydrogen, Brazil, Argentina, Colombia, and Chile are also the nations where clean H_2 could be applied domestically to reduce emissions of their hard-to-abate sectors.

This paper focused on the five areas, which are generally expected to be some as the 'lowest hanging fruits' for the direct application of clean blue and green hydrogen. These industries – oil refining and (petro)chemicals, the production of fertilizers, steelmaking, energy and power generation, and land transport – are generally not only the greatest contributors to carbon emissions worldwide, but also pose major challenges to these countries' efforts to achieve their net-zero pledges by mid-century. To a different extent in each of the four countries, these sectors also appear to be some of the main contributors to the national budgets and therefore their decarbonization rather than their overall deindustrialization would align with their national climate objectives while continuing to generate budget revenues and secure the welfare for the population at large.

Brazil, being the largest economy on the continent, has the greatest potential in decarbonizing its steelmaking and fertilizer production, while the incentives and techno-economic stimuli for the conversion of its oil refining, power generation, and land transport sectors to clean H_2 could still be viewed as pretty weak. At the same time, in case the price for nitrogen fertilizer imports will remain low and no carbon tax mechanisms are introduced for the target export markets for the country's steel products, the internal urge for the ramp-up of the Brazilian clean fertilizer and steel sectors is unlikely to be strong enough to force them to transition to clean hydrogen. These external nudges are, however, closely related to the global decarbonization trends and therefore cannot be controlled from within the country.

Having comparable natural endowment and potential for the development of both green and blue H_2, Argentina, the second largest economy on the continent, may also try to convert the same sectors to clean hydrogen while also exploring its potential for the manufacturing of sustainable fuels for the aviation and maritime sectors. On the other hand, with no clear incentives for the domestic off-takers of clean hydrogen and ongoing subsidies for conventional hydrocarbons, this conversion is unlikely to happen very soon. In addition to that, lack of external stimuli and the ongoing economic crisis are further delaying the start of any transition in Argentina.

With a developed oil and gas sector but still dependent on the imports of fertilizers, Colombia, in turn, could potentially follow the same path as Argentina and ramp up the domestic production of sustainable fuels as nitrogen fertilizers. In addition, with obsolete long-distance buses and a limited railroad network, the country is exploring taking advantage of the locally-sourced clean hydrogen with reference to long-distance and heavy-duty vehicles. These initiatives are, however, mostly in the early development stages, as is the case in the remaining three countries, and indeed most other nations around the globe.

When it comes to Chile, it appears to be the only country in this group concentrating solely on the development of green hydrogen. This is partially why clean H_2 is expected to play an important role there as a means of storing renewable power, which at the moment is massively underutilised. In addition, similarly to Colombia, long-distance and heavy-duty fuel cell land transport is expected to substitute combustion engine-powered vehicles for intercity trips and mining. Finally, green hydrogen could potentially be used for the build-up of the national decarbonised oil refining, steelmaking and fertilizer production – the sectors that are currently significantly dependent on imports.

While the four analyzed countries differ in their approach towards the overall development of their national clean hydrogen sectors as well as the specific industries that should become the first off-takers of this locally-sourced clean fuel and feedstock, the challenges for the introduction of clean H_2 into each of the five analyzed hard-to-abate sectors appear to be similar. They, for instance, relate to the higher LCOH in comparison with other low-carbon alternatives or conventional fuels and feedstock currently in use by the listed industries. This, in the absence of sound supportive policies and regulations that would help the national off-takers maintain their competitive advantage after the conversion, is likely to make the use of domestically-sourced clean H_2 pretty unpopular.

In this context, some of these industries that may potentially cater for external, export markets may also be stimulated from the outside if a clear signal, supported with binding standards or restrictions forcing the use of clean hydrogen, are applied. This, for instance, could be the introduction of CBAM by the EU, which will cover imported steel products. Such stimuli are, however, yet to be created and their presence may also not necessarily guarantee a fast adjustment of the existing sectors to the new export requirements. In fact, in some cases, it may also be cheaper to build new facilities specifically tailored for the use of clean hydrogen rather than to adjust the existing plants running on fossil fuels to the new decarbonised fuel. In addition, the costs related to the construction of new infrastructure and the repurposing of old infrastructure for H_2 storage and transport may further discourage the transition. The adoption of auctions to buy hydrogen for local demand, with government guaranteeing the difference in price between clean H_2 and alternative fuels, similar to mechanisms being implemented in Europe, could spur projects dedicated to industrial clusters.

Overall, as seen from the examples of South America's four biggest economies, decarbonizing hard-to-abate sectors through the use of domestically-sourced clean hydrogen is likely to be a very complex and challenging undertaking. This means that the 'low hanging fruits' may, in reality, not be hanging that low, since, without proper incentives and well-functioning supportive policies for the off-takers, the creation of H_2 export vector will most likely overshadow the importance and necessity for domestic application of this fuel. If this happens, these fruits may not be harvested at all.

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