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The decarbonization of gas in the Southern Cone of South America

GAS

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Executive Summary

Following the conclusion of 26th Conference of the Parties (COP26) to the United Nations Framework Convention on Climate Change (UNFCCC) in November 2021, countries around the globe continue to increase the ambition for measures to mitigate climate change, including reducing reliance on fossil fuels. Natural gas plays an important role in the supply of energy to the Southern Cone of South America, both from indigenous resources and from imports of LNG and pipeline gas. With increasing focus on decarbonisation as well as diversifying to indigenous resources, Argentina, Brazil and Chile have been increasing their use of renewable energy, notably wind and solar. For many years, South American countries have been looking for viable ways to develop decarbonized gas such as biomethane, biogas and, more recently, hydrogen. Against that background, this paper examines the nationally determined contributions of Argentina, Brazil and Chile, and the prospects for decarbonisation of gas in those countries.

The energy industry in the three countries is dominated by Brazil which accounts for around 75% of total primary energy consumption. Similarly, Brazil also accounts for the lions's share of CO2 emissions with 415 million tonnes out of a total of 664 million tonnes per year (2020 data). Natural gas has a very significant share of 50 per cent of primary energy consumption in Argentina, but only 12 per cent in Brazil and 14 per cent in Chile. Out of the 3 countries, Chile is the only one so far to have proposed achieving GHG neutrality by 2050. Brazil's nationally determined contribution (NDC) is compatible with a long term objective of reaching climate neutrality by 2060, whereas Argentina has not yet made commitments beyond 2030.

Taking each of the 3 countries in turn, Argentina has a very well established natural gas business, but its vast infrastructure is at risk of becoming stranded in the context of the energy transition. In 2019, gas represented 37 per cent of Argentina's total final consumption and 59 per cent of energy for power generation. 85 per cent of consumption was supplied from local production while 15 per cent came from imports (pipeline from Bolivia or LNG). As of 2021, there are 19 biogas plants producing electricity with a total capacity of 52 MW connected to the power grid. A recent update assesses the country's biogas potential as 416 ktoe per year, or around 2.1 per cent of final energy consumption of natural gas. In order to realise this potential, however, several barriers would need to be overcome. These include regulations or quotas to promote biogas projects, tax compensation and finance mechanisms. For hydrogen, Argentina's domestic demand (2017) was around 330 kt/year, of which roughly 92% was used in the petrochemical/refining sector. The most significant green hydrogen project i Argentina is the Hychico pilot plant in operation since 2009 producing around 100 tonnes per year. In 2020 the Argentine government launched a process for the development of a 'National Hydrogen Strategy Towards 2030', and several related initiatives are being developed. Argentina has high wind and solar capacity factors (50 per cent and 30 per cent respectively), but the need to access funding for highly capital intensive green hydrogen projects may hinder development.

In Brazil natural gas accounted for around 12 per cent of primary energy supply, but the state's Energy Planning Company (EPE) envisages that natural gas supply could grow by 45 per cent between 2019 and 2030. In 2020, consumption of natural gas was 26.3 bcm of which power generation accounted for 36 per cent. Since Brazil is one of the largest agricultural producers in the world, it has great potential for biogas and biomethane. According to the Brazilian Association of Biogas, Brazil has the potential to produce around 43 bcm per year of biogas, equivalent to 26 Bcm per year of biomethane: roughly equal to the total natural gas consumption in 2020. Actual biogas

production in 2020, however, was just 1.82 bcm, less than 5% of the potential. This is produced in 638 mainly small plants, with a further 37 due to be commissioned in 2021, adding 0.4 bcm per year. Several barriers hinder the growth of biogas and biomethane production, including lack of financial attractiveness, absence of a structured market, gaps in regulation and the need to adapt infrastructure.

For hydrogen in Brazil, current production is estimated at 400 kt per year, eith oil refining accounting for 83 per cent of demand. This is grey hydrogen produced by steam reforming of methane with the CO2 emitted to the atmosphere. Brazil does not yet have a strategy for the promotion of low carbon or renewable hydrogen, but it is seen, for example by Germany, to have great potential as a green hydrogen exporter on account of its competitive renewable energy production. Brazil already has several significant hydrogen projects under development including a GW scale project aiming to produce at least 600,000 tonnes per year of green hydrogen and one aiming to produce green ammonia from hydrogen. While most Brazilian projects are focussed on green hydrogen, the country also has the potential for carbon capture and storage and hence production of blue hydrogen. With considerable interest in hydrogen in Brazil, it is still necessary to introduce new regulations and incentives for large scale production to be realised.

In 2019, Chile consumed 6.5 Bcm of natural gas, with 1.5 Bcm of domestic production and the rest supplied by LNG and seasonal pipeline imports from Argentina. Despite rapid growth in recent year, the share of wind and solar in Chile’s energy mix is still modest at about 3 per cent of primary energy supply. Biofuels and waste are more significant at around 17 per cent. As Chile is a net energy importer, further development of renewable energy is a key component of the country’s security of supply strategy, and a legal and regulatory framework supports further renewables development. According to the counry’s Energy Commission, biogas potential is 1.72 Bcm per year (roughly 1 Bcm of biomethane equivalent). Actual production in 2020 from 38 plants totalled just 0.17 Bcm per year, equivalent to 0.09 Bcm of biomethane. Only one plant produces biomethane with the majority using biogas for power generation and / or heat. There are several barriers to implementation of further projects, including lack of financial incentives, and the small plants making it uneconomic to upgrade biogas to biomethane.

Chile currently produces around 200 kt per year for refining and a glass manufacturing plant. Most is grey hydrogen from natural gas, but the glass plant uses electrolysers to produce hydrogen. By 2030, with excellent wind and solar resources, Chile aims to achieve 70 per cent of power generation from renewable energy. In 2020 Chile unveiled its Green Hydrogen Strategy aiming for 5 GW of electrolyser capacity by 2025 and 25GW by 2030, initially for decarbonising domestic hydrogen use before starting green hydrogen exports after 2030. Chile has over 40 green hydrogen projects under development, with the largest planning to produce at MW scale by 2024 before expanding to GW scale thereafter. The national strategy aims for 300 GW capacity producting 24 million tonnes per year of hydrogen by 2050, although it assesses the potential to be at least five times that level, aiming to be one of the lowest cost producers worldwide. To reach this objective, Chile would need to attract investment totalling around US$ 300 million. Chile also faces several barriers for the development of green hydrogen including water availability in some areas, the need to construct new hydrogen transportation infrastructure, and the distance from key markets, particularly in Europe.

Looking at the region overall, there is significant potential for biogas and biomethane in Argentina and Brazil, but less so in Chile. In order to realise that potential, particularly for biomethane further incentives and regulations will be required. For hydrogen, while PV seems to be the most competitive source for green hydrogen, levelised costs of green hydrogen remain at least double the cost of hydrogen from natural gas without CCUS. Although the three countries are pursuing decarbonised gas projects, initial planning is still in progress and there is a lack of sufficient coordination between government and policy makers to drive the development. Particularly for hydrogen, large scale developments are likely to be beyond the current NDC horizon of 2030, but putting a clear transition pathway in place soon will increase the likelihood of achieving the significant potential for decarbonised gases in the Southern Cone.

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1. Introduction

A paradigm shift is due to take place in the energy sources that will underpin the world economy. Many countries have pledged to reduce global greenhouse gases (GHG) emissions based on the commitments made prior to the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC). To this end, countries that are parties to the Paris Agreement have been adopting measures to decarbonize their economies, by reducing the intensity of GHG emissions, in particular in the energy sector.

The agreements reached at COP26 in November 2021 are expected to accelerate the requirement for mitigation actions at different levels and regions across the globe. To be aligned with the Paris Agreement, those actions are likely to be progressively more ambitious with the aim of achieving global carbon neutrality by 2050. However, most likely and for the first time in the protracted and arduous process of constructing an international climate regime, the emerging regulations may be surpassed as a driver of transformational momentum by the radical changes occurring in the cost structure of investments and the availability of low carbon intensity technologies. Further, companies' long-term perceptions of the convenience and necessity of adopting low carbon business models and green investment development pathways will reinforce the pattern of change and provide incentives to decarbonize.

This need for radical innovation and the race by large economies to capture the major share of global markets by providing the key products and technologies required for the transition poses key challenges. In the Latin American and Caribbean region and, in particular, the Southern Cone., these challenges, as well as the constraints, are complicating decisions on their long-term low carbon pathways.

South America is endowed with vast energy resources and natural gas plays an important role in the supply of energy to the region. A few countries in the Southern Cone area[1] such as Argentina, Brazil and Chile, also meet part of their demand needs with imported liquefied natural gas (LNG) and/or pipeline gas. In line with the objectives of diversifying to indigenous sources, reduce GHG emissions and advance the Paris Agenda towards net-zero emissions, there has been a push to increase the use of renewable sources in those countries, mainly solar and wind. In 2019 the installed capacity of wind energy more than doubled in Argentina year-on-year (albeit from a small base) whilst solar grew 19.6 per cent and 23.9 per cent in Brazil and Chile respectively.

For many years, South American countries have been looking for viable ways to develop decarbonized gas such as biomethane, biogas and, more recently, hydrogen. This paper will analyze the efforts by Argentina, Brazil and Chile to decarbonize gas to reduce emissions, including some significant projects already being developed and in operation. It will also assess the initiatives, timing and challenges, and describe the bottlenecks – including costs, infrastructure, financing and regulatory issues - impacting on the development of projects and the more widespread use of biogas, biomethane and hydrogen in these economies. Finally, the possibility of creating a regional market for decarbonized gas is investigated. This analysis is reflected and summarized in Appendix I.

According to studies from the Brazilian Association of Biogas, the potential production of biogas from solid waste, treated sewage and agro-industrial waste in Brazil is equivalent to 44 Bcm/year[2] (26 Bcm equivalent of biomethane), which is roughly the same as the volume of natural gas marketed in the country in 2020.[3] In Brazil alone, 69 new biogas plants were commissioned in 2020. In Chile, there are estimates that the potential for biogas converted to power could account for four per cent of the country's installed capacity.

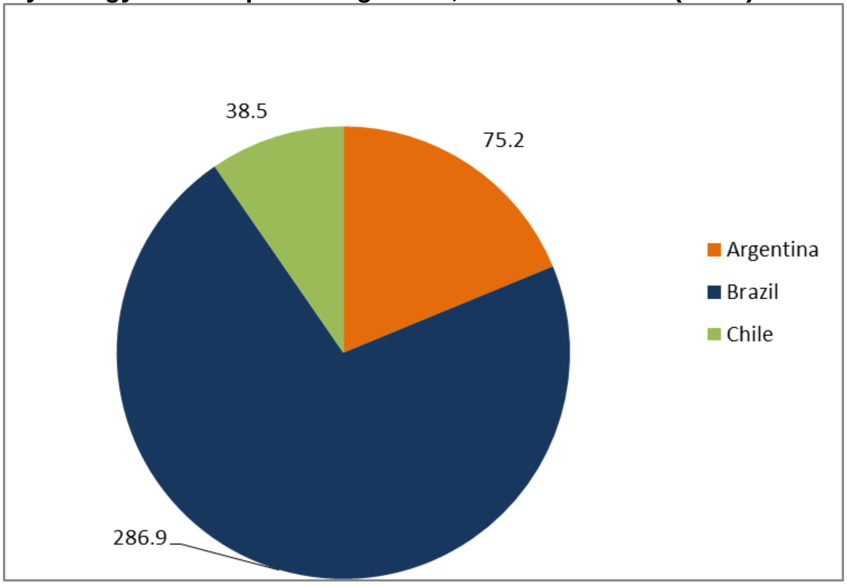
[1] The Southern Cone includes the countries of Brazil, Chile, Argentina, Paraguay, Peru and Uruguay. This paper will focus only on three key countries: Argentina, Chile and Brazil.
[2] Estimated 60% methane content
[3] (MME Brazil, 2021)

In 2020 the government of Chile published its National Strategy for Green Hydrogen,[4] which estimates a market value of US$23 billion for green hydrogen, based on domestic market uses and exports. In Argentina, legislation enacted in 2016 (Law 27,191/2016[5]) established that 20 per cent of domestic electricity demand should be provided by renewable sources by 2025.In Brazil, the government is already working on a strategic plan for green hydrogen.

2. Energy supply and demand - countries nationally determined contributions (NDCs)

Combined primary energy consumption in Argentina, Brazil and Chile (401 mtoe) accounts for only three per cent of world consumption (2020 data). Brazil's consumption is 2.4 times the combined consumption of Chile and Argentina, as shown in Figure 1.

Figure 1: Primary energy consumption: Argentina, Brazil and Chile (mtoe) - 2020



Source: (BP, 2021)

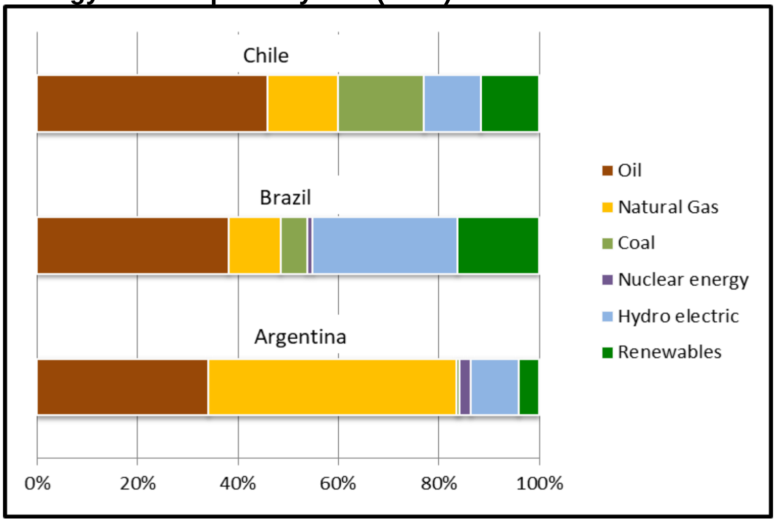
Oil consumption is dominant in Brazil and Chile and less significant in Argentina, where natural gas accounts for more than 52 per cent of the country's primary energy consumption (Figure 2). Renewable energy, which encompasses hydro, solar, wind and biofuels, plays an important role in Brazil, whereas in Chile, coal is more relevant than renewables and natural gas. Except for Argentina, natural gas infrastructure is very limited. All three countries import natural gas via pipeline and LNG terminals. Chile produces small volumes of natural gas in the far south and imports LNG via the Quintero and Mejillones terminals and pipeline gas from Argentina, mostly in the summer months. Brazil and Argentina's individual gross domestic gas production exceeds 100 MMm^3/day but in the case of Brazil only 50 per cent of this volume reaches the market, with large volumes of associated gas being reinjected, due to infrastructure bottlenecks and lack of firm gas demand. In Argentina the key constraints to developing the large, unconventional Vaca Muerta gas resources are macroeconomic and fiscal imbalances, pricing policies and lack of pipeline transmission capacity. Brazil imports pipeline gas from Bolivia[6] and LNG via five terminals. Argentina imports pipeline gas from Bolivia, and LNG via two LNG terminals.

[4] (Ministerio de Energia - Chile, 2020)

[5] http://servicios.infoleg.gob.ar/infolegInternet/anexos/250000-254999/253626/norma.htm

[6] A pipeline connects Argentina to a power plant in Southern Brazil, but it has been on-off for more than a decade

Figure 2: Primary energy consumption by fuel (2020)



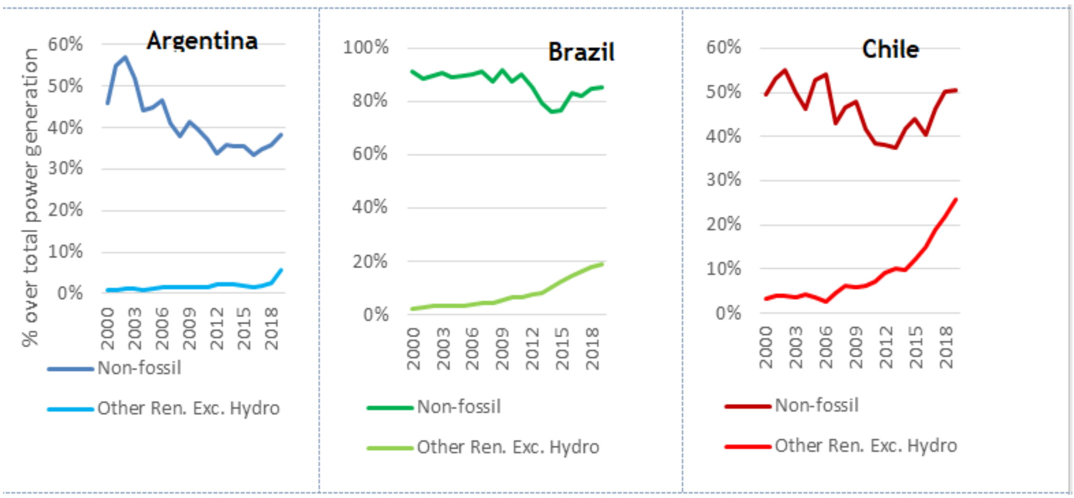
Source: (BP, 2021). Renewables include biofuels

In 2020 the combined carbon dioxide (CO_2) emissions of Argentina, Brazil and Chile reached 664.7 MMt[7] (down 6.2% from 2019), accounting for only 2.1 per cent of the world's emissions. Brazil was the largest emitter, with 415.2 $MtCO_2$ (1.3% of the total), followed by Argentina with 161.8 Mt (0.5%) and Chile, with 87.7 Mt (0.3%). In 2020, Argentina's GHG emissions were estimated at 334-343 $MtCO_2e$, with Brazil at 973-982 $MtCO_2e$, and Chile at 93-103 $MtCO_2e$.[8]

Over the last 10 years the use of solar, wind and biomass in power generation has increased steeply in Brazil and Chile and more slowly in Argentina.

The three countries have participated in the negotiations towards the adoption of the 2015 Paris Agreement; Argentina and Brazil signed and ratified it in 2016, Chile signed in 2016 and ratified it in 2017. Argentina submitted its second NDC in December 2020. Brazil also updated its NDC in December 2020, while Chile updated the submission of its First NDC in April 2020.[9]

Figure 3: Growth of non-fossil[10] and renewable electricity generation in Argentina, Brazil and Chile



Source: BP Statistical Review 2020

[7] BP Statistical Review 2021
[8] https://climateactiontracker.org/countries/, 2021
[9] https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx
[10] Non-fossil power generation includes nuclear, large hydro and other renewables such as wind, solar, biomass, biogas and small hydro

2.1 Argentina's NDC

In 2016 Argentina presented an amendment to its first NDC setting an unconditional absolute emissions target not to exceed 483 $MtCO_2e$ by 2030 (109 $MtCO_2e$ below the business as usual scenario) and additional reductions of 114 $MtCO_2e$ conditional on financial support and technology transfer, thus reaching an absolute emissions target of 369 $MtCO_2e$ if support with implementation is provided. These reductions would be attained through the implementation of undisclosed policies and measures in the energy, AFOLU (agriculture, forestation, and other land use), transport, industry, waste, and infrastructure sectors.

In 2019 the Ministry of Environment and Sustainable Development of Argentina issued an administrative order (Resolución 447/2019)[11] establishing sectoral plans supporting the implementation of the NDC, including specific plans for energy, transport, agriculture, industry, health, infrastructure and forestry, with individual measures for each of these sectors.

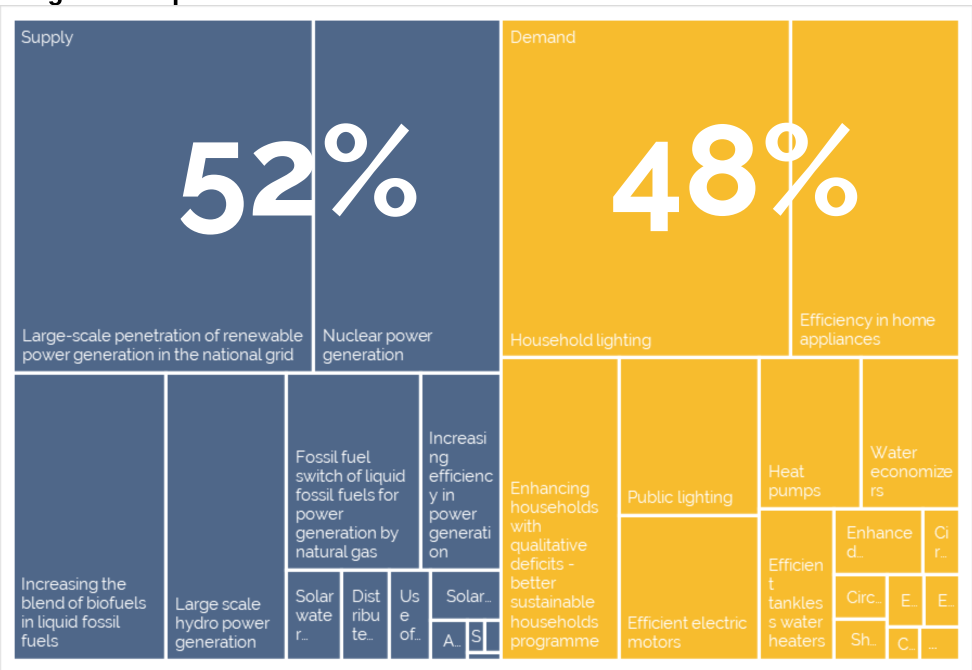
Regarding energy, 39 mitigation actions were analyzed, contained in National Sectoral and Climate Change Action Plans:

- National Energy and Climate Change Action Plan [2019],
- National Infrastructure and Climate Change Action Plan [2018]
- National Industry and Climate Change Action Plan [2018]

Only energy-related actions were evaluated for the infrastructure and industry action plans. These 39 mitigation actions account for 103.2 $MtCO_2e$ of unconditional emission reductions and 23.02 $MtCO_2e$ of emission reductions conditional to technology, financing and capacity-building, associated with the energy sector, both in supply and demand, totaling a maximum potential of 126.22 $MtCO_2e$ in 2030.

Figure 4 shows the main measures in the energy sector contained in those action plans, as well as the emissions saving and the relative share of each one. The total of the unconditional targets is just below 110 $MtCO_2e$ by 2030.

Figure 4: Argentina - summary of energy related measures disclosed in the sectoral and climate change action plans



Source: Deep decarbonization Latin America Project, review of proposed mitigation actions. FTDT/Decarboost, 2020

[11] All Sectoral plans: https://www.boletinoficial.gob.ar/detalleAviso/primera/222018/20191127

Further, Argentina submitted its second NDC to UNFCCC in December 2020, which sets an absolute, economy-wide and unconditional goal of limiting GHG emissions to 359 $MtCO_2e$ by 2030, (an increase of 33% compared to 1990). This second NDC represents an improvement in its ambition regarding mitigation in comparison with the first NDC, with an unconditional target set at a level below the previous NDC's conditional target. Argentina's second NDC covers emissions from all sectors and covers CO_2, CH_4 (methane), N_2O (nitrous oxide), HFCs (hydrofluorocarbons) and PFCs (perfluorochemicals). The NDC also states that the long-term strategy (LTS[12]) that will be presented at COP26 in Glasgow will include the goal of carbon neutrality by 2050.

As of mid-2021, the Argentine government is further elaborating new sectoral plans supporting this target. Both the submitted document and official public statements[13] related to 2030 include, in the case of energy, references to the expanded share of renewable energy (wind, solar PV, bioenergy), as well as the development of nuclear energy and other vectors such as hydrogen (not present in previous NDCs). In transport the NDC text refers to an increased use of natural gas, biofuels, electrification and hydrogen, as well as energy efficiency and modal shifts.

2.2 Brazil's NDC

In its Intended NDC to the UNFCCC in 2015 Brazil committed, and ratified in 2016, to reduce GHG emissions by 37 per cent by 2025 and 43 per cent by 2030, compared to the country's net emissions levels in 2005. In December 2020, the Brazilian government presented an update of this NDC through a document called 'New first NDC of the Brazil'.

This submission included the indicative objective of reducing the country's net GHG emissions to zero by 2060. In addition, the reduction targets (37% by 2025 and 43% by 2030) established in 2015 were confirmed. However, a change was applied in the basis for calculating the level of Brazil's net emissions in the reference year (2005), which caused an increase in the absolute values of Brazilian emissions. Table 1 below compares the emission reduction values proposed by the iNDC of 2015 and the new first NDC of 2020, in billions of equivalent tons of carbon dioxide ($GtCO_2e$).

Table 1: Brazil - comparative emissions reduction proposal (2015-2020)

Brazil GEE emissions reductions ($GtCO_2e$)	2005 base	2025 target	2030 target
iNDC (2015)	2.1	1.3	1.2
New 1° NDC (2020)	2.8	1.8	1.6
%	100%	-37%	-43%

Source: Instituto Clima e Sociedade (ICS), 2021[14]

The framework for Brazil's 2030 GHG emissions includes the following mitigation measures:

a) Energy: reach 45 per cent of renewable energies in the primary energy matrix, including raising the share of wind, biomass and solar energy.

b) Agriculture: adopting as the main strategy for the development of sustainable agriculture, the strengthening of the low carbon emission agriculture program (ABC), including the restoration of over 15 million hectares of degraded pastures and the expansion of 5 million hectares of integrated crop-livestock-forestry integration (ICLFS), both by 2030.

c) Industry: promote new clean technology standards and further improve energy efficiency measures and low carbon infrastructure.

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[12] In accordance with Article 4, paragraph 19, of the Paris Agreement, all parties should strive to formulate and communicate long-term low greenhouse gas emission development strategies

[13] https://www.vidasilvestre.org.ar/?21761/La-Cumbre-de-Lideres-ofrece-al-mundo-una-nueva-oportunidad-de-cumplir-las-metas-climaticas

[14] https://59de6b5d-88bf-463a-bc1c-d07bfd5afa7e.filesusr.com/ugd/d19c5c_9bc29d5e06a14fd0af3d38c042ac0cb7.pdf

d) Transport: establish new efficiency measures and improve transport and public transport infrastructure in urban areas.

e) Change in the use of land and forests, including:

- strengthen and enforce the implementation of the Forest Code at federal, state, and municipal levels;
- consolidate policies and measures aiming at achieving zero illegal deforestation in the Brazilian Amazon by 2030 and offsetting GHG emissions from legal vegetation clearing by 2030;
- promote the restoration and reforestation of 12 million hectares of forest by 2030 for multiple purposes;
- Improve sustainable native forest management systems, through georeferencing and tracking systems applicable to the management of native forests, aiming to curb illegal and unsustainable practices.

2.3 Chile's NDC

The National Energy Policy 2050 was adopted in 2015,[15] following public consultation. Energy legislation encourages investment in generating capacity across the electricity sector, in particular in solar and wind projects

Chile has pledged to reach GHG neutrality by 2050, in line with its 2020 NDC and the draft Climate Change Framework Law under discussion in the National Congress at the time of the writing (September 2021). The updated 2020 NDC also includes a new unconditional target and links the 2030 targets to the 2050 carbon neutrality goal. Chile's commitments to mitigate emissions, excluding the Land Use, Land Use Change and Forestry (LULUCF) sector are summarized below:[16]

- Goal 1: Chile commits to a GHG emissions budget not exceeding 1,100 $MtCO_2e$ between 2020 and 2030, with a GHG emissions maximum (peak) by 2025, and a GHG emissions level of 95 $MtCO_2e$ by 2030.[17] Chile recognizes that Article 6 of the Paris Agreement is a mechanism for countries to implement mitigation actions in a cost-effective manner and to advance in the implementation of new technologies in collaboration with other parties, through internationally transferred mitigation outcomes (ITMOs).
- Goal 2: reduce total black carbon emissions by at least 25 per cent by 2030, with respect to 2016 levels. This commitment will be implemented primarily through national policies focused on air quality.

Chile's unconditional NDC target is 95 $MtCO_2e$ by 2030, peaking by 2025, to be achieved with the full implementation of its planned policies, including the shutdown of all coal power plants and the implementation of a transportation electrification strategy. The previous NDC committed to 30 per cent emissions reduction by 2030 (when compared to a 2007 initial pathway) which could increase to 45 per cent if financial and technological conditions were to be met.

Chile will heavily rely on negative emissions by forests to reach its net-zero targets, expecting carbon sinks to contribute as much as 50 per cent of the emissions reductions required to reach the 2050 neutrality goal. Subject to international monetary resources contributions, the country is committed to reducing its CO_2 emission per unit of GDP by 2030 until it reaches a reduction of 35 to 45 per cent in relation to 2007 levels, subject to future economic growth that makes it possible to implement the appropriate measures to fulfil this commitment.

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[15] (Ministerio de Energia Chile, 2015)
[16] (Gobierno de Chile, 2020)
[17] Compared to the 2015 NDC, which committed to annual absolute emission levels of about 123 $MtCO_2e$ by 2030 (equivalent to the unconditional intensity target of 30% reduction by 2030 of the c/r 2007 indicator)

Chile commits to the sustainable management and recovery of 200,000 hectares of native forests, representing GHG captures of around 0.9 to 1.2 $MtCO_2eq$ annually by 2030. This commitment is subject to the approval of the law on the recovery of native forests and forest promotion. Chile has also committed to reforesting 200,000 hectares, of which 100,000 are native species, by 2030. This commitment is subject to the extension of the Decree Law 701[18] and the approval of a new Forest Promotion Law.

In 2019, 37 per cent of electricity was generated from coal, but Chile pledged to shut down half of its coal fired power plants by 2024 (2.5 GW) and the other 2.5 GW by 2040. By 2050, 94 per cent of electricity is expected to be generated from renewable sources.

2.4 NDCs: Key insights

At the time of writing, of the three countries, Chile was the first to propose achieving GHG neutrality by 2050 in addition to an intermediate target for 2030. Brazil's NDC is compatible with an indicative long-term objective of reaching climate neutrality by 2060, whereas Argentina has not yet made commitments beyond 2030. Both Brazil and Chile's NDCs rely heavily on the use of forests as a carbon sink and on commitments to restore degraded land, pasture and forest. The three countries aim to increase the use of renewable energy to decarbonize the economy but do not have explicit targets for replacing natural gas with decarbonized gas nor for the implementation of CCUS (carbon capture, utilization and storage) programmes for the existing consumption of natural gas. Because each country has different emissions profiles, their NDC mitigation actions focus on different measures:

- Chile: energy uses accounted for 78.0 per cent of total GHG emissions in 2019, of which 32 per cent was from power generation and 23 per cent from transportation. The country has a limited pipeline infrastructure for distribution of decarbonized gas countrywide, therefore the focus is on replacing coal with renewables in power generation, electrifying transportation modals and offsetting the remaining emissions.
- Brazil: agriculture and energy (of which 45% is for transportation) accounted for 49.5 per cent and 34 per cent of total GHG emissions. In Brazil 87 per cent of electricity comes from non-fossil fuel sources. There is an additional amount of 1.0 $GtCO_2e$ of LULUCF emissions caused by deforestation.[19] Therefore, the focus is on reducing deforestation, increasing the use of renewables in power generation and transportation (biofuels).
- Argentina: gross GHG emissions in 2019 were related to energy uses (46%) and agriculture, forest and other land use (AFOLU) (42%), therefore the substitution of alternatives to fossil fuels in power generation and transportation are priority areas to achieve 2030 improved targets.

3. The role of natural gas in the Southern Cone

Although the three countries NDCs do not have specific targets for gases, they all rely on the use of biomass and renewable energy as a means of reaching their goals. Therefore, the use of biomethane, for example, would be supportive of the NDC's goals. The three countries are also developing long-term hydrogen strategies, which might require the conversion of the existing natural gas infrastructure and consumers to decarbonized gases. Regarding long-term energy strategy, the three countries also have an ambition to further develop regional energy trading, which would require the use of the intra-regional pipeline infrastructure, currently connecting Argentina to Chile, Brazil and Bolivia. Therefore, it is important to understand domestic natural gas consumption, exports/imports, and enabling infrastructure, including domestic and inter-region pipelines.

[18] https://www.conaf.cl/cms/editorweb/normativa/DL-701.pdf
[19] http://plataforma.seeg.eco.br/total_emission#

A successful implementation of decarbonized gas strategies in the domestic markets will depend on the availability of pipeline infrastructure in which biomethane or hydrogen could be blended with and/or replace natural gas. Appendix II depicts the infrastructure of transportation pipelines and LNG terminals in the three countries.

As previously mentioned, natural gas plays a very large role in Argentina, accounting for about 50 per cent of primary energy consumption, but a less significant role in Brazil (12%) and Chile, (14%).

In the case of Brazil, there are 47,000 km of pipeline (38,300 km distribution and 9,400 km transportation) serving 3.8 million consumers, representing only 5.3 per cent of the total number of households in the country.[20] Most of Brazil's pipeline infrastructure is concentrated in the coastal areas and larger capital cities. About 95 per cent of Brazil's households use either bottled LPG or wood for cooking. The majority of Brazilian dwellings use electric showers for hot water and there is very little space heating. Brazil has five operating LNG terminals (Pecem, Porto de Sergipe, Bahia, Gas Natural Açu and Guanabara), and three more planned for commissioning by 2025 (Suape, Barcarena and Babitonga). See map in Appendix II.

Chile imports about 75 per cent of its energy requirement, including natural gas and oil. In Chile, there are around one million natural gas consumers, of which residential users representing 20 per cent of the total households in the country.[21] Chile has 11,200 km of pipeline (3,800 km transmission and 7,400 km distribution[22]). It has a peculiar geography, a very long and thin country, with 4,300 km from its northern border with Peru, to the southern tip at Cape Horn. Natural gas is consumed mostly in central and north Chile, which are served by LNG terminals and pipelines from Argentina. There are two LNG importing terminals, Quintero and Mejillones.

In the case of Argentina[23] there are 98,000 km of pipeline (16,000 km for transportation and 82,337 km for distribution) serving nearly nine million consumers, about 65 per cent of Argentine households.[24] Argentina has two LNG import terminals, Escobar and Bahia Blanca; the latter was mothballed in 2018 and reactivated in 2021. It is also connected by pipelines to Chile, Bolivia, Brazil and Uruguay, which could become outlets for potential hydrogen trade. Figure 24 (Appendix II) depicts the key pipeline and LNG infrastructure in the region.

4. Country analysis

4.1 Argentina

4.1.1 Context

Since the discovery of the Loma La Lata field in 1978, and enabled by the development of an extensive infrastructure, natural gas has taken over Argentina's energy mix with a rapid energy transition from 19 to 40 per cent of the total final energy consumption, entering a plateau by the beginning of the 21st century to date, constrained by infrastructure and domestic production bottlenecks.

This availability of natural gas and increased production has enabled a widespread penetration in most provinces and resulted in the gasification of several energy uses. For instance, in 2005 natural gas accounted for more than 22 per cent of total final energy consumption in Argentina's transportation sector (1.48 million vehicles and a consumption of 2,629 Ktoe or 8.7 m^3/d), a share which began to decline after commercial and regulatory constraints associated with domestic shortages.

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[20] https://www.abegas.org.br/estatisticas-de-consumo

[21] https://www.agnchile.cl/wp-content/uploads/2020/12/Presentacio%CC%81n-AGN-Comisio%CC%81n-de-Economi%CC%81a-del-Senado.pdf

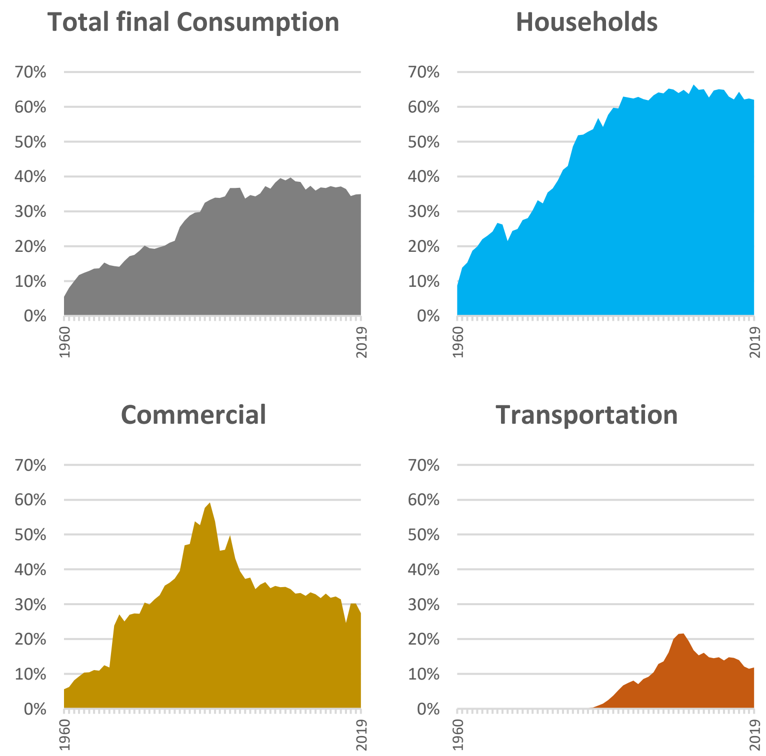
[22] Source: https://energia.gob.cl/sites/default/files/documentos/energy-policies-beyond-iea-countries-chile-2018-review.pdf and information provided by Chile Gas Association

[23] https://www.enargas.gov.ar/secciones/publicaciones/informes-graficos/pdf/GT_IG_10.pdf

[24] https://www.casarosada.gob.ar/informacion/archivo/25366-en-argentina-viven-40117096-habitantes-segun-el-resultado-del-censo

In 2019 natural gas represented 37 per cent of Argentina's total final energy consumption (see Figure 5) and 59 per cent of the energy for power generation (98% of thermal conventional power generation comes from natural gas). In 2019, 85 per cent of Argentina's consumption was supplied from local production, while 15 per cent came from imports (Bolivia and LNG[25]).

Figure 5: Argentina - share of natural gas in total and sector demand, 1960-2019 (% of total)



Source: Authors elaboration based on data from Argentina's National Energy Balance and ENARGAS.

A significant portion of Argentina's vast natural gas treatment, transmission and distribution infrastructure is at risk of becoming stranded in the context of energy transition. Conversely it could, to some extent, leverage the penetration of decarbonized gas, hence the strategic importance of analyzing decarbonized gas alternatives and complements as a means of making use of the existing infrastructure, practices, and regulations.

4.1.2 Biogas and biomethane

Regulatory framework

Argentina has a legal framework that regulates and promotes bioenergy as a renewable energy source. The biofuels Law N° 26,093, passed in 2006,[26] defines specific benefits including mandatory minimum blends for liquids in fossil fuels, such as gasoline and diesel oil. For bioethanol, biodiesel and biogas, which are produced from raw materials from agricultural, agro-industrial or organic waste, the law aims to promote and control the sustainable production and use of biofuels and establishes the requirements and conditions necessary for the authorization of biofuel production and mixing plants. It also lays out the requirements and selection criteria for the submission of projects. This law was modified in 2021 by Law 27,640,[27] extending the biofuels regime to 2030, but reducing mandatory blends for bioethanol and biodiesel.[28]

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[25] National Energy Balance of Argentina 2019. http://datos.minem.gob.ar/dataset/balances-energeticos
[26] http://servicios.infoleg.gob.ar/infolegInternet/anexos/115000-119999/116299/norma.htm
[27] https://www.boletinoficial.gob.ar/detalleAviso/primera/247667/20210804
[28] https://www.crea.org.ar/la-nueva-ley-de-biocombustibles-un-paso-atras-en-materia-ambiental/

In 2006, Law N° 26,190 'Legal Regulations on National Promotion for the Use of Sources of Renewable Energy to Generate Electric Power'[29] was enacted. It declared it was in the public interest to generate electricity r from renewable energy sources. Established sources of renewable energy are non-fossil sources suitable to be used in a sustainable way in the short, medium and long-term: wind energy, solar thermal energy, solar photovoltaic energy, geothermic energy, tidal energy, energy from ocean currents, hydraulic energy, biomass, landfill gas, treatment plant gas, biogas and biofuels.

Law N° 27,191 'Legal Regulations on National Promotion for the Use of Sources of Renewable Energy – Electric Power Generation' (2015[30]) modified this law and created the trust fund for the Development of Renewable Energies (FODER) which promoted incentives and benefits for those who generate energy from renewable sources. Additionally, it set a goal to reach a contribution of renewable energy sources equal to 20 per cent of total national consumption of electric power by the end of 2025.

The RenovAr programme was launched in 2016, with the objective of reaching 10,000 MW of renewable energy capacity by 2025.[31] During its three ('and a half') rounds, RenovAr awarded 96 MW of biogas projects, including 18 MW of landfill biogas.

In 2017, Argentina's National Congress sanctioned Law 27,424[32] for the promotion of distributed renewable power generation connected to the grid, which requires the adherence of each province, given the decentralized nature of Argentina's power distribution regulations. To date, according to the last update from the Ministry of Energy, 4.7 MW have been installed under this framework by 437 users in seven provinces, while 4.1 MW are pending approval.

In 2019, the gas regulator, ENARGAS, approved technical regulation NAG-602[33] regarding natural gas quality which, among other issues, addressed technical gaps regarding the use of biogas and biomethane for isolated gas networks.

The Ministry of Agriculture and the United Nations Food and Agriculture Organization (FAO) developed a program called Probiomasa to encourage energy production with biogas and biomass. This program ended in June 2020 but discussions are ongoing for an extension that would focus primarily on agricultural and agro-industrial waste.

In addition, in 2005 the Argentine Government launched the National Strategy for Integral Municipal Solid Waste Management (ENGIRSU, acronym in Spanish), designed in three phases over the period 2006-2020.[34] This is a comprehensive strategy based on addressing municipal solid waste management, including processing and final disposal.

Within the framework of ENGIRSU, the Ministry of Environment and Sustainable Development (MAyDS) is executing a GEF[35] project in order to develop sustainable business models for the production of biogas from organic municipal solid waste, including the development of pilot projects and the design of a new regulatory framework.

During 2020, MAyDS awarded a consulting contract for technical assistance in the design of proposals for the development of a comprehensive regulatory framework for biogas in Argentina. As of August 2021, the results of this study have not yet been made available.

Available resources

The most recent update of the Balance of Biomass for Energy Purposes in Argentina, published by FAO in 2020, estimates the country's biogas potential as 415.86 ktoe per year,[36] distributed in 15 areas of agriculture and livestock production spread over 23 provinces. Significant concentrations being in

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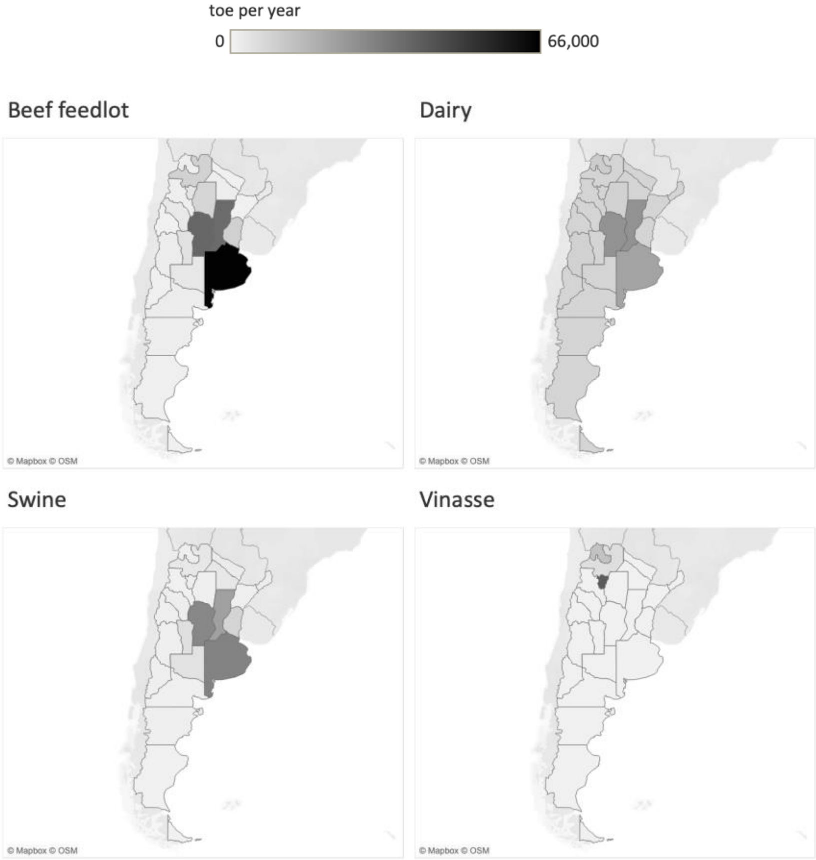
[29] http://servicios.infoleg.gob.ar/infolegInternet/verNorma.do?id=123565
[30] http://servicios.infoleg.gob.ar/infolegInternet/anexos/250000-254999/253626/norma.htm
[31] https://portalweb.cammesa.com/pages/renovar.aspx
[32] http://servicios.infoleg.gob.ar/infolegInternet/anexos/305000-309999/305179/texact.htm
[33] https://www.enargas.gob.ar/secciones/normativa/normas-tecnicas-items.php?grupo=6
[34] https://www.argentina.gob.ar/ambiente/control/estrategia-nacional
[35] Green Environmental Facility
[36] FAO 2020 a

Buenos Aires, Santa Fe, Córdoba and Entre Ríos Provinces, totalling 356.97 ktoe per year, as well as a potential of 58.89 ktoe per year from vinasse (a byproduct of the sugar industry[37]).

Based on FAO's figures, biogas potential is equivalent to roughly 2.1 per cent of Argentina's final energy consumption of natural gas in 2019 (19,460 ktoe), according to the country's National Energy Balance.[38] FAO studies include resources such as beef feedlots, dairy, swine and vinasse, but exclude the biogas potential from municipal and industrial waste, which should be assessed separately. A 2020 study has quantified a much larger potential, ranging from 3.9 to 14.4 Bcm/year, where 14.4 includes sequential crops, and 3.9s limited to waste such as agricultural residues, livestock effluents and agro-industrial by-products.

Figure 6: Argentina - regional distribution of biogas resources by source (FAO)



Source: Authors' adaptation of FAO 2020a.

Several examples of biogas applications can also be found in the waste sector. For instance, during RenovAr Round 2, three landfill biogas projects were awarded with a 13.12 MW capacity.

Biogas for power generation

The FAO's survey of bio digesters published in 2019 based on data from 61 plants in 16 provinces surveyed in 2015, showed that only four per cent were installed for energy purposes, resulting in sub-utilization of the energy (and non-energy) output (FAO 2019 a).

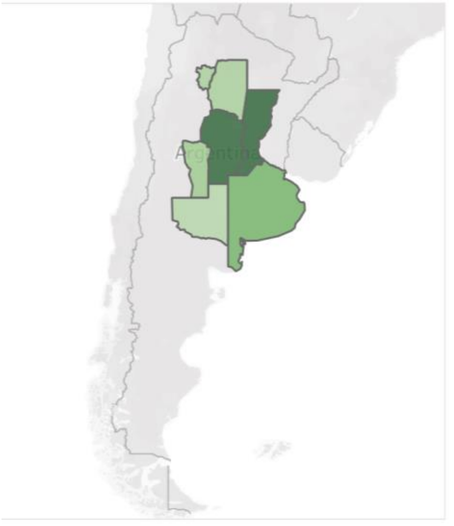
As of 2021, there are 19 biogas plants producing electricity and interconnected to the power grid, totalling 51.8 MW. The current installed capacity of biogas-fired power generation in Argentina, by region, province and entry date into the interconnected system is detailed in Appendix III.

[37] FAO 2020 a

[38] National Energy Balance of Argentina 2019. http://datos.minem.gob.ar/dataset/balances-energeticos

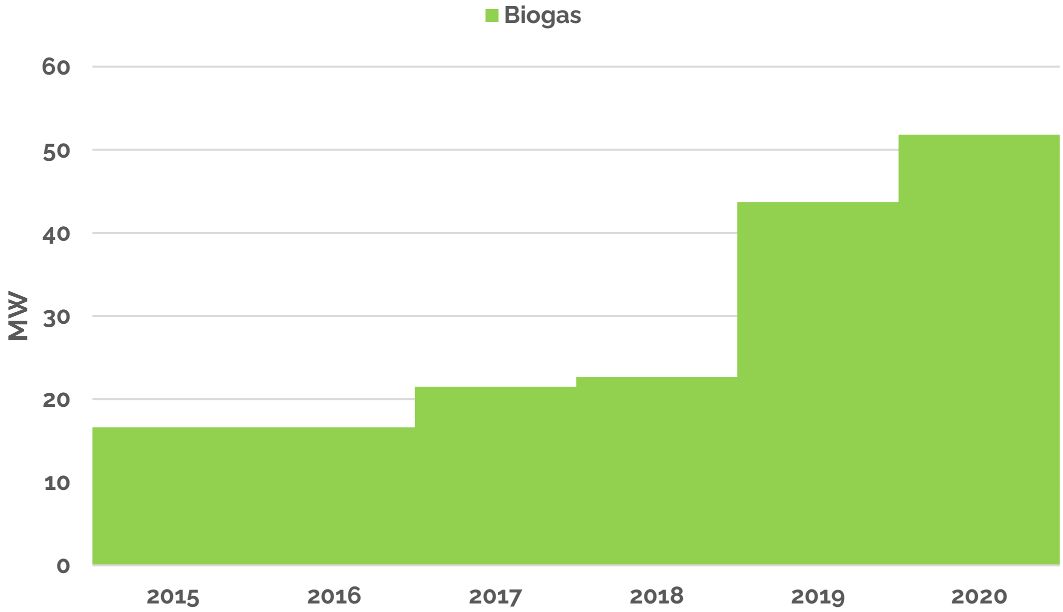
Table 2: Biogas projects awarded under RenovAR programme

Region	Province	Capacity (MW)	# of Projects
Bs As	Buenos Aires	9.82	7
Centro	Córdoba	21.42	13
	San Luis	4.00	4
Comahue	La Pampa	2.00	1
Litoral	Santa Fe	21.61	10
NOA	Santiago del Estero	3.00	1
	Tucumán	3.00	1



Source: Authors' elaboration based on Argentina's Secretariat of Energy.

Figure 7: Installed capacity from bioenergy sources, September 2020)



Source: Authors adaptation of data from CAMMESA

Argentina's ISO (independent system operator, CAMMESA) publishes a quarterly list of planned new start-ups. There are 23 plants totalling 51.96 MW planned over the period 2021-2022. Appendix III shows the expected new entries for the period 2020-2022, as well as several new power plants which have not yet determined their expected connection date. There is still uncertainty regarding the ability of these companies to completely finance these intended projects due to the economic conditions faced by the country.[39]

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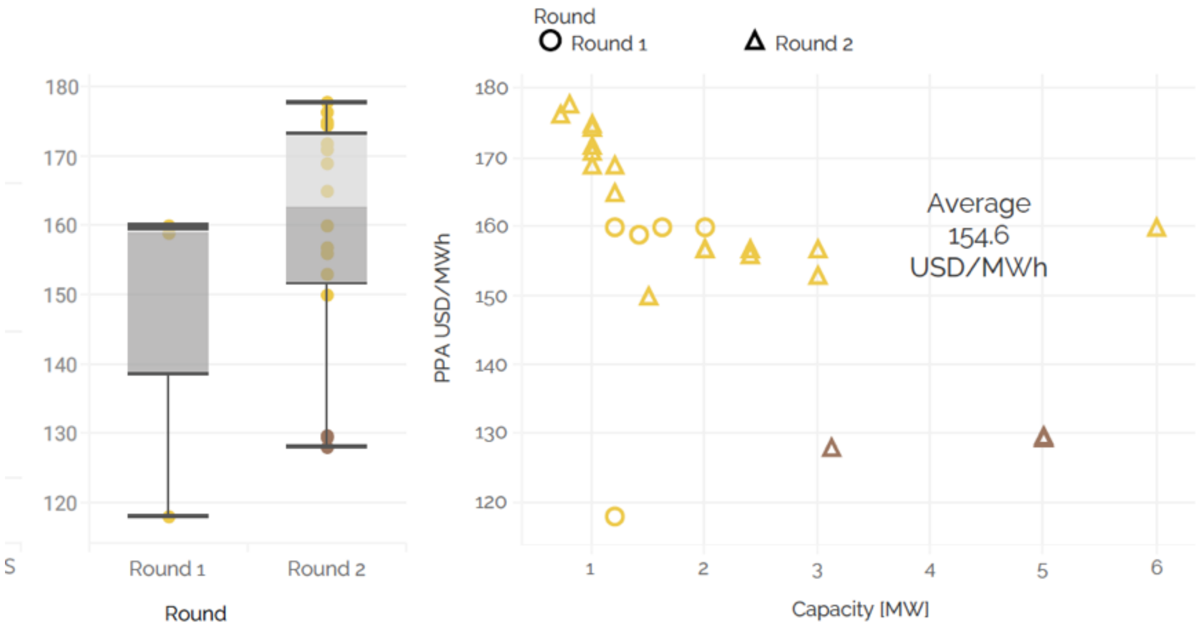
[39] (Samaniego, 2021)

Renewable power auctions held during 2016 and 2017 reached an average price of US$154.6/MWh for biogas-based power generation projects, vs. a weighted average of US$54.72/MWh for the renewable power generation projects awarded during RenovAr's three rounds and an average system cost of US$62.8/MWh during the last three years (2018-2020).

The following figure shows the distribution of biogas power generation power purchase agreements (PPA) prices by round and capacity.

Figure 8: Argentina - most recent auction prices for Biogas PPAs (2017-2018).



Source: Authors' adaptation of Argentina's Secretariat of Energy figures

Even after these increases in the total installed capacity, bioenergy-based capacity still shows only a modest share of 0.5 per cent of Argentina's total capacity mix in 2020. While biomass capacity grew 41 per cent during the period between 2015 and 2021 (7.1% compound annual growth rate (CAGR)), biogas capacity (previously nearly non-existent in Argentina), increased more than two-fold in the context of these auctions.

Biogas and Biomethane: thermal and mobility applications

In 2020, FAO published a technical report prepared by the Centre of Studies on Energy Regulation of Universidad de Buenos Aires (CEARE) analysing the feasibility of using biomethane in the main natural gas grid, the use of biogas and biomethane for isolated networks, and the substitution and blending of biomethane in transport and other CNG and LNG applications (FAO 2020 b).

In the case of transportation, Bio-LNG costs are considerably higher than CNG, whilst the cost of biogas from waste is roughly competitive with traditional liquid fuels, as shown in Table 3.

Table 3: Comparison of theoretical Bio-LNG process to alternative fuel prices for transportation, 2019

	Bio-LNG		Gasoline	Diesel Oil	CNG
US$/MMBtu	(a)[40]	(b)[41]			
Petrol motor (Otto)	17.36	24.90	17.34		7.84
Diesel oil motor (Diesel)	15.29	22.83		15.77	

Source: Authors adaption from FAO 2020 b

FAO and CEARE compared theoretical biogas and biomethane costs with piped and bottled LPG, as used by roughly 30 per cent of the households in Argentina. As a result, while biogas proved to be competitive for those areas with an existing distribution infrastructure, the associated network infrastructure costs challenged its ability to compete. When compared to natural gas (not available in those areas), biomethane prices would be from 4 to 5.6 times the price of natural gas at the time of the analysis (2019).

Table 4: Comparison of theoretical Bio-LNG process to alternative fuel prices for household consumption, 2019

	Biogas		Biomethane		Network LPG	Bottled LPG	Natural gas
US$/MMBtu	(c)[42]	(d)[43]	(e)[44]	(f)[45]			
Existing network	11.26	18.80			13.99	16.5	4.67
With new network	20.93	28.47	18.28	25.82		16.5	

Source: Authors adaptation from FAO 2020 b

As of July 2021, a regional natural gas sub-distributor, BAGSA (Buenos Aires Gas SA) is testing the use of biogas and biomethane (upgraded biogas) for isolated networks in the province.[46]

Biogas: key factors and barriers

The recent report by the Digital Global Biogas Cooperation (DiBiCoo 2020) identified key factors and recommended a set of actions to support the development of the biogas market in Argentina:

- Biomethane law - promotion and regulation with a mandatory quota for cutting natural gas and bottled gas sold in Argentina (mandatory for large users and cargo and passenger vehicles). Currently, some drafts proposed by CADER, the Argentine Chamber of Renewable Energy, and other entities are under discussion.
- Optimization of financing mechanisms based on the experience gained.
- Improvement of tax compensation mechanisms also based on the experience acquired by producers.
- Expansion of quotas for biomass and biogas projects and new bidding rounds for the power sector PPAs.
- Optimization of mechanisms for receiving biomass and biogas projects.

[40] (a) Biogas from waste, converted to biomethane and liquefied
[41] (b) Biogas from maize silage, converted to biomethane and liquefied
[42] (c) Biogas from waste, compressed, with and without new network capex
[43] (d) Biogas from maize silage, compressed, with and without new network capex
[44] (e) Biogas from waste, converted to biomethane, with and without new network capex
[45] (d) Biogas from maize silage, converted to biomethane, with and without new network capex
[46] https://www.citecus.com/el-biogas-y-su-aporte-para-el-desarrollo-comunitario/

- Definition of incentives for the development of thermal exploitation (biogas and dry biomass in industrial and residential heat generation), and promotion of technology transfer for the take-off of the sector.

Additionally, the current regulations set by ENARGAS through the NAG rulings should be enhanced to include the certification and validation of equipment for use in isolated natural gas networks, where biogas can be used as fuel without enhancing its quality to main grid conditions (FAO 2019 c). While specific regulation is still to be defined regarding commercial and physical issues related to the entry of biomethane into the natural gas transmission grid, such as the definition of specific point of entry to the transport system (PIST - acronym in Spanish).

4.1.3 Hydrogen

Legal framework

In 2006 Argentina set a legal framework that regulates and aims to promote the production and use of hydrogen, but in practice this initiative has remained inactive since its sanction.

Law 26,123, enacted in 2006, established the development, production and use of Hydrogen as a national interest. This law also created a specific fund for the promotion of Hydrogen, as well as fiscal incentives and a National Hydrogen Plan. However, this law has never regulated in detail, and is set to expire by the end of 2021.

A new bill has been introduced to Argentina's National Senate and is currently under discussion, promoted by research institutions, academia, NGOs and industry stakeholders.

The new proposed bill law complements the existing elements in Law 26,123, adding an emphasis towards renewable energy sources, and extends the benefits of the current regime for 20 years after its entry into force.

Additionally, several provinces, such as Río Negro, Chubut and Tierra del Fuego, have begun to discuss local regulations in order to promote the development of Hydrogen production and consumption.

Consumption and Resources

As of 2017, Argentina's domestic demand for hydrogen was 327.7 Kt/year, of which roughly 92 per cent was used in the petrochemical sector, while the chemical sector represented 7.8 per cent of demand, followed by food (0.1%), pulp and paper (0.06%) and power generation (0.03%). Most of Argentina's hydrogen consumption (97.7%) is self-produced by industrial users, with few volume transactions between companies (2%). According to the International Energy Agency (IEA), the demand in 2019 rose to 400 Kton/year.[47]

[47] (IEA (b), 2021)

Table 5: Hydrogen consumption by sector in Argentina (2017)

Sector	Subsector	Ton/year	% over total
Power generation		92	0.03%
Industry	Petrochemical	301,408	91.98%
	Chemical	25,590	7.81%
	Food	327	0.10%
	Pulp and paper	194	0.06%
	Automotive	68	0.02%
	Steel	9	0.00%
	Other metals	7	0.00%
	Total	327,695	100%

Source: Y-TEC[48] - Launch presentation of the Consortium for the development of a hydrogen economy in Argentina.

Resources

The diversity and availability of Argentina's natural resources for the production of hydrogen, including renewable resources, installed nuclear capacity and natural gas reserves, may provide it with competitive advantages in terms of flexibility to compete in global markets. See Table 6.

Table 6: Current installed power capacity and estimated resources, 2019

Resource	Installed Capacity [a][49]	Generation (12 months)[a]	Capacity factor (12 months)[a]	Overall gross potential [b][50]
	MW	MW Average	%	GW Average
Solar PV	760	188	29.9%	1,873
Wind	3,092	1,200	47.8%	1,387
Hydro	11,344	3,323		40
Nuclear	1,755	1,022	58.3%	
Natural gas	Reserves (P1)[51]	Production[c]	Reserves-to-production ratio[c]	
	BCM	BCM/year	Years	
	376.61	43.62	8.63	

Sources: CAMMESA, Secretariat of Energy and Paredes, 2017 (IDB)

Notes:

- Capacity factor differs from the ratio of generation to installed capacity because of the evolution of installed capacity during the period analysed.
- Gross potential has been extracted from IDB 2017.
- In the case of natural gas reserves, only proved (P1) reserves are shown. However, shale resources are abundant and could be put into production in the short-to-medium terms, depending on the development of the required infrastructure to increase evacuation capacity and domestic price signals.

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[48] (Y-Tech, 2020). Petrochemical includes refining, fertilizer and methanol

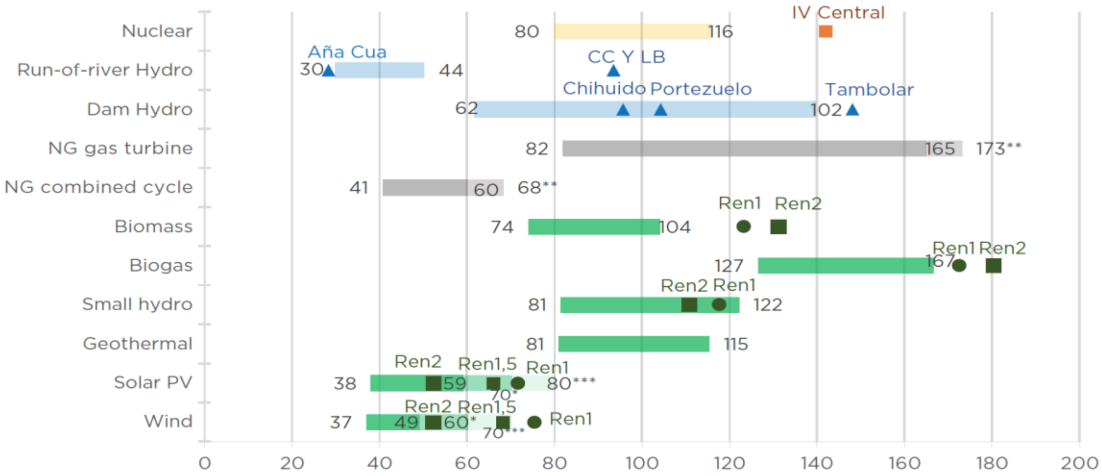
[49] (a) CAMMESA. https://cammesaweb.cammesa.com/informe-sintesis-mensual/

[50] (b) (Paredes, 2017)

[51] (c) Secretariat of Energy. http://datos.minem.gob.ar/dataset/reservas-de-petroleo-y-gas

An estimate of costs for power generation projects under development in Argentina, as well as the levelized cost ranges are presented below, expressed in US$/MWh. Studies of hydrogen costs are on-going but figures are not yet available as of October 2021.

Figure 9: Levelized cost of power generation and specific projects under development in Argentina in 2019, in US$/MWh



Source: Undersecretariat of Energy Planning (SsPE 2019)

Bar colour notes:

- Bullets show specific (real) projects, while bands show LCOE (levelized costs of electricity) ranges.
- (*) Includes required additional power transmission capacity (light green)
- (**) Includes required additional natural gas transport capacity (light grey)
- (***) Includes required backup (light green).

Projects and initiatives

The first relevant institutional initiative for hydrogen research and promotion in Argentina is directly related to the creation in 1996 of the Argentine Wind Energy Association (AAEE) and the Argentine Hydrogen Association, which catalysed research on the subject and made the first attempts to quantify Argentina's —and particularly Patagonia's— potential for producing and exporting liquid hydrogen.[52] Some of the major results of this research were presented at the 12th World Hydrogen Energy Conference, which was held in Buenos Aires in 1998.

As of August 2021, the most relevant green hydrogen project in Argentina is located in the province of Chubut, in Patagonia. Hychico, created in 2006 as a subsidiary of CAPSA (Companias Asociadas Petroleras SA), completed its first pilot project, producing hydrogen electrolysis, which started operation in January 2009.[53]

Hychico's plant has a total capacity of 120 Nm^3/h or 94.5 tonnes/year of high-purity hydrogen (H_2) (99.998%) using electricity generated on its own operated wind park, 'Parque Eólico Diadema', with an installed capacity of 6.3 MW and a capacity factor of 48.3 per cent, according to power generation data from 2018 to April 2021.[54] Hydrogen is then blended with natural gas (up to 42% in volume) to feed a 1.4 MW internal combustion engine power generator, while the oxygen obtained as a byproduct from the electrolysis process is sold in the domestic market to industrial users.

[52] (Spinadel, 1998)
[53] (Rabalo, 2010)
[54] CAMMESA. https://cammesaweb.cammesa.com/informes-y-estadisticas/

Since 2010, Hychico has also begun the development of hydrogen transport and underground storage facilities.[55] It has built a 14.3 mile hydrogen pipeline from the production facilities to a depleted well that is being tested as an underground hydrogen storage and methanation pilot project through the use of depleted wells located in an oil and gas field in the Golfo San Jorge Basin.

Other smaller scale initiatives have been promoted by the public and private R&D system in Argentina, such as:

- The ITHES Institute (Institute for Hydrogen Technology and Sustainable Energies) of the National Council of Scientific and Technology Research (CONICET and University of Buenos Aires), focused on hydrogen derived from biofuels (bioethanol, glycerol and biogas), with a small-scale hydrogen pilot plant.
- The IEDS Institute (Institute for Energy and Sustainable Development) of the National Nuclear Energy Commission (CNEA), including three work-streams (some of these discontinued) focused on hydrogen production (enzymatic production, hydrogen as a byproduct of bio-remediation and 'pink' hydrogen, obtained from nuclear power generation) and one on hydrogen use, focused on the mixture of hydrogen with compressed natural gas for public and freight transport.

In 2019, during the second Hydrogen Energy Ministerial Meeting held in Japan, the government of Argentina (Ministry of Treasury) signed a memorandum of cooperation with the Ministry of Economy, Trade and Industry of Japan (METI) for the exchange of information on the development of green hydrogen, the development of a strategic roadmap for hydrogen, as well as increasing production efficiency, among other issues.[56] [57]

Recently, several government-led and private initiatives have been launched to progressively transform the hydrogen landscape in Argentina. In 2020 the Argentine government launched a process for the development of a 'National Hydrogen Strategy Towards 2030', through a process led by the Secretariat of Strategic Affairs and the Economic and Social Council, involving several ministries, and public and private stakeholders. In October 2021, the Secretariat of Strategic Affairs launched a set of three tenders to assess potential hydrogen supply and demand, as well as to study the required regulation needed to develop this market in Argentina.[58]

The Agency for the Promotion of Research, Technology Development and Innovation of the Ministry of Science, Technology and Innovation has launched a participative process related to energy transition in Argentina, mostly focused on the use of hydrogen and lithium.

The most relevant public-private consortium, the Consortium for the Development of Hydrogen Economy in Argentina (H2AR), was launched by Y-TEC, a joint company funded by YPF, Argentina's National Oil Company with CONICET, to promote the knowledge and strategies for the technology and market development of hydrogen in Argentina through the coordination of stakeholders along the hydrogen supply chain. As of August 2021, H2AR comprises more than 30, mostly energy, companies.

In 2020, the Centre of Studies on Energy Regulation of the University of Buenos Aires (CEARE-UBA), the National Technology University (UTN-BA), the Argentine chapter of the World Energy Council (CACME), the Global Legislators Organisation (GLOBE) and the Argentine Association for Wind Energy (AAEE) launched Plataforma H2 Argentina, focused on contributing to energy policy and regulation for the development of green hydrogen. In September 2021, this platform promoted a bill for updating Argentina's hydrogen law.[59]

In 2020 the Province of Río Negro commissioned a Study on the production of green hydrogen in the province to the Fraunhofer Institute of Energy Economics and Energy System Technology (Germany),

[55] (Perez, 2010)
[56] https://www.meti.go.jp/english/press/2019/0927_002.html
[57] https://www.cancilleria.gob.ar/es/actualidad/noticias/la-argentina-y-japon-trabajaran-juntos-en-el-desarrollo-del-hidrogeno-como
[58] https://www.argentina.gob.ar/consejo/estudios-hidrogeno
[59] https://www.plataformah2.org/l/presentaron-un-proyecto-para-actualizar-la-ley-nacional-de-hidrogeno/

which was finished in 2021, including several domestic and exports scenarios for monetizing Río Negro's potential production.[60]

Several research institutions from Argentina became part of H2TRANSEL, an Ibero-American network for the promotion and use of hydrogen in the power and transport sectors.

Finally, during the Clean Energy Ministerial (CEM12), hosted by Chile in June 2021, the port of Bahía Blanca became part of the 'hydrogen initiative'; a Memorandum of Understanding for the Global Ports Hydrogen Coalition was signed.

Hydrogen: key factors and barriers

Hydrogen production is highly capital-intensive in the case of green hydrogen and highly capital and feedstock intensive in the case of natural gas-based hydrogen. Capacity factors, capital costs and availability of natural gas and CO_2 injection sites, as well as the ability to match supply with demand regimes and attaining scale economies are, in consequence, key to the economic feasibility of hydrogen projects.

Hence, Argentina's reduced access to funding and high costs may hinder its capacity to successfully develop these capital-intensive projects despite the high-capacity factors (circa 50% in wind, mostly in Patagonia and circa 30% in solar PV, mostly in the Northern provinces). With regard to blue hydrogen from natural gas, Argentina cannot produce more gas in summer because of the low summer demand and cannot produce more in winter because of pipeline capacity constraints. The gas resource is there and is abundant, and one of the opportunities for the development of Vaca Muerta is to create more demand —in this case by producing hydrogen— near the gas fields or through exports.

Wind power and natural gas availability in Patagonia, with nearby coastal areas suitable for the construction and use of high-capacity ports, could avert power transmission and natural gas transport constraints by building export facilities near the feedstock and energy sources.

At the early stages of commercial hydrogen development in the domestic market, several uses have been identified, such as in freight and passenger transport, in a blend with natural gas, and access to the current natural gas grid for blending hydrogen. In these cases, amendments to current regulations are required and have been identified as barriers. Additionally, when it comes to green hydrogen, assessing traceability and certification of origin pose technical-regulatory challenges which need to be addressed.

An opportunity to facilitate the use of hydrogen in Argentina's energy mix is through methanation of green hydrogen, introducing a product compatible with the country's current infrastructure and end-use equipment.

Additionally, four axes were identified and recommended by Verónica Gutman in 2021[61] for guiding actions to develop a hydrogen market in Argentina:

- Research and development axis: enhance research projects to include not only green hydrogen, but also transitional grey and blue hydrogen, making use of the scale of natural gas production and current market conditions, while expanding research into transport infrastructure and charging stations.
- Supply axis: leverage on existing initiatives and consortia to encourage the participation of stakeholders through the value chain and making use of fiscal and business incubation initiatives.
- Demand axis: map uses and applications at national and international levels for hydrogen as a domestic fuel and feedstock, as well as potential international markets for short and medium-term horizons.

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[60] https://rionegro.gov.ar/download/archivos/00014487.pdf
[61] (Gutman, 2021)

- International cooperation axis: encourage the participation of Argentina in global cooperation initiatives.

Overall, decarbonized gases in Argentina are at different stages of development: while the development of biogas from agricultural residues (and to a lesser extent from urban waste) has already materialized in power generation projects and certain heat and steam applications, biomethane has been developed only for pilot projects related to isolated gas networks (BAGSA), and low-carbon hydrogen is still in the strategy definition phase with only one (pioneering) project, operated by Hychico since 2006.

However, several government and private initiatives show an increasing enthusiasm, mostly for the potential to produce green and blue hydrogen, in line with some regional initiatives.

All three decarbonized gases analyzed for Argentina share an outstanding potential from available resources (crops, waste, renewable sources and natural gas), but are constrained due to high capital costs (and access), as well as to the lack of development of domestic or export markets.

4.2 Brazil

4.2.1 Context

In 2020, according to Brazil's Energy Planning Company (EPE), natural gas accounted for approximately 12 per cent of Brazil's domestic primary energy supply, as shown in Figure 10 and still has great growth potential. In a publication associated with the 2030 Energy Expansion Plan, the company projects growth of just over 45 per cent in natural gas supply in the period 2019 to 2030,[62] and a prominent position in the diversification of the Brazilian energy matrix. This important role is justified by the consistent growth of gas production resulting from greater technological and production efficiency in pre-salt areas, the expansion of private operations based on Petrobras' divestment policy, the regulatory framework of the new gas law and the need to increase national energy security.

In recent years, the public policies defined by the Federal Government for the oil and gas sector had as their main objective the revitalization of the industry through the creation of a fiscal and regulatory environment that would provide greater attractiveness for new investors and greater competition among all industry segments. In line with this objective, the new regulatory framework for natural gas laid the foundations for the promotion of the natural gas market, focusing on increasing competition, diversifying agents, greater dynamism, and access to information. These actions will enable greater commercial use of the growing production of natural gas.

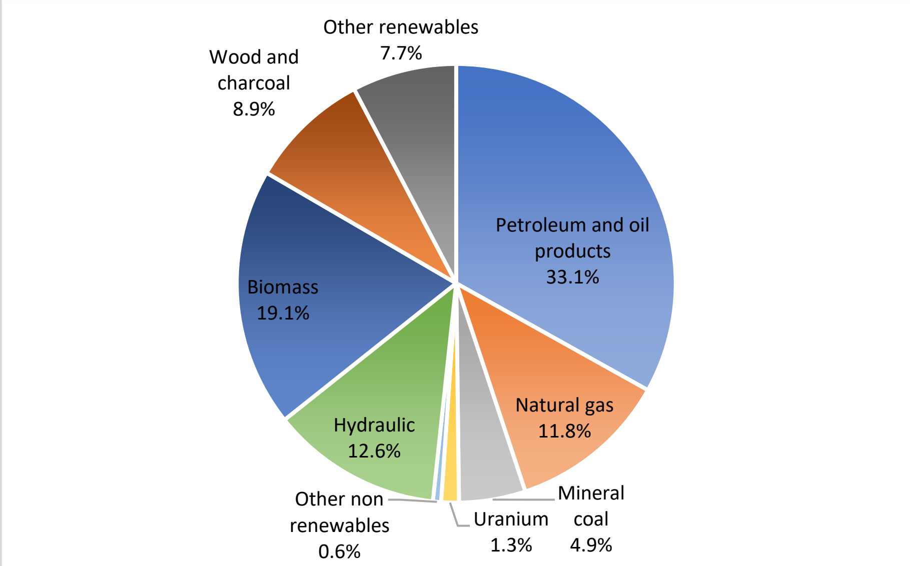
In 2020, gross domestic production of natural gas was 46.5 Bcm. Most of the gas production is associated to oil and offshore. Reinjection accounted for 43% (20 Bcm) of the gross natural gas production due to a combination of reservoir pressurization needs, high CO_2 content in some fields and lack of offshore pipeline capacity.

In 2020, the consumption of natural gas was 26.3 Bcm of which power generation accounted for 9.5 Bcm (36%). In order to meet demand, Brazil imported 9.7 Bcm, of which 6.5 Bcm was from Bolivia and 3.1 Bcm as LNG. In the first half of 2021, gas imports rose to 14.2 Bcm due to the increased dispatch of power plants, as a result of a very dry season.

The liberalization of the Brazilian natural gas sector allows the development of new business models, focused on renewable energies, and future decarbonization of the gas sector. In this context, the great potential for the development of the biogas and biomethane segments stands out.

[62] O papel do gás na transição energética – ABEGÁS (abegas.org.br)

Figure 10: Brazil domestic energy supply (2020)



Source: Brasil, 2021b[63]

4.2.2 Biogas and bio methane in Brazil

Brazil is one of the largest agricultural producers in the world. In recent years, Brazilian agriculture production has reached record levels, supplying the domestic market and more than 150 countries.[64] One of the direct impacts of agricultural product harvesting and processing is the generation of significant amounts of biomass. The reuse of this residual biomass for the generation of biogas represents a solution that allows the production of renewable energy. In addition, it allows the avoidance of the accumulation of residues and reduces dependence on imported chemical fertilizers, since the production of biogas can have organic-mineral fertilizers as a co-product.[65]

According to the Brazilian Association of Biogas (Abiogás) the potential applications for biogas in Brazil are the direct generation of heat, the generation of electric energy in motor generators or cogeneration systems, and the use of purified biogas in the form of biomethane, for use as a fuel equivalent to natural gas.[66]

Brazil has great potential for the development of the biogas and biomethane segment. This is because the country has a great diversity of biogas sources, including in regions where the supply of gas through pipelines is a challenge. For instance, according to Abiogás, Brazil has the technical potential to produce around 43 Bcm/year of biogas, equivalent to 26 Bcm/year of biomethane.

One of the great advantages of biomethane is its high potential for reducing greenhouse gas emissions. Among the fuels, biomethane stands out for having the lowest level of GHG emissions - virtually zero (Table 7), since decomposed organic matter captures the CO_2 produced by the recovery of biomethane simultaneously. Thus, when talking about transport emissions, this source is an alternative to help cities face the challenges of climate change**.**

[63] Apresentação do PowerPoint (epe.gov.br)
[64] https://www.embrapa.br/documents/10180/9543845/Vis%C3%A3o+2030+-+o+futuro+da+agricultura+brasileira/2a9a0f27-0ead-991a-8cbf-af8e89d62829
[65] (PDF) POTENCIAL DE PRODUÇÃO DE BIOGÁS E ENERGIA ELÉTRICA A PARTIR DE RESÍDUOS DE HORTIFRUTICULTURA EM COLOMBO-PR (researchgate.net)
[66] Each of these applications requires a level of impurity removal, depending on the regulated composition or the sensitivity of the system components to the biogas elements. In the generation of energy from biogas, the chemical energy of the gas is converted into mechanical energy by means of a controlled combustion process (ABIOGÁS.indd (abiogas.org.br)).

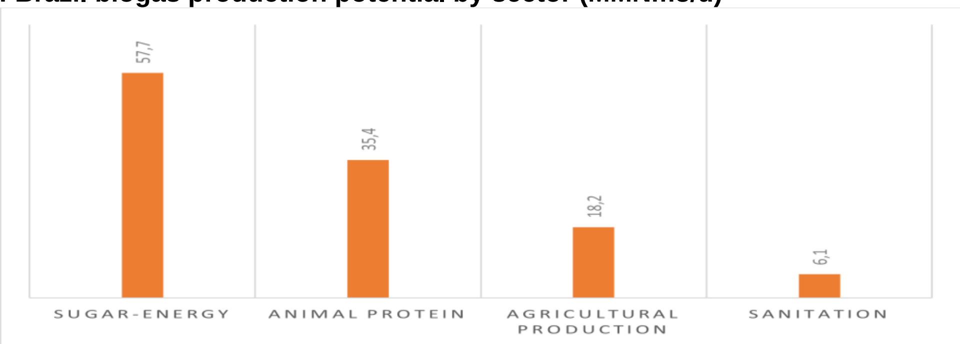
Table 7: CO_2 emission comparison - biomethane[67]

Fuels	Diesel	CNG	Electric	Hybrid-Electric	Biomethane
Yield [1)]	2.2 km/L [(1)]	1.8 km/Leq [(2)]	4.8 km/Leq [(3)]	3.7 km/Leq [(4)]	2.1 km/Leq [(1)]
CO_2 emissions (grams/km)	134 [(5)]	103 [(5)] 23% lower than diesel	20 [(5)] 85% lower than diesel	65 [(4)] 50% lower than diesel	20 [(5)] 85% lower than diesel
CO_2 emissions per passenger[(5)] (grams/person/km)	9	7	1	1	1

Source: Lofhagen and Freitas, 2020[68]

As mentioned, in Brazil there is a large potential for biogas due to the availability of large quantities of waste from three different sectors: sanitation (urban solid waste and sewage), agribusiness (waste from corn, dairy products, soy, cassava, slaughterhouses, and animal waste), and sugar-cane (vinasse, straw, bagasse and filter cake[69]). The potential by type of waste is shown in Figure 11.

Figure 11: Brazil biogas production potential by sector (MMNm3/d)



Source: (Abiogas, 2021)

According to Abiogás, potential biogas production (117.7 MMm³/d, circa 43 Bcm/year) would allow generation of around 166 TWh/year of electricity or 26 Bcm/year of biomethane. In other words, this means that biogas could supply 34.5 per cent of the demand for electricity consumed in 2019. This is theoretically equivalent to the country's total gas consumption in 2020 (26.3 Bcm).[70] However, when comparing this potential with Brazilian biogas production in 2020 (1.83 Bcm[71]) it appears that less than five per cent of the potential is used. Therefore, there is an opportunity to expand biogas production in Brazil.

The analysis of the national biogas production potential reflects the potential of each source sector. It is estimated that the sugar-ethanol sector should play an important role in increasing biogas production due to its investment capacity, quality of waste, and experience in the energy sector. Biogas projects associated with vinasse (by-product of the sugar or ethanol industry) and filter cake (residue that is eliminated during the cane juice decantation process) already represent about 16 per cent of the sector's total biogas potential, that is, they correspond to approximately 14 TWh of electric energy or 3.7 Bcm/year of biomethane (3.4 billion liters of oil equivalent) per year.[72] About 40 per cent of the sugar-energy sector's potential is in plants that have the necessary attributes for the implementation of biogas or biomethane projects in the next 5-10 years, that is, it is possible to develop 5.6 TWh of

[67] Leq – equivalent litres
[68] Microsoft Word - Artigo - Políticas Publicas para a Mobilidade Urbana Sustentável.docx (submissao.com.br)
[69] https://abiogas.org.br/wp-content/uploads/2021/06/PANORAMA-DO-BIOGAS-NO-BRASIL-2020-v.8.0-1_1.pdf
[70] (MME Brazil, 2021)
[71] (Abiogas, 2021)
[72] (Abiogas, 2021)

electricity or 1.48 Bcm/year of biomethane in this sector. To achieve this potential, it is estimated that investments in the order of R$6.4 billion are needed.

In turn, sanitation is seen as one of the most promising areas. This is because there is great development know-how in the area and this sector is responsible for the production of more than 70 per cent of all biogas used for energy purposes in Brazil through the capture of landfill gas. The potential of the sanitation sector is 2.2 Bcm/year of biogas, which corresponds to 8.8 TWh of electricity or 1.3 billion m^3 of biomethane. However, it is noteworthy that while about 75 per cent of this potential is technically viable, only 16 per cent is economically viable due to infrastructure, scale and logistics constraints. Therefore, in the short term, around 1.4 TWh of electricity or 0.35 Bcm/year of biogas is viable in the sanitation sector, which requires investments of around R$1.6 billion.

Finally, the agriculture sector holds great promise due to the preeminence of the agriculture industry in Brazil. However, unlike the other sectors, biogas from agriculture is still in the demonstration phase, due to the great diversity presented by the sector itself and the necessity to break through the barrier of high-efficiency technology. The attractiveness of this sector is its spread through most Brazilian regions, allowing decentralized electricity to be produced through small/medium power plants near load centres that face problems with power quality and have high diesel demand. Due to this more internalized presence when compared to other potentials, this sector could allow for the creation of 'local structuring gas pipelines'.

The Brazil Biogas Map (Figure 12), an online and interactive tool, created by CiBiogas in partnership with Abiogás, allows the visualization of the production units and the energy use of biogas by state.

Table 8 summarizes the production and uses of biogas in Brazil in 2020. Data collected by CiBiogas indicated that 64 per cent of the plants are very small, with production of less than 500,000 m^3/year, with only three plants producing above 125 MMm^3/year of biogas. In addition to 638 plants in operation, another 37 plants will be commissioned in 2021, adding 0.4 Bcm/year of biogas production.

Table 8: Brazil biogas production and uses (2020)

Biogas use	Plants		Production (Bcm/year)	
Power generation	543	85%	1.33	73%
Heating	81	13%	0.15	8%
Biomethane	8	1%	0.33	19%
Other uses	6	1%	0.01	0.4%
Total	638		1.83	

Source (Abiogas, 2021)

Most biogas production, around 77 per cent, is supplied by large plants, although these represent only 6 per cent of the plants in operation. The main source for the generation of biogas in these plants is agriculture. About 80 per cent of the plants are fed by this segment, however, these plants account for only 12 per cent of the volume of biogas produced in the country. On the other hand, plants fed by urban solid waste and effluents represent 8 per cent of the plants in operation and are responsible for producing 76 per cent of the national biogas.[73]

One of the outstanding projects is the Raizen Geo Gas plant located in Guariba (SP). This plant has 21MW of installed capacity and is the first in the country to use bagasse (sugarcane pulp) filter cake to produce biogas on a commercial scale. Other highlights are two projects belonging to the company ZEG Biogás. The first is an electric power plant with a capacity of 1 MW, located in the northern state of Pará, which uses biogas from palm vinasse, produced from palm oil. The second is a biogas purification project for biomethane, the Sapopemba Landfill project in São Paulo, with initial production

[73] Produção de biogás cresce 36% em 2019, segundo Biogásmap – ABiogás (abiogas.org.br)

of 30,000 m^3/day of biomethane and potential expansion to 90,000 m^3/day.[74] The company has not disclosed the amount of biogas needed to produce this volume of biomethane.

Figure 12: Brazil interactive biogas map 2021

Source: Cibiogás, 2019[75]

The exploitation of the potential of biogas and biomethane involves developing adequate regulation and public policies providing favourable market conditions. According to the National Biogas and Biomethane Program Proposal prepared by Abiogás, the national regulatory agenda has made recent advances in establishing parameters for better use of biogas/biomethane. In general, the production and use of biogas and biomethane are driven by Law no. 12,187/2009, which deals with Brazil's National Policy on Climate Change and provides guidelines for the reduction of greenhouse gas emissions, and by Law no. 12,305/2010, which instituted the National Solid Waste Policy and regulates the destination of solid waste generated in the national territory.[76] Specifically for the biogas and biomethane market, the following regulatory frameworks stand out.[77]

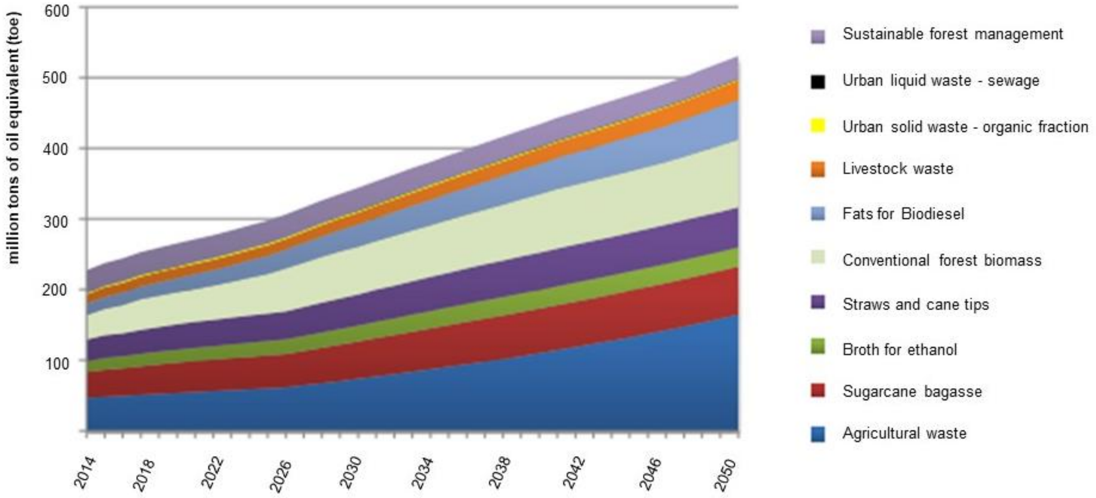
- EPE Technical Note no. 13/14 (2014): inclusion of biogas/biomethane in the National Energy Plan and details of possible applications of these fuels;
- ANP Resolution no. 08/15 (2015): setting parameters for the use of biomethane as fuel;
- ANP Resolution no. 685/17 (2017): regulation of biomethane as a vehicle fuel from landfills and sewage treatment plants;
- ANP Dispatch no. 1084 (2017): approval of the quality control of biomethane from Dois Arcos, with permission to commercialize the biomethane produced.

[74] ABiogás News Especial: Dezembro 2020-Janeiro 2021 – ABiogás (abiogas.org.br)
[75] Biogasmap (cibiogas.org)
[76] (PDF) Tecnologias de produção e uso de biogás e biometano (researchgate.net)
[77] PNBB_Versao_Final.pdf (abiogas.org.br)

In addition to these, Law no. 13.576/2017 establishes the National Biofuel Policy (Renovabio), which is regulated by Federal Decree no. 9.308/2018. This policy defined a set of strategies to expand the production of biofuels, increasing their contribution to the energy matrix.

The EPE report about the potential of energy resources to 2050 confirms this estimate of growth in biogas production, as shown in Figure 13.

Figure 13: Brazil biogas production potential to 2050



Source: Potential of Energy Resources in Horizon 2050 (2018[78])

Biogas: key factors and barriers

Brazil has a great potential for biogas production due to the availability of residues from agriculture, industry, and urban areas. However, the production and use of energy from this source faces some obstacles that could hinder growth:[79]

- lack of financial attractiveness, especially in relation to alternatives such as natural gas;
- difficulty in financing projects, due to the absence of a structured market;
- gaps in regulation, both in terms of biogas/biomethane specification and by-product marketing rules;
- the need to adapt infrastructure as well as change the planning paradigm, aiming to integrate energy and sanitation issues.

The first two problems reflect the high costs of implementing (Capex) and maintaining (Opex) biogas projects. These costs are the result of three main factors: (1) need for high investment volumes to acquire knowledge, develop clients and suppliers, professional training, and offer services in the market; (2) small size of most projects; (3) requirements for compliance with high-quality standards and continuity of biogas production for commercial purposes. In addition, factors such as equipment prices, limited options for comparison and choice, and high import taxes, contribute to the increase in the costs of biogas projects.[80]

As for the barriers related to regulation, there is a lack of clarity and specific regulations for the use of biogas and by-products. Thus, it is necessary to apply policy instruments, such as the regulatory

[78] NT04 PR_RecursosEnergeticos 2050.pdf (epe.gov.br)
[79] www.ie.ufrj.br
[80] giz_barreiras_digital_simples.pdf

framework, environmental licensing, fiscal and tax incentives and energy auctions specifically adapted to the reality of the sector.[81]

Finally, the development of biogas and biomethane projects requires government incentives for investment in infrastructure, including biogas capture, treatment, transport and distribution.

4.2.3 Hydrogen in Brazil

The production of hydrogen in Brazil is estimated at 400 Kt/year (2019), with oil refining accounting for 83 per cent of the demand; the balance is consumed in the production of ammonia. Hydrogen is produced by steam reform of methane, without carbon capture (grey hydrogen[82]).

It can be noted that Brazil, does not have a specific strategy for regulation, production, consumption, transport and storage and even exports that would allow the incorporation of hydrogen into the country's energy planning and energy matrix. The National Energy Plan 2050 (PNE 2050[83]), published in November 2020 didn't consider a large contribution of hydrogen in the long run.

Brazil occupies a privileged position, compared to most countries in the world, in view of the significant contribution of renewable energy to its energy matrix, accounting for more than 80 per cent of power generation.[84]

In the context of the European Green Deal,[85] it has been observed that Germany[86] regards Brazil as a country with a great potential to produce and export green hydrogen due to competitive renewable energy production. Naturally it is necessary to consider the cost of transport to consumer markets and whether that would be considered competitive.[87] According to Ansgar Pinkowski, innovation and sustainability manager at the Brazil-Germany Chamber of Commerce and Industry of Rio de Janeiro (AHK Rio), Brazil has the largest base of German companies developing hydrogen in the world; 66 per cent of German companies working with green hydrogen already have subsidiaries in Brazil. Additionally, according to Pinkowski, 'there is no other country in the world with conditions as favorable for the production of hydrogen as Brazil, perhaps Australia'.[88] These factors provide great chances of a partnership between the two countries.[89]

In broad terms, the main challenges for hydrogen in Brazil are the expansion of its production and consumption at scale, and the elaboration of norms for hydrogen use. The PNE 2050 recommends the design of regulatory improvements related to quality, safety, transport, and storage and supply infrastructure.[90]

A policy for hydrogen development in Brazil would not necessarily imply the substitution of sources, but complementation, considering the growth of energy consumption in the country. According to the Ten-Year Expansion Plan for Energy 2030,[91] energy consumption is expected to grow 27 per cent between 2021 and 2030. The country has the fifth largest population in the world and the ninth largest economy, so the prospects for developing a domestic market for hydrogen should not be underestimated.

In August 2021 the Ministry of Mines and Energy (MME) presented a proposal for guidelines for the National Hydrogen Program (PNH2). The proposal incorporated a comprehensive vision of challenges and opportunities that should be considered in the development of the industry and of the hydrogen market in Brazil. The PNH2 proposes to define a set of actions that facilitate the joint development of three fundamental pillars for the successful development of a hydrogen economy: public policies,

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[81] giz_barreiras_digital_simples.pdf
[82] (IEA (b), 2021)
[83] https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/Plano-Nacional-de-Energia-2050
[84] Fontes de energia renováveis representam 83% da matriz elétrica brasileira — Português (Brasil) (www.gov.br).
[85] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
[86] Abeeolica,. (2020); Kelman,. et al. (2020); FGV Energia, 2020
[87] (Cesar, et al., 2019), (Kelman, et al., 2020), (Heuser, et al., 2019)
[88] https://fundacaofhc.org.br/iniciativas/debates/hidrogenio-verde-a-descarbonizacao-da-europa-e-o-interesse-do-brasil
[89] Projetos de hidrogênio verde pelo mundo somam mais de US$ 80 bi (epbr.com.br)
[90] Considering that hydrogen is very flammable since it reacts explosively with oxygen, standardization is relevant to protect public safety and health.
[91] PDE 2030_RevisaoPosCP_rv2.pdf (epe.gov.br)

technology and market. The program's guidelines are structured in six axes, which encompass the strengthening of scientific and technological bases, the training of human resources, energy planning, the legal and regulatory-normative framework, the opening and growth of the market and competitiveness and international cooperation.

The different technological routes for hydrogen production provide flexibility and the use of Brazil's renewable resources. In Brazil, there are pilot projects that use hydrogen production routes such as ethanol reform, biogas, glycerol, and agro-industrial residue fermentation. These projects have the capacity to produce up to 2.9 MMm^3/year.[92] The Brazilian Energy Research company (EPE) (2021c[93]), is mapping the potential for production of green hydrogen in Brazil within the scope of the Cooperation Project on Technologies for Energy Storage. This study, without a defined date for publication will serve as a basis for structuring the guidelines for the National Hydrogen Program.

Proposed hydrogen projects in Brazil

Base one project in Ceará

The Base One project was launched by the Australian company Enegix Energy with the intention of building a green hydrogen plant at the Pecém Industrial Complex, in the state of Ceará. According to the company, solar and wind energy will be used to produce, by electrolysis, more than 600,000 tonnes of hydrogen annually. With this, the project, which requires a total investment of US$5.4 billion, is being hailed as one of the largest green hydrogen projects in the world and the largest single project to reduce carbon emissions. Base One has the potential to reduce CO_2 emissions by up to 10 Mt/year.[94]

The project is in the feasibility study and fund-raising phases (as of August 2021), with the plant expected to operate at 100 per cent capacity by 2025. The project already has preliminary contracts signed with engineering and construction companies, energy suppliers, and the Government of the State of Ceará. One of these companies is Enerwind, which will be responsible for providing 3.4 GW of solar and wind power for the project. According to Enegix, Base One has the capacity to expand this initial supply of 3.4 GW to more than 100 GW, increasing by about 30 times the hydrogen generation initially planned. Another aspect highlighted by the company is the location of the plant. Since it is being built near a deep-sea port, international exports of the product, which is the focus of the project, will be facilitated. Thus, it is expected that hydrogen will be transported in liquid state to the United States, Europe, Africa and Asia.[95]

Green hydrogen plant in Porto do Açu

Feasibility studies for the installation of a green hydrogen plant at the Port of Açu, with a capacity of 300 MW, are being conducted by Fortescue Future Industries in partnership with Porto do Açu Operations SA. In February 2021, the companies signed a memorandum of understanding to evaluate the possibility of developing the project with the intention of producing 250,000 tons of green ammonia per year. This production would serve to boost the sustainable industrialization of the port, enabling the clean production of products such as steel, fertilizers, fuels, and others.[96]

Other projects

- Hydrogen Brazil program: the German government, through the German Agency for International Cooperation (GIZ), is supporting the implementation of the Hydrogen Brazil program, which aims to foster the development of a green hydrogen economy in the country. As of August 2021, GIZ, in partnership with experts in the field, is evaluating potential Brazilian partners that can contribute significantly to the program. One of the first partnerships that is being analyzed is with the Bahia State Government. According to the Secretary of Environment of the State, Bahia is one of the leaders in the production of renewable energy in Brazil and still

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[92] Relatorio_Hidrogenio_Verde_Boll_FINAL.pdf (boell.org)
[93] Hidrogênio_23Fev2021NT (2).pdf (epe.gov.br)
[94] Brazilian green H2 plant to (briefly) be world's biggest CO2 reducer (newatlas.com)
[95] Exportação de hidrogênio atrai plano de investimento de US$ 5 bi para o Ceará (epbr.com.br)
[96] Fortescue Future Industries e Porto do Açu unem forças para desenvolver planta de hidrogênio verde no Brasil - Porto do Açu (portodoacu.com.br)

has great potential for expansion of these sources and therefore fits well into the profile of the program.[97]

- Research and Development project: Furnas, a Brazilian company controlled by the Federal Government, is developing a project that aims to evaluate the synergy between hydroelectric and solar photovoltaic sources seeking to store seasonal/intermittent energies in the form of hydrogen. As of August 2021, the project is in the construction phase of the solar plant near the Itumbiara hydroelectric plant in Midwest Brazil[98]).

- Project for technological cycle: a partnership between Eletrobras, Siemens Energy and Cepel signed a memorandum that aims at carrying out studies to look at the development of technologies for all stages of the hydrogen chain, from its production to commercialization. The evaluation of the technological cycle will occur through a pilot production plant and, from the results obtained, the companies will evaluate the possibility of building a hydrogen production plant on a commercial scale.[99]

Although most Brazilian projects are focused on green hydrogen, it is worth highlighting the country's capacity to produce other types, such as grey, and blue, hydrogen. Currently, grey hydrogen is produced by the fertilizer and refining industries in Brazil, mainly in the form of ammonia, which is used as a fuel treatment. According to Heloisa Borges Esteves, director of EPE,[100] projects to modify existing plants are being evaluated, considering the addition of a carbon capture and storage system, which will allow the production of blue hydrogen. Until then, the main barriers are related to technological and financial limitations in the implementation of CO_2 capture and storage systems. An additional barrier for producing blue hydrogen is the high price of natural gas (>US$8/MMBtu at the city gate[101]) and the fact that Brazil is a net gas importer, thus domestic gas prices are set at import parity, whilst large scale ammonia plants require prices of US$2-5/MMBtu.[102]

Hydrogen: key factors and barriers

The expectations about the future of hydrogen translate into an intensely planned growth of this market in the coming years and the development of energy policies for the post-pandemic economic recovery.[103] In Brazil, the debate on the use of hydrogen in the energy matrix has intensified due to the competitive advantages of the use of hydrogen energy nationally, such as: possibility of using the natural gas distribution infrastructure; generation capacity from renewable sources with competitive prices and expansion potential; availability of liquefied natural gas for production and the need to mitigate the intermittence of renewable energy sources that currently make up the Brazilian energy matrix.[104]

However, it is still necessary to introduce new regulations and incentives so that hydrogen can be efficiently inserted into the matrix. In this respect, the Ministry of Mines and Energy published Resolution No 6/21 aimed at starting studies for the elaboration of guidelines for the National Hydrogen program. According to the National Energy Research Council (CNPE), the guidelines should be elaborated focusing on the development of the hydrogen market in Brazil, making it one of the priorities for investment in research and innovation.[105]

Also at the national level, there has been interest from foreign countries and national and international entrepreneurs in developing green hydrogen generation projects in Brazil.

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[97] Bahia debate programa H_2 Brasil para fomento da produção de hidrogênio verde - Portal Gov Bahia
[98] Furnas começa produção de hidrogênio na UHE Itumbiara | CanalEnergia
[99] Eletrobras e Cepel assinam acordo com Siemens para domínio do ciclo do hidrogênio verde | CanalEnergia
[100] https://www.udop.com.br/noticia/2021/07/08/brasil-quer-adotar-abordagem-arco-iris-para-hidrogenio.html
[101] (MME Brazil, 2021)
[102] https://www.epe.gov.br/pt/imprensa/noticias/epe-lanca-o-informe-tecnico-competitividade-do-gas-natural-estudo-de-caso-na-industria-de-fertilizantes-nitrogenados
[103] https://www.gov.br/mme/pt-br/assuntos/noticias/brasil-apresenta-pactos-energeticos-em-biocombustiveis-e-hidrogenio-no-dialogo-de-alto-nivel-da-onu-sobre-energia
[104] ConJur - Opinião: Hidrogênio: usos, políticas públicas e regulamentação
[105] MME inicia elaboração de diretrizes do Programa Nacional do Hidrogênio — Português (Brasil) (www.gov.br)

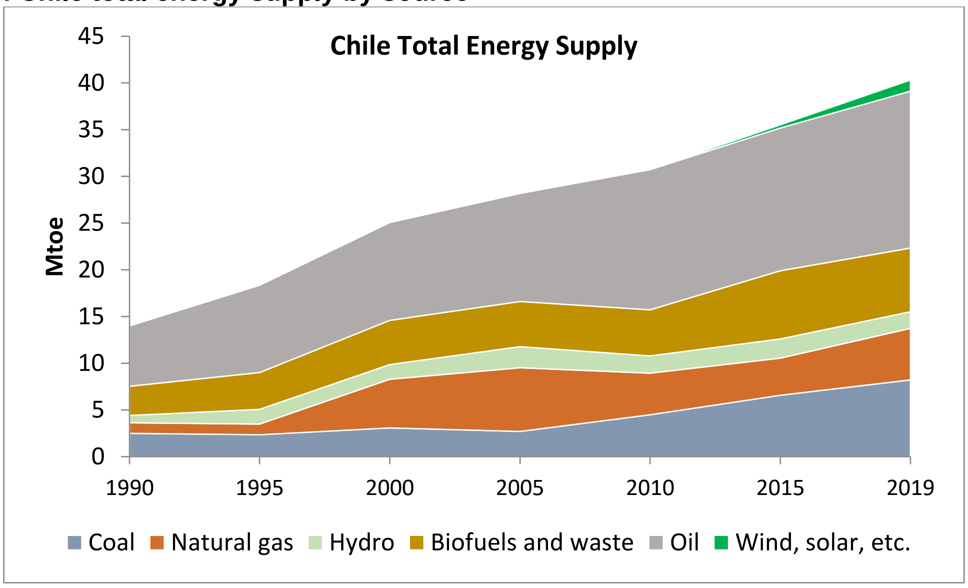
4.3 Chile

4.3.1 Context and regulation

In 2019 Chile consumed 6.5 Bcm of natural gas.[106] Domestic production in Chile accounted for 1.46 Bcm, concentrated in the southern region of Magallanes. As there is no national pipeline infrastructure, domestic gas is consumed locally and other regions are supplied by LNG and seasonal pipeline imports from Argentina, accounting for 77.5 per cent of Chile's supply. In 2019, Chile's LNG imports totalled 3.26 Bcm (2.4 mtpa), predominantly imported from the USA and Trinidad and Tobago. In 2020 LNG imports slightly increased to 2.69 mtpa (3.65 Bcm[107]).

Figure 14 shows that, despite an impressive compound growth of 65.8 per cent in the period 2005-2019, the share of renewable energy (solar/wind) in Chile's total energy supply is still modest, about 2.9 per cent. The participation of biofuels and waste is more significant, at 16.9 per cent, but the compound average growth has been slower at 2.5 per cent (2005-2019).

Figure 14: Chile total energy supply by source



Source: IEA World Energy Balances 2020

Despite the modest share in the overall energy matrix, renewable energy is capturing an impressive share in the power generation installed capacity sector. Of a total capacity of 28 GW, solar PV and wind accounted for respectively 17.5 per cent (4.9 GW) and 9.8 per cent (2.7 GW), as of April 2021.[108] Solar capacity is now similar in size to coal and natural gas installed capacity (4.9 GW and 4.8 GW respectively), albeit with a lower load factor (about 20%) when compared to coal and gas (40-50%).

Chile's energy policy is geared towards three objectives: security of supply, efficiency, and sustainability. A key component of the energy policy is the diversification of supply sources, encompassing the following elements

- Exploitation of local sources (coal, oil and gas)
- Diversification of suppliers (LNG - Coker Industrial Complex)
- Renewable energy: biofuels, solar, wind, geothermal, conventional hydro, biogas and others

Chile is a net energy importer, therefore the development of renewable energy is a key component of the country's security of supply strategy.

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[106] International Energy Agency gas database (provided by OIES team)
[107] (IGU, 2021)
[108] (Generadoras de Chile, 2021)

The National Energy Commission is the Government organization responsible for implementing the energy policy, including policies related to biogas, biomethane and hydrogen.

Chile has set up a legal and regulatory framework establishing targets related to renewable energy.

- Law N° 20,257 (2008),[109] amended by Law No. 20,698 (2013),[110] introduces modifications to the General Law of Electricity Services with respect to the generation of electric power from renewable energy sources. It requires, by 2025, that 20 per cent of the injections to the electrical system should come from renewable energy for generators with installed capacity greater than 200 MW.
- Decree 119/2017,[111] Ministry of Energy. Approves safety regulation for biogas plants.
- Decree Nº 189/05, Ministry of Health. Establishes that sanitary landfill projects must consider using a biogas management system based on a projection of the amount of biogas that will be generated and that guarantees adequate safety conditions both inside the facility and in its surroundings.
- Standard NCH3213 (2010) establishes the specifications for biomethane for transportation, distribution and supply to industrial, commercial and residential customers and vehicles. The standard defines biogas and biomethane and establishes that biomethane injected into a gas supply network must be interchangeable with the gas distributed by that network.
- In 2017 Chile started the implementation of Article 8, Law 20,780,[112] establishing a 'green tax' on emissions of CO_2, NO_x, particulate matter and SO_2. As of August 2021, the CO_2 tax is US$5/ton, which is a long way below recommendations from the International Monetary Fund (IMF) and other international entities.[113] [114]
- In November 2020, Chile launched its Green Hydrogen Strategy[115] establishing its ambition towards becoming a large hydrogen exporter by 2050. In addition, the Ministry of Mines and Energy has published the following documents:
  - A guidebook for the request for authorization for special hydrogen projects in the entire value chain. Such projects shall be authorized by the Superintendents of Electricity and Fuels of the Ministry of Mines and Energy.[116] An amended version of the Law, effective in 2023, intends to catch a larger number of CO_2 emitters – which will also be able to offset their emissions.
  - In parallel the Ministry is working with international consultants to set up a green hydrogen certification scheme, underpinned by international benchmarks. [117]

4.3.2 Biogas and biomethane potential and projects

According to a study from Chile's Energy Commission, the potential for biogas in Chile could reach 1.72 Bcm/year (roughly 1 Bcm/year of biomethane equivalent) with nearly two thirds originating in the metropolitan region of Santiago and the Region VI (south of Santiago). About 76 per cent of the biogas potential originates from agro-industrial waste. Despite the estimate of 1.72 Bcm/year, most of the potential projects are small and scattered and would be used for self-consumption, therefore biogas is not expected to play a major role outside Santiago's metropolitan region. Appendix IV provides a detailed overview of the biogas potential by region and type of waste.

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[109] https://www.iea.org/policies/4853-non-conventional-renewable-energy-law-law-20257
[110] https://www.bcn.cl/leychile/navegar?idNorma=1055402
[111] https://www.bcn.cl/leychile/navegar?idNorma=1099847
[112] https://spaces.oneplanetnetwork.org/system/files/2.-institutional-infrastructure-for-chiles-green-tax.pdf
[113] https://www.df.cl/noticias/opinion/columnistas/df-tax-impuestos-verdes-una-revision-real-y-a-tiempo/2021-03-01/170952.html
[114]https://obtienearchivo.bcn.cl/obtienearchivo?id=repositorio/10221/26723/1/BCN___Implementacion_de_Impuesto_Verde_en_Chile.pdf
[115] (Ministerio de Energia - Chile, 2020)
[116] https://energia.gob.cl/sites/default/files/guia_proyectos_especiales_hidrogeno_2021.pdf
[117] https://energia.gob.cl/sites/default/files/documentos/green_hydrogen_certification_-_presentation.pdf

In 2016, the Ministry of Mines and Energy approved Resolution 14841 which established the procedure for registry of new, proposed and operational biogas plants.[118]

In December 2017, the Registry showed 107 biogas plants – proposed and existing - for different applications mostly very small projects.[119] By March 2020, the updated Registry contained 38 plants, with a total production of 0.17 Bcm/year (457,000 m^3/day) of biogas, equivalent to 0.09 Bcm/year (256,000 m^3/day) of biomethane or natural gas equivalent. The four largest plants (36,000-156,000 m^3/day) produced biogas from sewage or municipal solid waste, the others were small projects related to agriculture and livestock farming, and some of them have not yet been built.

By August 2021, there is only one plant producing biomethane from a sewage treatment plant, La Farfana, which produces 98,000 m^3/day of biogas, equivalent to 64,000 m^3 of biomethane (see details below). There are four projects recovering biogas from landfill and injecting 45 MW into the national electricity system.[120]

The entire biogas potential of 1.72 Bcm/year could generate circa 3.4 GWh, which is equivalent to 4 per cent of Chile's electricity generation in 2019. In the Santiago metropolitan area and Region VI alone there is potential to generate 2.1 GWh, equivalent to 2.5 per cent of Chile's generation in 2019.

La Farfana biogas and biomethane project (grid distribution)

In 2009 the gas distribution company Metrogas and the water company Grupo Aguas Andinas, commissioned the La Farfana sewage to biogas project, initially producing around 50,000-60,000m^3/day of biogas. The project consists of a biogas conditioning facility at the sewage plant, a 13.5 km pipeline connecting the biogas plant to a Metrogas town gas facility where biogas is further purified and injected into the Metrogas town gas network. The total cost of the project was US£6 million with capital investment divided equally between Aguas Andinas and Metrogas. According to a World Bank report, in 2017 the project generated an EBITDA (earnings before interest, taxes and depreciation) of US$1 million for Agua Andinas whereas Metrogas saved US$1.6 million/year related to the price difference between biogas and natural gas.[121] The project was subsequently upgraded to convert biogas into biomethane, with further investment of over US$3 million.

According to Metrogas, the landfill and sewage plants in the metropolitan region of Santiago could produce 400,000 m^3/day (0.15 Bcm/year) of biogas (equivalent to 0.08 Bcm/year of biomethane) (Figure 15).

Santa Marta landfill biogas project (biogas to power)

Consorcio Santa Marta (CSM) developed the 'Santa Marta NCRE Power Station' project, with an initial investment of US$36 million. The plant was connected to the grid in 2013 and generates electricity from biogas produced by solid waste deposited in the Santa Marta landfill. The 20 MW plant operates with motor-generators with 40 per cent performance in electrical conversion and injects its power to the Central Interconnected System (SIC), through the Alto Jahuel–Chena 220 kW line.

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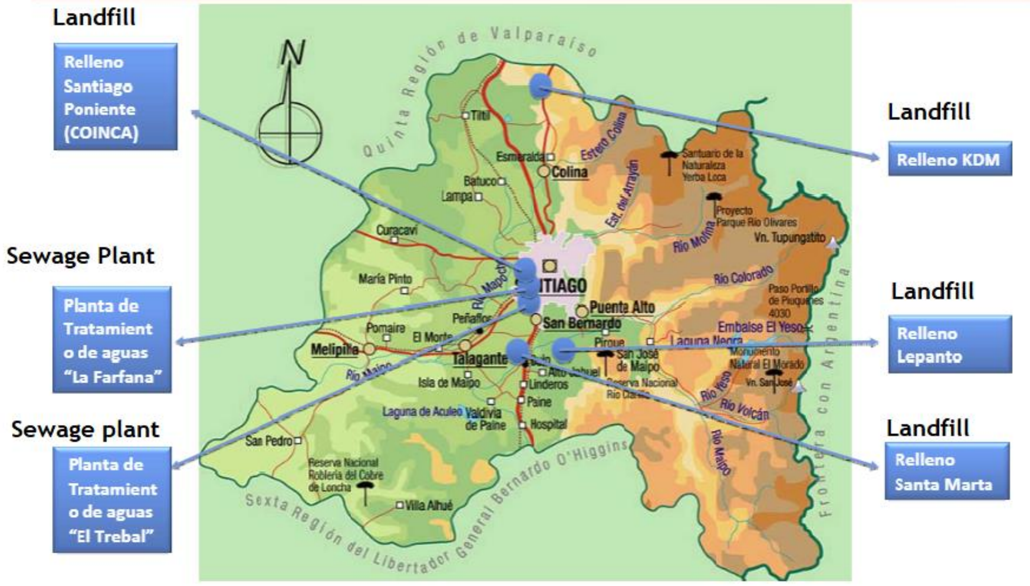
[118] https://www.sec.cl/transparencia/docs2017/Resolucion14841.pdf

[119] https://www.revistaei.cl/2018/01/05/taller-biogas-presenta-buenas-practicas-seguridad-plantas/

[120] (ALCALDE, 2019)

[121] https://documents1.worldbank.org/curated/en/284951573498126244/pdf/Wastewater-From-Waste-to-Resource-The-Case-of-Santiago-Chile.pdf

Figure 15: Potential sources of biogas in Santiago metropolitan area



Source: Metrogas[122]

Biogas: key barriers and issues

The potential for developing biogas and biomethane projects in Chile is quite limited (1.72 Bcm/year of biogas, circa 1 Bcm/year biomethane) and equivalent to only 16 per cent of the country's natural gas consumption in 2020 (6.1 Bcm). Due to the small size of most projects, it would be more realistic to develop biomethane and biogas-to-power-to grid in the metropolitan area of Santiago, with other projects designed for self-consumption. In addition to limitation in volumes, there are other barriers to the implementation of a larger number of projects:

- There are no financial incentives to develop projects for industrial use, power generation and blending in the existing natural gas grids.
- Data and information about potential resources and performance of existing projects is not easily accessible nor updated, which prevents sharing best practice among industry participants.
- Most of the potential projects are very small, in the range of 1200-7500 m^3/day, therefore destined for self-consumption, rather than contributing to the power and gas grid.
- Due to the small scale of the projects and lack of gas distribution in Chile, it would be uneconomical to convert biogas into biomethane on a large scale.

4.3.3 Hydrogen supply potential and projects

Chile currently produces circa 200 Kt/year of hydrogen[123] to supply ENAP's (Empresa Nacional del Petróleo) refineries and a glass manufacturing plant.[124] Most of the hydrogen is produced from natural gas using steam methane reform (SMR), whereas the glass plant consumes hydrogen produced from electrolysers.[125]

Chile has increased the generation capacity from solar and wind five-fold since 2014 and, by 2030, the goal is to achieve 70 per cent of power generation with renewable energy. According to the five scenarios projected by the Ministry of Energy, renewable energy will account for 82-88 per cent of total

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[122] https://docplayer.es/15819049-Biogas-de-la-farfana-aprovechando-la-energia-hecha-en-chile-i-ian-d-nelson-ii-metrogas-s-a.html
[123] (IEA (b), 2021)
[124] https://energia.gob.cl/sites/default/files/proposicion_de_estrategia_regulatoria_del_hidrogeno_para_chile.pdf
[125] (GIZ - Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 2018)

generation by 2050.[126] Chile has excellent wind and solar regimes in different regions in the north and south, which are assets for the development of a green hydrogen proposition.

In 2020 Chile unveiled its National Green Hydrogen Strategy,[127] based upon its vast potential of solar and wind energy, and aiming to serve the domestic market and to position Chile as a world class hydrogen exporter. Being a natural gas and coal importer, Chile has not developed plans to produce blue or grey hydrogen.

Wave I 2020-2025 **-** Domestic ramp up and export preparation, aimed at supplying the following sectors, underpinned by 5 GW of electrolysis capacity

- Oil refineries
- Ammonia production
- Heavy duty trucks
- Long range buses

Wave II – Includes the supply to mining haul and heavy-duty trucks, green ammonia exports (2025-2030), blending in the gas grids (max.20%), underpinned by 25 GW of electrolysers.

Wave III – Green hydrogen exports (2030 onwards)

In order to implement the hydrogen strategy, the Ministry of Energy unveiled an action plan based on four core pillars:

- Promotion of domestic and export markets
- Standards, safety and monitoring
- Capacity building and innovation
- Social and local development

The Ministry of Energy will coordinate and monitor the execution of the action plan with updates every three years, in coordination with the National Council for Green Hydrogen.

Hydrogen projects

In the wake of the announcement of the Green Hydrogen Strategy in 2020, 20 green hydrogen project concepts were disclosed by several players. By April 2021 this number had doubled to 40 potential projects.[128] They include transportation and substitution of fossil fuels, heat production in industry, green ammonia, methanol, and synthetic fuels for export, among others.

In April 2021 the Government of Chile started a tender calling for green hydrogen pilot projects, with funding of US$30 million available. The projects should be above 10 MW with completion by December 2025.

The largest proposed projects are summarized below:

- HyEx, being developed by Engie and Enaex Chile and located in Antofagasta, in the north of Chile. The project is based on solar PV which will feed 1.6 GW of electrolysers. Green hydrogen will be used in mining operations. The pilot project aims to install 16 MW of electrolysers by 2024.
- Highly Innovative Fuels (HIF), a joint development by AME, ENAP, Enel Green Power, Porsche and Siemens Energy. The project is located in the southern region of Magallanes, and Chilean Antarctica, and will use wind power to produce green fuels - 350 tons per year of methanol and 130,000 litres of gasoline per year. The pilot project consists of a 1.25 MW electrolyser with electricity supplied by a 3.4 MW wind turbine, whereas the commercial project is expected to

[126] https://www.energia.gob.cl/sites/default/files/documentos/20201230_actualizacion_pelp_-_iaa_2020_1.pdf
[127] (Ministerio de Energia - Chile, 2020)
[128] https://webpicking.com/chile-convoca-proyectos-de-hidrogeno-verde/

reach 1 GW. The pilot is due to start operations by 2022, with construction started in September 2021.[129]

Potential for hydrogen production

Assuming the higher efficiencies for solar PV and onshore wind given in the national hydrogen strategy and 76 per cent electrolyser efficiency,[130] the potential for green hydrogen by 2050 is estimated at 104 Mt/year although the strategy aims at a lower figure of about 24 Mt/year.

Table 9: Chile potential for green hydrogen production by source

	GW	Capacity factor	TWh	Mt H2
Solar CSP	509	20%[131]	892	17
Wind	191	60%	1004	19
Solar PV North	1180	35%	3618	68
Total Potential	1880		5514	104[132]
2050 Hydrogen Target	300	47%[133]	1235	24

Source: Authors estimates based on Green Hydrogen Strategy data

To put the numbers in perspective, Chile's national electricity system installed capacity reached 28GW in May 2021, of which 53.5 per cent was renewable (including 6.8 GW hydro, and 7.7 GW of solar/wind).[134] According to the Chilean government forecasts, power generation to supply the Chilean market is expected to increase from 77 TWh in 2019 to 220 TWh in 2050. Therefore, the electricity necessary to produce hydrogen under the Green Hydrogen Strategy (1235 TWh) is almost six times the supply of electricity to the whole of Chile's domestic market. Achieving the goals of the Hydrogen Strategy will be quite challenging, requiring a monumental mobilization effort, very large investments and dedicated renewable energy projects.

To achieve the Strategy's targeted annual production target of 24 Mt/year, it will be necessary to build 300 GW of electrolyser capacity, with a mix of solar and wind power supply, with an expected 76 per cent efficiency by 2050.[135] The CAPEX for the electrolysers is around US$800-840/kW (2020) and this is expected to reduce to US$130-307/kW by 2050.[136]

In order to meet the Green Hydrogen Strategy ambition for 2050, Chile will need to attract investments of about US$295 billion, as follows

- CAPEX electrolysers: US$39.0-92 billion
- Solar and wind plants CAPEX US$220 billion137
- Hydrogen pipelines connecting production facilities to domestic demand centres US$20-30 billion20

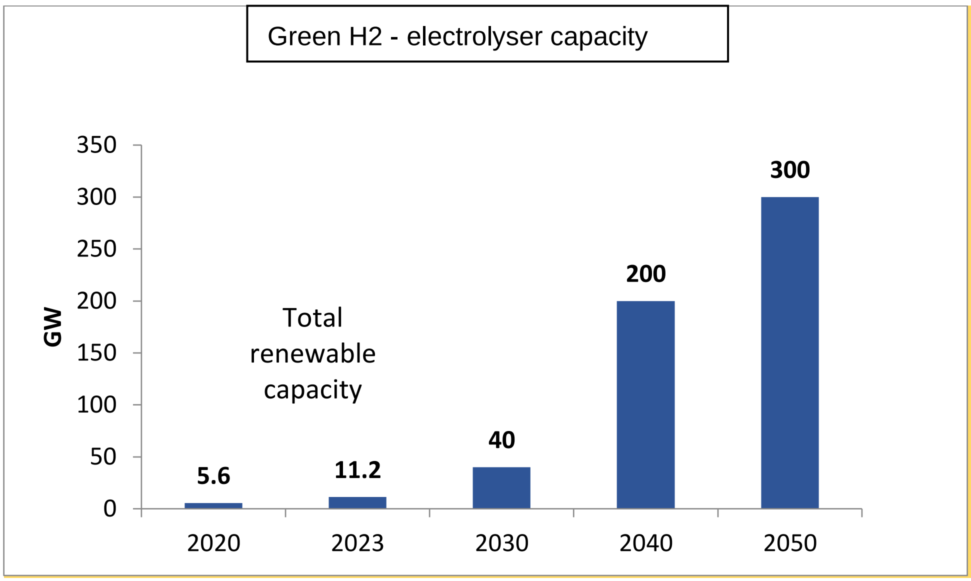
[129] https://www.energiaestrategica.com/comienza-la-construccion-de-la-primera-planta-comercial-de-combustibles-co2-neutrales-en-chile/
[130] 39.4 KWh and 53 KWh produce 1 kg of green hydrogen at 100% and 76% electrolyser efficiency, respectively
[131] https://www.brunel.net/en/blog/renewable-energy/concentrated-solar-power
[132] The lower range (92 Mt of hydrogen) does not include the contribution of CSP
[133] Assuming 50:50 solar and wind
[134] http://generadoras.cl/documentos/boletines/boletin-mercado-electrico-sector-generacion-julio-2021
[135] Efficiency expected to increase to 70-76% beyond 2030
[136] (IRENA, 2020)
[137] Figures based on IRENA midpoint CAPEX for solar and onshore wind in 2050. https://www.irena.org/-/media/Files/IRENA/Agency/Webinars/07012020_INSIGHTS_webinar_Wind-and-Solar.pdf?la=en&hash=BC60764A90CC2C4D80B374C1D169A47FB59C3F9D

The above costs do not include storage, transmission, distribution and other logistics costs. The figures also do not include the investment to convert hydrogen into ammonia, which is the most likely carrier for hydrogen exports. The figures are based solely on solar PV and wind electricity supply to the electrolysers, because the costs for Solar CSP (Concentrated Solar Power) in 2050 are still very high, based on the US National Renewable Energy Laboratory cost projections for 2050 of US$2800/4200/kW.[138]

The vessel-borne export of liquid hydrogen faces technical and cost issues; so green hydrogen will probably be converted into green ammonia, with production sites closer to port facilities. Therefore, renewable electricity needs to be transported to ports in the north (solar power) and south (wind), where the electrolysers and hydrogen-to-ammonia plants would be located.

By the end of 2020 the country's installed solar and wind capacity was 5.6 GW,[139] which should grow to 11.2 GW by 2023 with projects already being developed. The Green Hydrogen Strategy calls for 40 GW by 2030, 200 GW by 2040 and 300 GW by 2050. This implies a 13 per cent growth in the period 2023-2050 and 19.94 per cent growth in the period 2023-2030, as shown in Figure 16.

Figure 16: Chile expected growth of renewable capacity associated to hydrogen electrolyser capacity

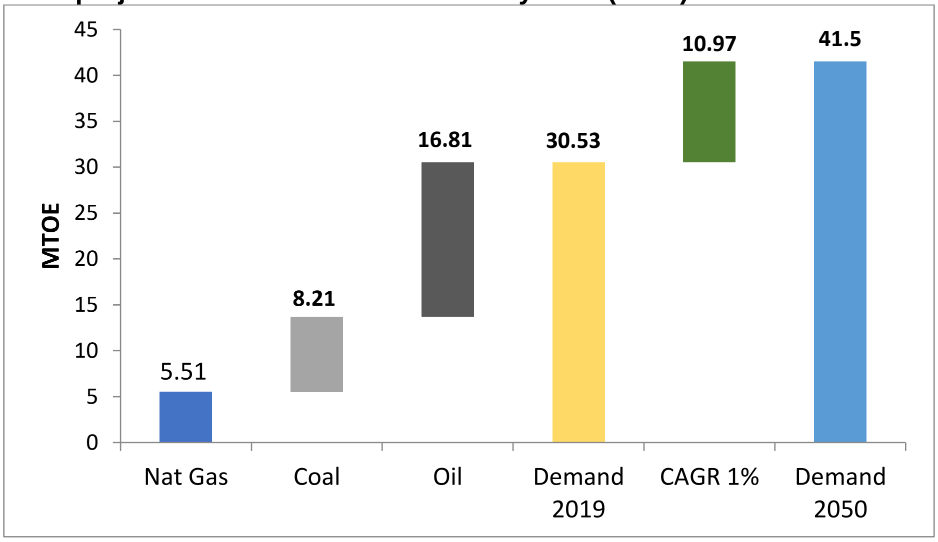


Source: (Ministerio de Energia - Chile, 2020)

In order to reach carbon neutrality by 2050 Chile would need to either replace all fossil fuels or capture/offset the carbon associated to any remaining fossil fuel utilization. Assuming a subdued compound annual growth rate (CAGR) of 1% per annum (compared to 3.1% in the period 2015-2019), the demand for fossil fuels by 2050 would be equivalent to 41.5 mtoe, as shown in Figure 17.

[138]https://atb.nrel.gov/electricity/2021/concentrating_solar_power#:~:text=From%202030%20to%202050%2C%20CSP,fall%20to%20approximately%20%244%2C213%2FkWe.
[139] Already reached 7.6 GW in April 2020

Figure 17: Chile projected demand for fossil fuels by 2050 (mtoe)



Source: Author estimate based on IEA database

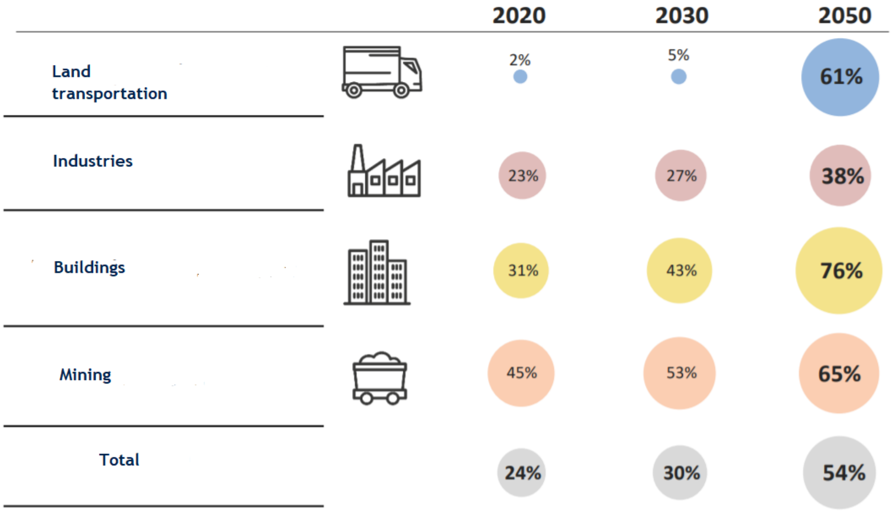
Assuming that all fossil fuels could be replaced by a combination of hydrogen and biomethane/biogas the potential – and theoretical - maximum domestic demand for hydrogen would reach 14.5 MtH_2/year by 2050,[140] which is equivalent to 60 per cent of the production volume targeted by the Green Hydrogen Strategy.

However, Chile's hydrogen strategy assumes that the domestic consumption of hydrogen will reach only 600 Kt/year in 2050, concentrated on heavy transportation, refining and fertilizer production. Due to logistics and costs issues, the domestic demand for hydrogen is estimated to reach only 2.5 per cent of the Strategy goal (24 Mt/year); therefore, most of the targeted production by 2050 will be for exports. Based upon the addressable production potential (as discussed in the biogas section), the contribution of biogas would be equally modest, about 0.08 Bcm/year of natural gas equivalent (75 Ktoe). The decarbonization goals for 2050 set by Chile are predicated on the progressive electrification of main economic sectors, from the 2019 level of 24 per cent to 54 per cent by 2050, with land transportation and industry becoming electrified by respectively 61 per cent and 38 per cent by 2050. The Strategy calls for blending up to 20 per cent of hydrogen in the gas distribution grid. The demand from residential, commercial and industrial sectors represents 1.5 Bcm/year; therefore, a 20 per cent blend is equivalent to only 0.3 Bcm/year of natural gas.

Under Chile's decarbonization pathway for 2050, natural gas will still play a role in power generation, industry and residential, where it is not possible to electrify. According to four decarbonization scenarios produced by the Inter-American Development Bank (IADB) for the Ministry of Energy, natural gas keeps the same absolute contribution in the power generation mix until 2050, and it would actually grow if all coal-fired power plants are discontinued as planned.[141]

[140] 1 ton of hydrogen=2.82 TOE
[141] https://energia.gob.cl/sites/default/files/20181204_presentacion_bid_reporte_macro_sesion_8.pdf

Figure 18: Chile outlook for electrification of economic sectors

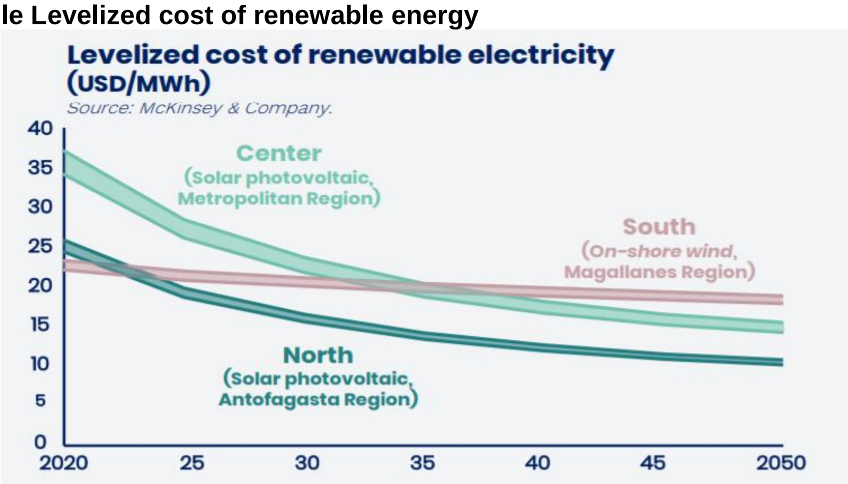


Source: (Generadoras de Chile, 2021)

Hydrogen cost and prices

To enable its 2050 hydrogen goals, Chile pledges to achieve one of the lowest costs of renewable energy generation worldwide, down from US$23-38/MWh in 2030 to US$13-20/MWh by 2050.

Figure 19: Chile Levelized cost of renewable energy



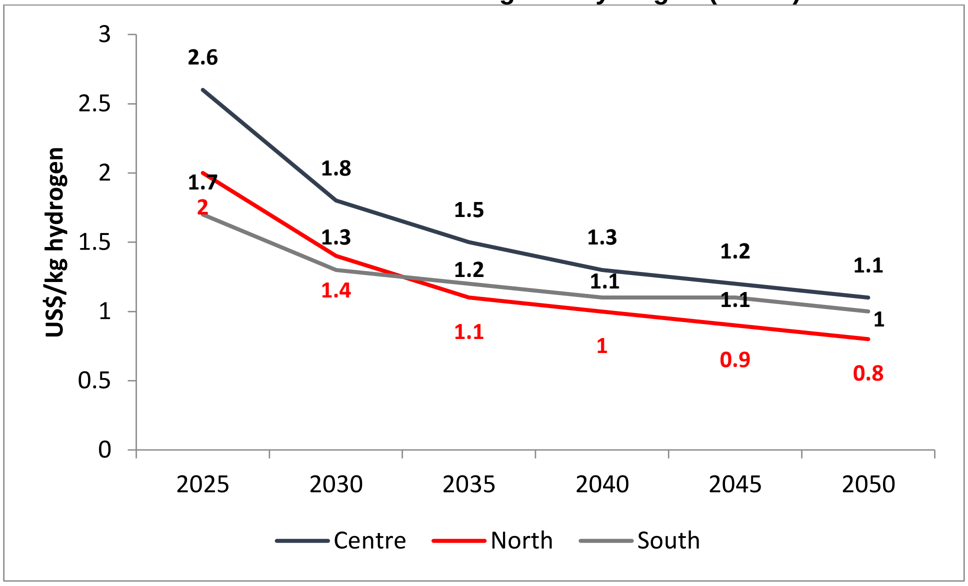
Source: (Ministerio de Energia - Chile, 2020)

Those lower renewable costs would enable the reduction of the cost of green hydrogen from US$1.7-2.6/kg (2025) to US$0.8-1.1/kg by 2050, which is very competitive when compared to other producing regions, as indicated by IEA regional analysis, which estimates that blue hydrogen from natural gas will cost around US$1-2 per kg by 2050, with green hydrogen at US$1.0-2.50/kg.[142, 143]

[142] (IEA (a), 2021)

[143] Electricity costs of US$20-25/MWh deliver hydrogen prices of US$1/kg

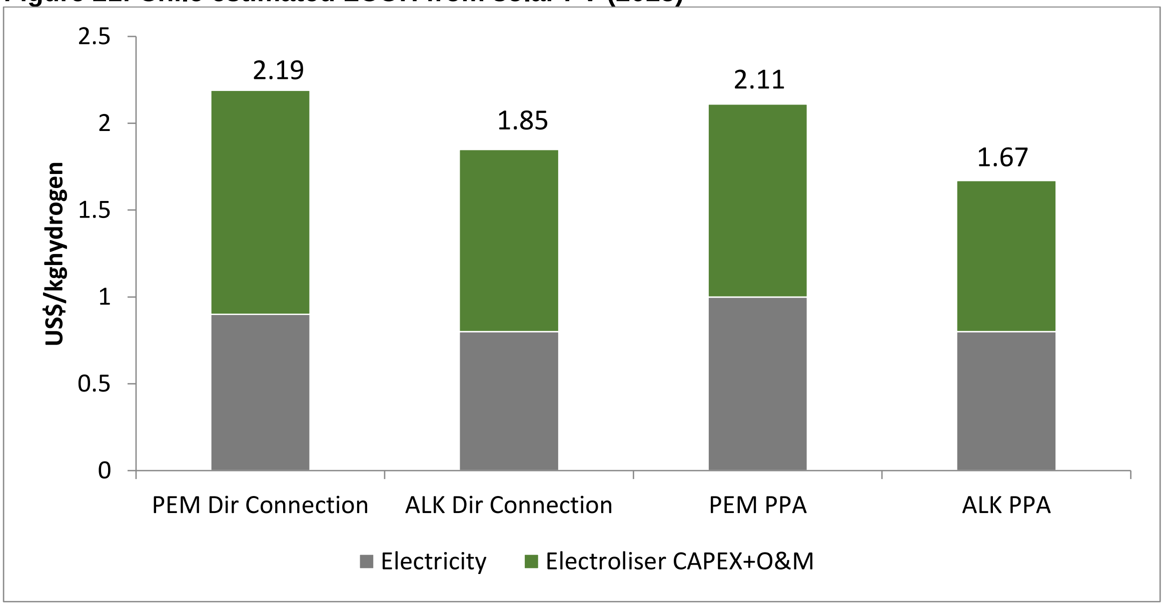
Figure 20: Chile outlook for the levelized cost of green hydrogen (LCOH)



Source: (Ministerio de Energia - Chile, 2020)

A study published in 2021[144] estimated the cost of hydrogen produced in the Atacama Desert, fed by solar PV either by direct connection of the electrolyser to the solar array, with a PV efficiency of 32 per cent, or via a PPA, which allows for higher capacity factors and lower electrolyser CAPEX. The study calculated the LCOH using PEM and Alkaline electrolysers and considered a cost reduction of 25 per cent by 2025. The author also calculated the costs using electricity supply from CSP plants, estimated at US$2.7/kg$H_2$ by 2025 (not shown in Figure 21).

Figure 21: Chile estimated LCOH from solar PV (2025)



Source: (Gallardo, 2021)

These costs are quite competitive, in particular regarding the alkaline technology, if electricity is supplied via PPAs which increases the number of hours of operation.

[144] (Gallardo, 2021)

Hydrogen costs for Chile are in line with Bloomberg New Energy Finance (BNEF[145]) estimates that green hydrogen could be produced for US$0.8 - 1.6/kg in most parts of the world before 2050. This is equivalent to a natural gas price of US$6-12 /MMBtu if hydrogen is used directly as a fuel.

Table 10: Chile and international benchmark hydrogen costs

Technology	Hydrogen costs (US$/Kg)	Natural gas equivalent price US$/MMBtu
Green H2 2020 (worldwide)	3.3-6.5[146]	24.78-48.8
Grey H2 (without CO2 capture) 2020	1.5 -1.80[147] [94]	11.2-13.5
Blue H2(SMR[148] [86] with CO2 capture and storage) - 2020	2.1 -2.40	15.8-18.0
IEA projections green H2 2030	1.7-3.4	12.8-25.5
IEA projections for green hydrogen 2050[149]	1.0-2.5	7.5-18.8
Chile green H2 2025[150]	1.6-2.7	12-20.3
Chile green H2 2050 [99]	0.8-1.1	6.0-8.3
Chile gas/LNG import price	5.0-10.0[151]	5.0-10.

Source: Industry sources and IEA

The cost of hydrogen in 2025 is expected to be two to three times higher than the price of natural gas, and this might be a barrier to supplying hydrogen to the domestic market, unless the government implements carbon price mechanisms to level hydrogen costs with natural gas import prices, which is yet to be considered. That is why it is very important to ensure hydrogen costs of US$0.8-1.1/kg by or before 2050, equivalent to natural gas prices of US$6-8.3/MMBtu. In the period 2025-2030 the economics indicate that it makes sense to replace higher priced diesel in heavy vehicles and mining equipment.

Another point of attention relates to the availability of fresh water to feed the electrolysers. The production of 24 Mt/year of green hydrogen in 2050 will require about 216 million cubic metres per year[152] of fresh water to run the electrolysers. This represents around seven per cent of the ground water used for human activities in Chile and might become a serious problem in the future as some regions are already facing hydric constraints and water scarcity.[153] [154] In view of this issue, it is possible to use desalinated water, which would add around US$$0.02/kg hydrogen (1.5-2% of the cost of US$1/kg in 2050[155]).Chile has already 83 desalination plants in operation, most of them supplying the mining industry in the Antofagasta region.

Hydrogen: key factors and barriers

- With regard to green hydrogen, the availability of water in regions such as the Atacama Desert in the north and Patagonia in the south might be an issue; those regions are further away from the ocean, which make it difficult to use of desalinized water. Therefore, it seems more viable

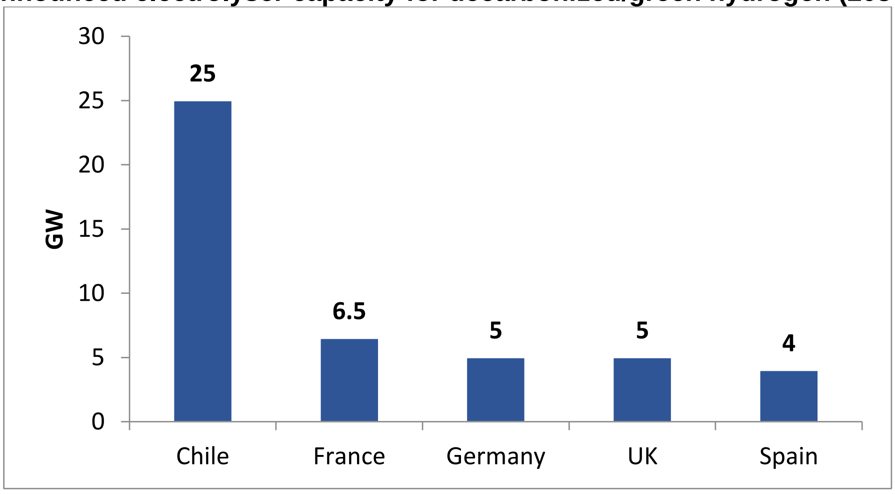
[145] https://www.spglobal.com/platts/en/market-insights/latest-news/coal/033020-green-hydrogen-costs-can-hit-2kg-benchmark-by-2030-bnef; https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf
[146] Based on electrolyser @US$750/kW, electricity cost US$30-100/MWh, load factor 20-30%. https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf
[147] (IEA (b), 2021). Natural gas prices US$3.5-4/MMBtu
[148] SMR: Steam methane reforming
[149] (IEA (a), 2021)
[150] (Ministerio de Energia - Chile, 2020), includes CSP and Solar PV
[151] From various sources, including Argus LNG Daily and US EIA
[152] 1 kg of green hydrogen requires 9 litres of water ((IEA, 2019)
[153] https://www.bnamericas.com/en/features/spotlight-chiles-water-shortage-problems-reach-its-rainy-south
[154] (Duran-Llacer, 2020)
[155] (IEA, 2019)

to transport lower cost renewable electricity produced in those regions to demand centres and export ports, which would have the electrolysis and ammonia plants. This will require investment in new power transmission lines and reinforcement of the existing grid to cope with the additional load and the intermittency of the renewable energy supplies.

- Chile does not have a comprehensive gas transportation pipeline network, therefore the transportation of hydrogen from the production regions to domestic demand centres, such as the Santiago metropolitan region and mining sites in the north, will require the construction of new infrastructure, resulting in additional transportation costs. Those costs might add US$0.2-04/kg to the cost of hydrogen.
- In the period 2025-2035, the cost of green hydrogen does not seem competitive with domestic and imported natural gas prices, therefore carbon price mechanisms would be necessary to allow for the substitution of hydrogen for natural gas in some industrial segments and for blending in the gas grid. The current domestic tax on carbon (US$5/ton) is insufficient, with some authors suggesting carbon prices ranging from US$50-200/ton to allow for fuel switching.[156]
- Due to the intermittency of renewable energy sources, a hybrid solution of purchasing electricity via PPAs would allow a high load factor for the electrolysers. However, despite renewable energy prices expected to go down to US$20-25/MWh, as of April 2021 the marginal costs of electricity at the main connection systems were still high, at US$68-76/MWh.
- Europe is one of the largest markets for green hydrogen but distances from Chile are significantly higher when compared to other hydrogen export markets such as the USA, North Africa and NE Brazil. The transportation of molecular hydrogen by ship is not yet economically and technically viable, therefore hydrogen would have to be converted into ammonia at the export facilities, adding additional conversion and storage costs which have not yet been quantified.
- The IEA projects a global production of 306 Mt/year of green hydrogen, requiring 3600 GW of electrolyser installed capacity. Chile's targets are very ambitious, accounting for eight per cent of the world's hydrogen production and electrolyser capacity. To put this into perspective, it is equivalent to India's ambition for 2050. The implementation of this strategy will require considerable investment and efforts in local capacity and engineering.

Chile's plans to develop 25 GW of electrolyser capacity by 2030 also seem too ambitious when compared to countries in Europe, which have announced capacity developments of around 5 GW in the same period. Funding for new starters might also become a bottleneck; whereas France and Germany have pledged funds of US$8-10 billion to develop green hydrogen, Chile is making available only US$50 million to kick-start smaller projects.

Figure 22: Announced electrolyser capacity for decarbonized/green hydrogen (2030)



Source: (Zissler, 2020)

[156]https://www.lse.ac.uk/granthaminstitute/publication/how-to-price-carbon-to-reach-net-zero-emissions-in-the-uk/

The most immediate challenge is to implement pricing and regulatory mechanisms allowing the acceleration of the construction of new installed capacity for solar and wind from 11.2 GW in 2023 to 40 MW in 2030, (CAGR of 19.9%), considering the current challenging political and macro-economic situation in Chile. The new Constitution Assembly elected in June 2021 will be responsible for discussing and enacting the national economic and political model.

5. Regional potential for decarbonized gas

The consumption of natural gas in the three countries reached 89 Bcm/year in 2019,[157] which is the upper potential which could be theoretically replaced by a combination of biomethane and green and blue hydrogen. But, in reality, none of the three countries have so far developed a comprehensive decarbonization substitution policy for the domestic market. Table 11 summarizes the existing, planned and potential production of biogas and hydrogen.

Table 11: summary production and planned/potential decarbonized gas volumes (2019-2030)

	Biogas (Bcm/year[158])		Hydrogen (Mt/year)	
	Production 2019	Country potential (2030)	Production 2019	Planned/potential 2030
Argentina	<0.1	3.9-14.4[159]	0.3	NA
Brazil	1.83	11	0.4	0.7-1.0
Chile	0.17	1.72	0.2	2.0
Total	2.0	16.6-27.1	0.9	2.7-3.0

Sources: (IEA (b), 2021), (Ministerio de Energia - Chile, 2020), Engie[160]

The three countries have implemented biogas projects, but there is a lack of updated data on the resources, and projects are often developed on a one-to-one basis, depending on the type of the waste, its organic content and ownership (municipalities, sanitation companies, ethanol producers, etc.). It has not yet been possible to implement a national database of the resource potential due to the vast size of each country and the decentralization of the potential sources.

In regard to hydrogen, the three Southern Cone countries are endowed with resources to produce hydrogen from decarbonized and non-decarbonized sources as summarized on Table 12.

Table 12: Possible hydrogen sources and processes based on domestic resource abundance

	Decarbonized						Not decarbonized	
	Not based on fossil fuels			Based on fossil fuels				
	Renewable electrolysis	Nuclear electrolysis	Industrial by-product	Mixed sources	Methane Pyrolysis	Natural gas with CCUS	Steam methane reforming	Gasification of fossil fuels
Colour[161]	green	pink	white	yellow	turquoise	blue	grey	brown
Argentina	x	x	x	x	x	x	x	x
Brazil	x	x	x	x	x	x	x	x
Chile	x		x	x				

Source: Author elaboration based on National Energy Balances.

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[157] Since consumption went down in 2020 due to the pandemic, the authors used 2019 data
[158] Biogas with 60% methane content. In the case of Brazil, production of biogas refers to 2020
[159] 14.4 includes sequential crops, while 3.4 is limited to residues and effluents. Dale, B. E. et al. (2020) The potential for expanding sustainable biogas production and some possible impacts in specific countries. *Biofuels, Bioprod Biorefining*. 2020;14(6):1335-1347. doi:10.1002/bbb.2134
[160] https://umsoplaneta.globo.com/patrocinado/engie/noticia/2021/07/16/entenda-por-que-o-brasil-e-uma-potencia-de-producao-de-biogas-e-biometano.ghtml
[161] Although there is no standard defined for categorizing hydrogen according to its source or production technology, several initiatives have assigned colours to different combinations of sources and technologies However, it should be noted that the vector's characteristics are independent of these. See, for example: https://www.weforum.org/agenda/2021/07/clean-energy-green-hydrogen/

Argentina has gas resources and potential to develop grey, blue and turquoise hydrogen in addition to green hydrogen, whereas Chile and Brazil, which are net gas importers and have a large potential for renewable energy, will most likely follow the route towards green hydrogen.

Based upon renewable power projections for the regions by the IADB,[162] a gross and illustrative scenario for the potential production of green hydrogen in the three countries is estimated at 276 Mt/year by 2050,[163] with a total value of around US$276 billion/year.

The full development of green hydrogen would require electrolyser capacity of 4.3 TW, with required CAPEX for the electrolysers at US$1,200 to 1,900 billion and another US$4 to 5 trillion for the wind and solar power plants (Table 11). The figures do not include the CAPEX required to build ammonia plants, hydrogen pipelines, methanation facilities, power transmission lines and other logistics and storage costs.

This scenario does not intend to be a forecast, but an approximation of the potential production under a combination of gross energy production potentials, capacity factors, costs, and technology availability assumptions, which are likely to vary during the following years.

Given the high availability of wind and solar resources, illustrated in each country's sections, production potential is unlikely to be bound to resource constraints which are abundant, but to access and cost of financing, the construction of an adequate infrastructure (both on the energy side and on the domestic transportation/export side), as well as the most relevant factor; demand, materialised by the development of domestic markets, and the ability to compete with suppliers in Southern Europe and Africa,[164] as well as other factors summarised in the barriers section.

Additionally, and particularly for Argentina, vast natural gas resources (particularly unconventional gas in Vaca Muerta) show a relevant potential for developing natural gas-based hydrogen (through methane pyrolysis, natural gas with carbon capture, utilization and storage (CCUS) or steam methane reforming), which is not depicted below.

Table 13: Southern Cone gross green hydrogen potential, CAPEX and power capacity (2050)

Mt/year H2 (@ 53 kWh/kg H_2), 76% efficiency				
	Argentina	Brazil	Chile	Total
Solar PV	79.28	92.77	15.10	187.15
Wind	58.69	27.14	3.23	89.06
Mt/year	**137.98**	**119.91**	**18.32**	**276.21**
Value for the region, in US$ billion[165]				
	Argentina	Brazil	Chile	Total
H2 price US$1.0/kg	137.98	119.91	18.32	**276.2**
Required electrolyser capacity				
	Argentina	Brazil	Chile	Total
GW	2,080.8	1,932.1	300.0	4,312.9

[162] https://publications.iadb.org/es/publicacion/14076/la-red-del-futuro-desarrollo-de-una-red-electrica-limpia-y-sostenible-para

[163] Based upon 26% of the total gross renewable energy potential in Argentina, Brazil and Chile

[164] Regions with favourable wind and solar resources

[165] Billions = Thousands of Millions of US$

Required electrolyser CAPEX in US$ billion

	Argentina	Brazil	Chile	Total
Low	619	575	89	**1,283**
High	916	851	132	**1,899**

Required power generation CAPEX in US$ billion

	Argentina	Brazil	Chile	Total
Low	1,876	1,668	256	**3,801**
High	2,680	2,646	416	**5,742**

Source: Authors elaboration based on industry sources and authors assumptions

6.Summary, conclusions and long-term perspectives

6.1 Summary

Over the last 20 years, hundreds of biogas projects have been implemented in Argentina, Brazil and Chile on a regional and scattered basis. Biomethane and hydrogen initiatives have been promoted more recently, spurred by policy discussions and new targets for decarbonization and the prospects for building hydrogen production capacity for export.

The production of biogas and biomethane is a significant potential source of decarbonized gas in Argentina and Brazil, but not so much in Chile; the most scalable sources are sewage/landfill projects in metropolitan areas and rural projects in sugar/ethanol/agriculture producing regions. The combined potential in the three countries could reach 16.6-27 Bcm/year of biogas led by Brazil's large population and agriculture sector.

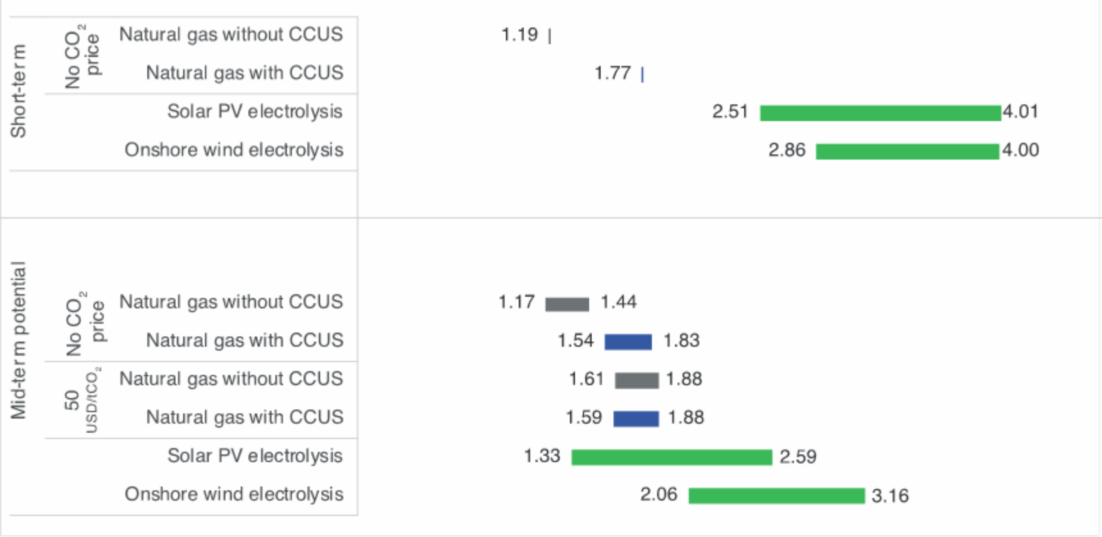
The small scale and decentralization of sources – agriculture, sewage, landfill - weigh down the economics of biogas/biomethane projects and the existing regulatory frameworks are not yet sufficiently developed to encourage extensive implementation of projects in the three countries. The most common utilization of biogas is combustion on site to produce electricity.

The implementation of biomethane projects is more challenging because usually the cost of production is higher than the price of natural gas. Therefore, the adoption and enhancement of carbon pricing, support mechanisms and minimum blend obligations in the gas distribution grid would probably be needed to foster new projects. So far there are very few biomethane projects in operation in the three countries.

According to IEA data, the levelized costs for hydrogen production in the region are not yet competitive,[166] albeit in line with international costs, with natural gas without CCUS costs remaining 50 per cent below those of green hydrogen. From 2025-2030, solar PV seems the most competitive source for green hydrogen. In the case of Chile, and most likely in the other two countries, the economics improve if the supply of solar PV electricity is topped up by PPAs, which increase the daily availability for the electrolysers.

[166] Other sources place onshore wind electrolysis costs, particularly in the Provinces of Santa Cruz and Chubut, Argentina at 2.5 US$/kg$H_2$ levels. Rabinovich, J. (2020)

Figure 23: Levelized costs of hydrogen in Latin America short/midterm (2020-2030) (US$/kgH2)



Source: Adapted from (IEA (b), 2021). All rights reserved

The vast resource availability, most likely several orders of magnitude above potential demand, shows that the development of a regional Southern Cone market for hydrogen will likely be partially hindered by the limited availability of interregional pipelines and the pace, cost-competitiveness, and extent of the adoption of hydrogen for domestic end-use sectors.

- Argentina is well connected to Chile by pipeline, but Chile is already developing its ambitious green hydrogen strategy, with most of the production intended to be exported, so Chile might possibly restrict imports or transit of imported blue hydrogen from its neighbour.
- Uruguay, on the other hand, is not likely to import blue hydrogen from Argentina,[167] as it has surplus and curtailed renewable power generation[168] capacity of its own which could be used to produce domestic green hydrogen. Uruguay has already begun to explore the development of green hydrogen through several cooperation agreements, including the development of pilot projects for the production, domestic use and export of green hydrogen, such as Proyecto Verne[169] and an agreement with the port of Rotterdam for the development of a hydrogen supply chain.[170]
- Argentina's exports to the larger southern Brazil market depends on the construction of at least 600 km of pipelines in Rio Grande do Sul state.

6.2 Conclusions

The deployment of biogas and hydrogen can effectively support the decarbonization agenda in Southern Cone countries. There is widespread experience and knowledge of biogas production and utilization, but not in the case of decarbonized hydrogen (blue and green).

For biogas it is necessary to acquire and disseminate accurate and comprehensive information regarding the quality of biomass (landfill, sewage and agriculture) and its geographical distribution. Therefore, governments should support the creation of national databases and robust georeferenced energy data.

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[167] Via the Argentina-Uruguayana (Brazil) and Litoral and Cruz del Sur (Uruguay) pipelines.
[168] This phenomenon has currently (2020-2021) been halted in Brazil's increasing needs for electricity to substitute reduced domestic availability in a low-hydrology season and declining Bolivian gas production
169 https://www.ancap.com.uy/innovaportal/file/8385/1/verne---presentacion-general-agosto-2020-web.pdf
170 https://www.gub.uy/ministerio-industria-energia-mineria/sites/ministerio-industria-energia-mineria/files/documentos/noticias/Hydrogen%20-%20Uruguay%20%26%20Port%20of%20Rotterdam.pdf

The conversion of biogas to biomethane – from landfill and sewage treatment plants – makes sense in cities which have natural gas grids, in particular in the metropolitan areas of Buenos Aires, Sao Paulo, Rio de Janeiro and Santiago. Due to the higher cost of biomethane, when compared to natural gas, governments might need to implement carbon taxes on their competitors, carbon price schemes and/or temporary subsidies. Gas distribution companies could benefit from local resource availability, particularly in regions far from traditional hydrocarbon basins.

The supply of green hydrogen to replace and/or blend with natural gas in the domestic markets is likely to face hurdles considering the limited pipeline capacity in Brazil and Chile. Argentina, on the other hand, has an extensive pipeline network which could at least be partially retrofitted to transport hydrogen to demand centres or to be blended into natural gas; however, domestic gas prices in Argentina are largely subsidized and broad enough carbon pricing mechanisms to include natural gas have not been implemented. A relevant opportunity to facilitate the insertion of hydrogen into Argentina's energy mix is through methanation of green hydrogen, introducing a vector (energy carrier) compatible with the country's current infrastructure and end-use equipment.

Another hurdle for blue hydrogen is the limited availability of underground sites for storing carbon dioxide, although several sites in Patagonia (both Chile and Argentina) are being studied to assess carbon capture potential and costs.

If developers decide to build green hydrogen production facilities near renewable energy sources, which are often far from demand centres, this will require dedicated pipelines and/or truck transportation and possibly storage facilities.

In order to develop competitive blue and green hydrogen projects at efficient scales, the most immediate alternative is to install the facilities near existing ports. This would create opportunities for the development of industrial and exporting hydrogen-powered hubs, harnessing synergies between basic resource availability, domestic demand, and production and export capacity. The three countries are considering the opportunity to transform existing ports into green hydrogen export facilities.

If hydrogen is obtained via electrolysers powered by grid electricity and underpinned by PPAs, transmitted via regional or national grids, it will be necessary to develop and/or adopt internationally accepted certification processes to convince customers (particularly importers) that the electricity used to produce hydrogen actually comes from renewable sources. Tracing and certification are likely to become critical to enable traceability and ensure market (mostly supply-side) transparency.

The production of green hydrogen entails the production of oxygen as a by-product; therefore, further analysis is required of the opportunities to generate additional income flows from oxygen production to be used for other industrial and medical applications. A similar situation occurs when hydrogen is produced in conjunction with carbon capture and use technologies, such as blue or turquoise hydrogen, where the gaseous (blue) or solid (turquoise, through methane pyrolysis) carbon is obtained and could be potentially, or at least partially, monetised thus benefitting from potential circular carbon economy initiatives.

There are also issues regarding the role of the development of hydrogen as a domestic, cost-effective mitigation alternative for the three countries. In domestic markets, hydrogen competes with low-carbon and cost-effective options such as liquid biofuels (mostly in Brazil and Argentina), where markets have been developed for more than a decade, as well as with the electrification of energy end use in several sectors, which could be attained using the power generation required to run electrolysers. Notwithstanding that, domestic markets could be limited due to infrastructure bottlenecks and the effect of competing prices, or at least decreased by mitigation costs (measured as the differential cost vs. the displaced energy source over avoided emissions). However, other attractive niches could be found, for example in heavy and petrochemical industries, as well as in freight transport (both land and water transportation).

In the case of green hydrogen, water availability might be a challenge for the installation of electrolysers near electricity supply, particularly in the north of Chile and Northeast Brazil, which are very attractive for solar and wind projects, but which have been facing hydrological constraints and droughts over the last few years.[171] However, desalination of sea water might be an option, while adding only about two per cent% to hydrogen costs.[172]

If Carbon Border Adjustment Mechanisms (CBAM) — such as those under consideration by the European Union, United States and China — are put in place, pressure to reduce lifecycle carbon content for regional exports is likely to incentivize the use of hydrogen in heavy industries when renewable electricity alone cannot adequately supply these sectors end use.

In this context, in order to achieve efficient production scales, a large proportion of the hydrogen produced would be destined for export markets. Since NDCs and national emissions/mitigation accounting methodologies are focused on mitigation within each country's boundaries, and not on reduction of emissions through the use of hydrogen at export destinations, only a small proportion of hydrogen production would contribute to comply with the producer country's mitigation pledges. This circumstance may result in a possible divergence between mitigation strategies and hydrogen development strategies, meaning that hydrogen will contribute to regional mitigation only if significant domestic and regional markets are developed or if (currently non-existent) mechanisms to acknowledge, quantify and account for this contribution to mitigation abroad are eventually developed and put in place.

Although the three countries are pursuing decarbonized gas projects, initial planning is still in progress and there is a lack of sufficient coordination between government and policy makers to define targets for decarbonized gas and to decide what will be the role of hydrogen and biogas/biomethane. Technical capabilities for the development of projects and for a better understanding of hydrogen economics are currently being developed but long-term goals have not been set; this could be further enhanced by the implementation of specialized courses in universities and training centres.

6.3 Long-term perspectives

It should be noted that typical timeframes for the development of significant domestic markets and hydrogen production capacities are likely to place full hydrogen development beyond current NDC horizons (2030). Hence this technology's contribution to decarbonization is more likely to be appropriate for subsequent NDCs and be made a relevant component of low carbon Long-Term Development Strategies under the Paris Agreement (2050).

Due to these challenges and timeframes, a successful hydrogen development strategy and the selection of the right pathway (grey-to-blue-to-green, plain green, parallel pathways or dedicated export projects) should be integrated with comprehensive energy and climate action planning and long-term transition pathways. Consideration should be given to the three countries national priorities, resource availability, installed capacity and infrastructure, and regional integration opportunities, avoiding lock-in effects and the investment in assets at risk of becoming stranded by energy transitions. Additional consideration is needed of the potential for decarbonized gas to utilize otherwise stranded transport infrastructure, thus extending the economic life of installed physical capacity.

Technology for electrolysers supplied with intermittent electricity is not yet fully developed. To cope with idle capacity of electrolysers for green hydrogen and the intermittency of renewable energy, the need for energy storage systems has to be recognized in the structure of tariff regulation. In Brazil, the intermittency of renewable energy could be compensated by coupling the electrolysers with relatively abundant hydropower, thus increasing the plant capacity factor.

Worldwide, it is expected that by 2025, green hydrogen could become competitive with blue hydrogen (1.8-2.4 US$/kg) or with grey hydrogen if coupled with a US$60 per ton CO_2 price, according to the Hydrogen Council, 2020.[173] By 2030 green hydrogen could become competitive with grey hydrogen, at 1.2-1.8 US$/kg. However, a few fundamental questions remain to be answered:

[171] According to the Aqueduct Water Risk Atlas, published by the World Resources Institute (WRI) in 2019, the Brazilian states of Bahia, Piauí, Ceará and Rio Grande do Norte suffer from 'extremely high' levels of water crisis risk, similar to that of Middle Eastern countries.
[172] (Gallardo, 2021)
[173] When hydrogen is produced from natural gas, every €10 per ton CO_2 price adds about €0.1/ kg to the price of hydrogen

- Since hydrogen prices are expected to be much higher than natural gas at least until 2030-2035, will import countries effectively impose carbon pricing mechanisms through which differential prices are equalized?
- Exporting countries in South America will need massive investment in renewable energy capacity, electricity transmission, ammonia plants and H_2/NH_3 storage and port facilities. Investors will typically seek stable regulatory and institutional frameworks, which are not yet fully in place in any of the three countries. In conjunction with enhancing enabling conditions for long-term investment in the region, will new green, sustainable and transition bond markets contribute to supply the vast financial requirements?
- Exporting countries in the Southern Cone should have strategic concerns about their role as commodity hydrogen exporters to Europe and Asia, with importing countries reaping additional benefits as technology providers, and GHG mitigation ultimately being accounted for in importer countries mitigation commitments.
- Green hydrogen producing countries in South America should consider the benefits of also producing fertilizers. Brazil and Chile are net importers of these commodities.
- Hydrogen export country stakeholders will possibly require assurances that this new industry is conducive to the creation of local jobs and domestic value chain developments, will not further stress their water resources, and are consistent with the sustainable development of their economies.

The massive increase in renewable power capacity and increased water use requirements will also probably entail social and environmental issues such as dealing with perceptions and real impacts on local communities, indigenous rights, cultural heritage, biodiversity and protecting ecosystems.

On the other hand, there are a number of potential co-benefits resulting from the development of a decarbonised gas industry: including job creation; development of regional economies at the national level; strengthening of R&D capacities and creation of industrial clusters associated with the development of biogas, biomethane and hydrogen value chains; progress in reverting to specialization in primary products, as well as enabling the transformation of jobs related to the fossil fuel industry towards these nascent industries.

The Southern Cone countries will face the same challenges as many other countries in promoting green hydrogen projects: steep cost and learning curve of the projects, power grid and supply chain constraints, and infrastructure financing, with the additional challenge of developing a significant regional market.

The abundance and quality of resources and lower costs of renewable energy in the region create export opportunities contributing to compliance by European and Asian countries with their 2050 climate pledges, as well as creating new economic activities and growth vectors in the three countries. Hydrogen export projects could generate revenues in excess of US$276 billion/year but would require investment of US$5.0-7.6 trillion in solar/wind power and electrolysers (plus related facilities), which represents two to three times the combined GDP of the three countries.

7. Appendices

Appendix I: Summary indicators

Table 14: Argentina, Brazil and Chile summary energy and decarbonized gas potential

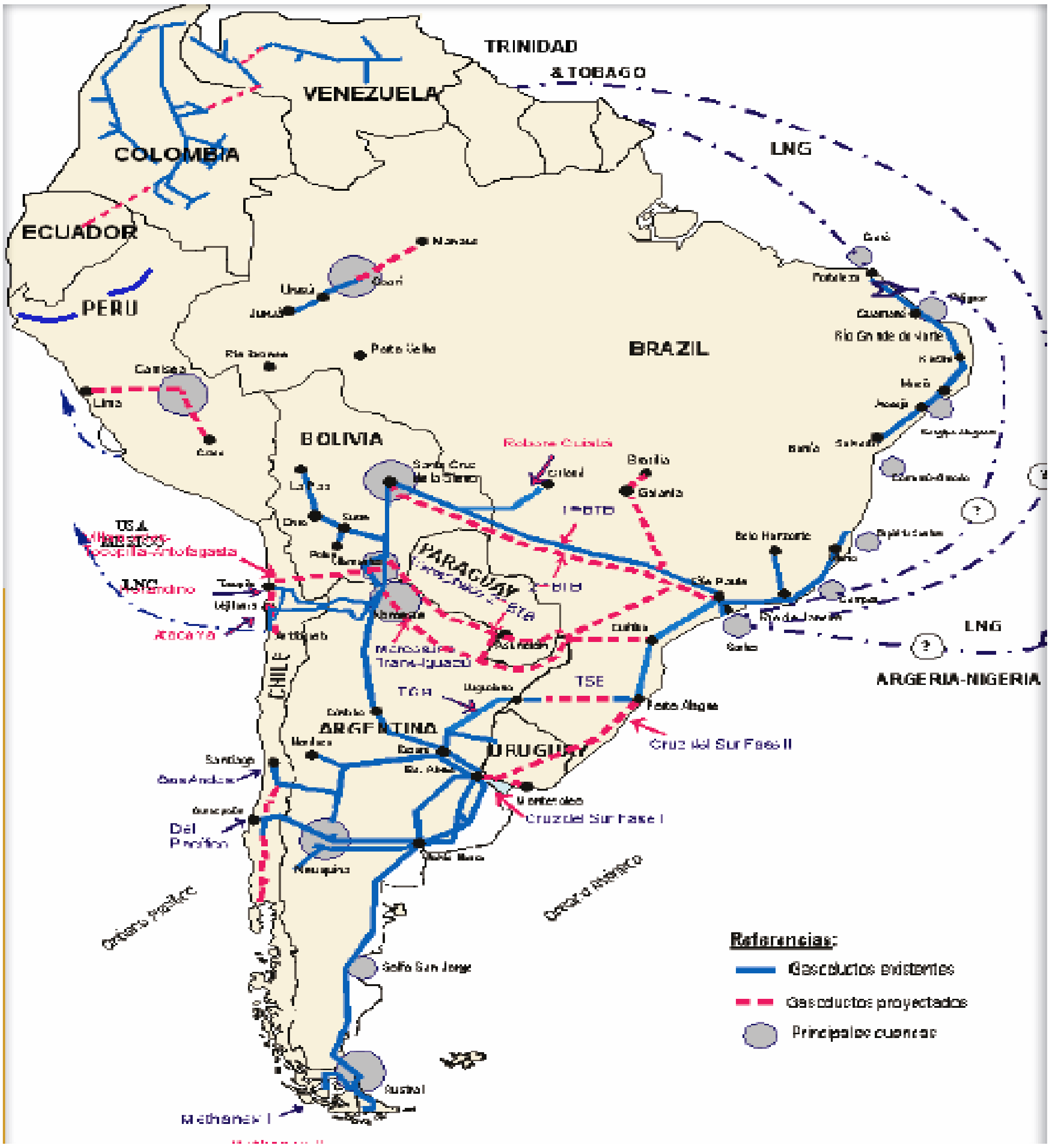
Figures for 2019		Argentina	Brazil	Chile
Primary Energy Consumption	Ktoe/year	82,707	296,251	39,549
Electricity Generation	TWh/year	139.93	625.60	83.88
Gaseous fuels production and consumption				
Gaseous fuels as % of Primary Energy Consumption	%	49.4%	10.4%	14.1%
% of Electricity Generation from Natural Gas	%	58.8%	9.4%	18.3%
Gaseous fuels as % of Final Energy Consumption	%	37.9%	3.6%	12.5%
Gaseous fuels as % of Energy Consumption for transportation	%	11.9%	2.1%	0.3%
Natural gas production	Bcm/year	41.65	25.84	1.34
Natural gas consumption	Bcm/year	47.44	35.76	6.51
Natural gas Import-Export balance	Bcm/year	(6.61)	(9.61)	(6.20)
Biogas production	Bcm/year		1.83	0.17
Hydrogen production	Kt/year	327.7	400	200
Biofuels production	Kboe/d	46.0	444.2	NA
Infrastructure				
Natural gas transportation pipelines	km	16,037	9,400	3,800
Natural gas distribution pipelines	km	82,337	47,000	7,400
Capacity of LNG import facilities	mtpa	7.6	22.3	5.5
Biogas and biomethane power generation installed capacity	MW	43.7	55.98	>36.0
Number of households consuming gaseous fuels through grid services	Millions	8.55	3.8	1.0
Energy-related emissions				
Energy-related emissions level	$MtCO_2e$	174.9	419.1	92.4
Energy-related emissions intensity over primary energy consumption	tCO_2e/Toe	2.11	1.49	2.34

Power generation emissions level	$MtCO_2e$	36.1	64.9	32
Power generation emissions intensity	tCO_2e/MWh	0.275	0.079	0.413
Climate and energy-related targets				
Current Nationally Determined Contribution target year	Year	2030	2025 and 2030	2030
Current Nationally Determined Contribution target		Absolute limit 359 $MtCO_2e$	Relative, 37% below BAU in 2025 and 43% below BAU in 2030	Absolute limit 95 $MtCO_2e$
Renewable Energy target (total) year	Year	2030	2030	2030
Renewable Energy target % of total		16.3%	33%	40%
Renewable Energy target (power generation) year	Year	2025	2030	2025
Renewable Energy target % of power generation		20%	23%	20%
Hydrogen production target year	Year	Under development	2050	2050
Hydrogen production target	Mt/year	Under development	Under development	24
Net-Zero pledges		Verbal, 2050	'Indicative', 2060	2050
Legislation and policy instruments		Promotion Law	Partially	Partially

Source: Authors elaboration from industry sources

Appendix II: South America natural gas pipeline infrastructure

Figure 24. Southern Cone transmission pipeline infrastructure



Source: http://nacionalistasperu.blogspot.com/2014/

Appendix III: Argentina biogas to power plants in operation

Table 15: Argentina biogas to electricity plants in operation (January 2021)

Station ID	Agent	Region	Province	Source	Capacity (MW)	Date
SMAN	C.T.SAN MARTIN NORTE 3- ENARSA	GRAN BS.AS.	BUENOS AIRES	Biogas	5.1	05/19/2012
SMIG	CT SAN MIGUEL NORTE III-ENARSA	GRAN BS.AS.	BUENOS AIRES	Biogas	11.5	10/04/2012
BRC1	CENTRAL BIOELECTRICA R.CUARTO1	CENTRO	CORDOBA	Biogas	2	07/22/2017
YANQ	BIO ENERGÍA YANQUETRUZ S.A.	CENTRO	SAN LUIS	Biogas	1.5	08/09/2017
SPEV	ENERGIA AGRO S.A.U	LITORAL	SANTA FE	Biogas	1.4	11/03/2017
BRC2	C.BIOELECT.R.CUARTO2 REN1	CENTRO	CORDOBA	Biogas	1.2	09/21/2018
BRC2	C.BIOELECT.R.CUARTO2 REN2	CENTRO	CORDOBA	Biogas	1.2	01/17/2019
AVEL	BIOGAS CT AVELLANEDA SECCO	LITORAL	SANTA FE	Biogas	6.3	03/16/2019
ENRS	BIOGAS RS CT ENSENADA SECCO	GRAN BS.AS.	BUENOS AIRES	Biogas	5.3	03/22/2019
BRC1	C.BIOELECT.R.CUARTO1 REN2	CENTRO	CORDOBA	Biogas	1.6	08/10/2019
CITR	BIOGAS CTBG CITRUSVIL-ALCOVIL	NOROESTE	TUCUMAN	Biogas	3	09/06/2019
GIG1	BIOGAS CTBG GIGENA I	CENTRO	CORDOBA	Biogas	1.2	12/11/2019
PERG	BIOGAS CTBG PERGAMINO	BUENOS AIRES	BUENOS AIRES	Biogas	2.4	12/21/2019
JDAR	BIOGAS CTBG JUSTO DARACT	CENTRO	SAN LUIS	Biogas	1	01/14/2020
TIGO	BIOGAS CTBG TIGONBU	CENTRO	SAN LUIS	Biogas	2	03/11/2020
VROS	BIOGAS CTBG VILLA DEL ROS. CGY	CENTRO	CORDOBA	Biogas	1	05/08/2020
PACU	BIOGAS CTBG PACUCA BIO ENERGÍA	BUENOS AIRES	BUENOS AIRES	Biogas	1	08/13/2020
GALV	CTBG GENERAL ALVEAR	BUENOS AIRES	BUENOS AIRES	Biogas	1	09/01/2020
VTBG	BIOGAS CTBG VENADO TUERTO	LITORAL	SANTA FE	Biogas	2.1	09/05/2020
	Total biogas				51.8	

Source: Author elaboration based on data from CAMMESA.

Table 16: Argentina biogas power plants under development, January 2021

Station ID	Agent	Province	Source	Capacity (MW)	Date (expected)
ABEF	C.T. ARREBEEF ENERGIA	Buenos Aires	Biogas	1.5	Oct-2020
RES1	C.T. RESENER I	Buenos Aires	Biogas	0.72	Oct-2020
GUAT	C.T. ENRECO. GUATIMOZIN. CORDOBA	Córdoba	Biogas	2	Oct-2020
ABBG	C.T. AB ENERGIA. 25 DE MAYO. LA PAMPA	La Pampa	Biogas	2	Oct-2020
YAN2	C.T. YANQUETRUZ II	San Luis	Biogas	0.8	Oct-2020
PSMA	C.T. POLLOS SAN MATEO	Córdoba	Biogas	2.4	Oct-2020
SCAB	C.T. BIOGENERADORA SANTA CATALINA. CORDOBA	Córdoba	Biogas	2	Nov-2020
LAMO	C.T. SANTIAGO ENERGÍAS RENOVABLES. LOS AMORES S.A.	Santiago del Estero	Biogas	3	Feb-2021
GCRS	C.T. GONZALEZ CATAN. BRS	Buenos Aires	Biogas (SWD)	5	Feb-2021
VCAN	C.T. BIOCAÑA. VILLA CAÑAS. SANTA FE	Santa Fe	Biogas	3	Dec-2022
	Total biogas dated			22.42	
GRA3	C.T. CAP. SARM. GRANJA TRES ARROYOS S.A.C.A.F.I.	Buenos Aires	Biogas	7.2	
MANG	C.T. EL MANGRULLO. SALADILLO. BSAS	Buenos Aires	Biogas	2	
VGAB	C.T. GENERAL VILLEGAS. BG.	Buenos Aires	Biogas	1.2	
HREN	BIOGÁS HUINCA RENANCO	Córdoba	Biogas	1.62	
JCRA	C.T. JAMES CRAIK	Córdoba	Biogas	2.4	
SFRB	C.T. SAN FRANCISCO BIOGAS	Córdoba	Biogas	2.4	
RICA	Biog. Ricardone	Santa Fe	Biogas	1.2	
BITA	C.T. BELLA ITALIA	Santa Fe	Biogas	2.4	
BOMB	C.T. BOMBAL BIOGAS	Santa Fe	Biogas	1.2	
REYB	C.T. DEL REY	Santa Fe	Biogas	1.2	
DONI	C.T. DON NICANOR. RECONQUISTA. SANTA FE	Santa Fe	Biogas	1.2	
RECB	C.T. RECREO	Santa Fe	Biogas	2.4	
RIC2	C.T. RICARDONE II	Santa Fe	Biogas	3.12	
	Total biogas not dated			29.54	
	Total Biogas			51.96	

Source: Author elaboration based on data from CAMMESA.

Appendix IV: Chile biogas potential by region and by source

Table 17: Chile potential biogas production by region (thousand m^3/year)

Region	Landfill	Sewage	Industrial waste	Agriculture waste	Total
I	1070	6458	101	25417	33046
II	606	7233	114	2175	10128
II	45	3818	1285	426	5574
IV	2049	8088	8422	8515	27074
V	0	22314	11951	35207	69472
Metropolitan	37034	104470	42459	337542	521505
VI	3480	33367	17681	500288	554816
VII	1693	9856	22043	72365	105957
VIII	5762	0	18811	105382	129955
IX	231	9245	6633	127839	143948
X	1318	10424	5884	80131	97757
XI	8	1078	339	3201	4626
XII	0	2315	688	3404	6407
Total	53296	218666	136411	1301892	1710265

Source: https://www.biorrefinerias.cl/wp-content/uploads/2017/12/CNE_J.A_Ruiz.pdf

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Units

Bcm = Billion cubic metres
Btu = British Thermal Units
$GtCO_2e$ = Gigatons of carbon dioxide equivalent
GW = Gigawatt
GWh = Gigawatt hour
Kboe/day = Thousand of barrels or oil equivalent/day
Kg/H_2 = Kilograms of hydrogen
Kt = Thousands of tons
Ktoe = Thousand of tons of oil equivalent
LCOH = Levelised Cost of Hydrogen
LCOA= Levelised Cost of Ammonia
m^3 = Cubic metres
m^3/d = Cubic metres per day
MMBtu = Million British Thermal Units
MMm^3/d = Million cubic metres per day
$MMNm^3/d$ = Million normal cubic metres per day
$MtCO_2e$ = Million tonnes of carbon dioxide equivalent
Mtpa = Million tonnes per annum
Mt= Million tonnes
mtoe = Million of tonnes of oil equivalent
MW = Megawatt
MWh = Megawatt hour
tCO_2e = Tonnes of carbon dioxide equivalent
Tons = metric tonnes
TWh = Terawatt hour
US$ = US dollars
US$/MMBtu = US$ per Million BTU

Glossary

ALK Alkaline water electrolysis
CAMMESA Compañía Administradora del Mercado Mayorista Eléctrico (Argentine Wholesale Electricity Market Dispatch Operator)
CBAM = Carbon Border Adjustment Mechanisems
CO_2 = Carbon Dioxinde
CO_2e = CO_2 equivalent
CCUS = Carbon Capture Utilisation and Storage
CSP = Concentrated Solar Power
ENAP = Empresa Nacional del Petroleo (Chile)
ENARGAS = Ente Nacional Regulador del Gas (National Gas Regulatory Board)
ENARSA = Energía Argentina S.A. (Argentine State-owned Energy Company), now IEASA
EPE = Empresa Brasileira de Pesquisa Energetica (Brazil)
GHG = Greenhouse gases
H_2 = hydrogen
MME = Ministry of Mines and Energy (Brazil)

NH_3 = ammonia
PEM = Polymer electrolyte membrane electrolysis
PV = Photovoltaics
Y-TEC = a joint company funded by YPF, Argentina’s National Oil Company with CONICET