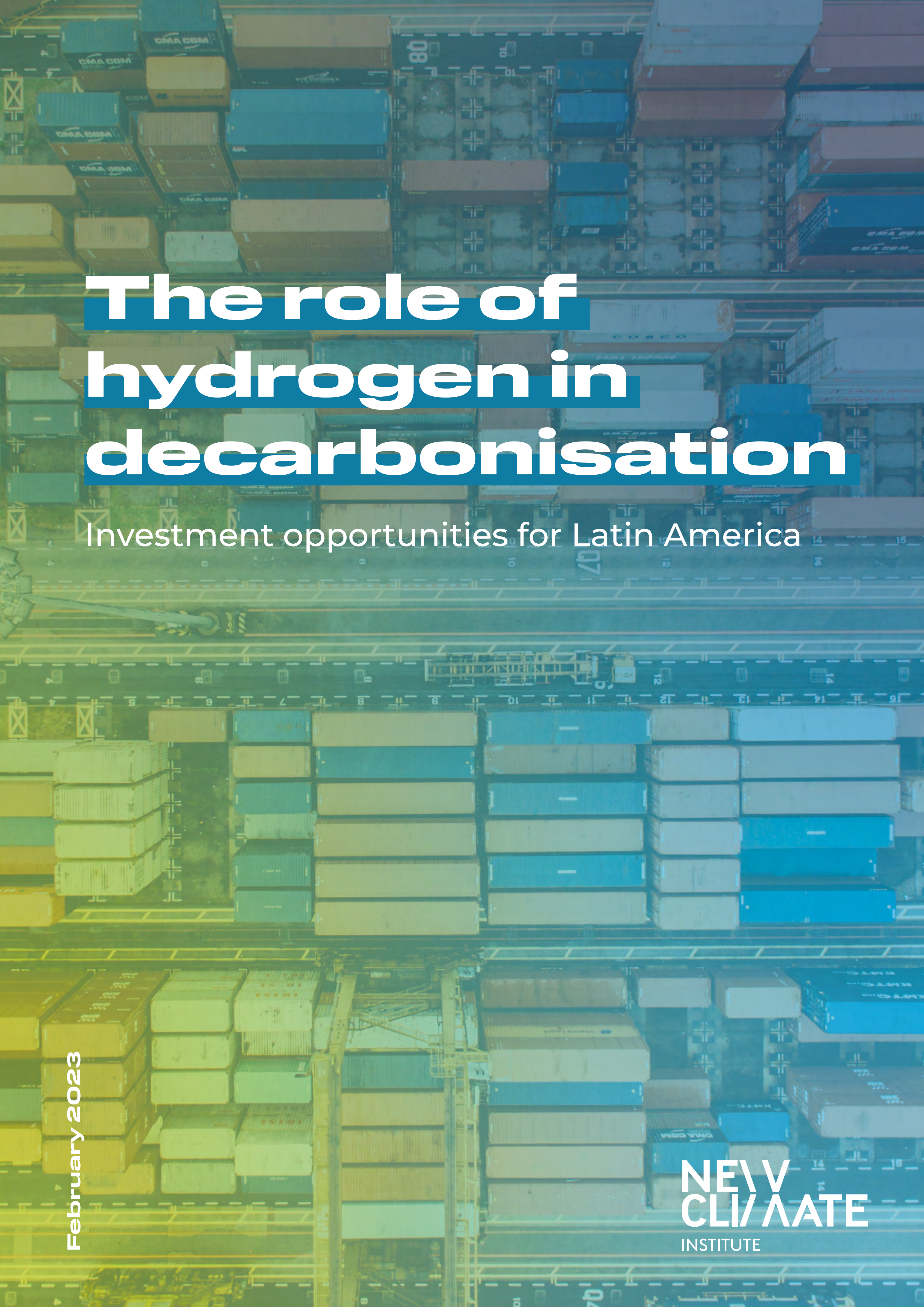

The role of hydrogen in decarbonisation

Investment opportunities for Latin America

February 2023

NEW CLIMATE INSTITUTE

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Acknowledgements

The compilation of this report was supported with discussion and inputs from a number of practitioners and experts. We are particularly grateful for inputs from Luciano Caratori, Micaela Carlino, Agustin Gogorza and Hernan Carlino (Fundación Torcuato Di Tella), Max Horstink and Rocío García (SouthSouthNorth). We would also like to thank Polina Korneeva (NewClimate Institute) for the graphic design and layout and Aman Gill-Lang (NewClimate Institute) for the editing.

This project is part of the International Climate Initiative (IKI), implemented by the Federal Ministry for Economic Affairs and Climate Action (BMWK) in close cooperation with the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) and the Federal Foreign Office (AA).

Project number

217002

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

INTERNATIONAL CLIMATE INITIATIVE

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Abbreviations

AA	Foreign Office
AE	Alkaline electrolysis
AEM	Anion exchange membrane
AR6	Sixth Assessment Report
ATR	Autothermal reforming
BF-BOF	Blast furnace-basic oxygen furnaces
CAPEX	Capital expenditure
CCUS	Carbon capture, utilisation, and storage
CO_2	Carbon dioxide
DRI	Direct reduction of iron
EAF	Electric arc furnace
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas
H_2	Hydrogen
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LAC	Latin America and the Caribbean
LCOH	Levelised cost of hydrogen
LH_2	Liquified hydrogen
LOHC	Liquid organic hydrogen carrier
MeOH	Methanol
NH_3	Ammonia
NG	Natural gas
PEM	Polymer electrolyte membrane
SMR	Steam methane reforming
SOE	Solid oxide electrolysis
TFC	Total Final Consumption
TFEC	Total Final Energy Consumption
TRL	Technology readiness level
WRI	World Resources Institute

Summary

The claim to reach climate neutrality by mid-century requires the phase out of all fossil fuels by 2050. This means that energy consumption must be reduced through efficiency measures and remaining energy demand must be met with renewable energies. Green hydrogen is seen as an important component of the energy transition and has taken centre stage in the international climate debate. Decarbonisation scenarios compatible with the Paris Agreement's target of 1.5 degrees all include hydrogen use in most sectors, albeit with different penetration levels.

The need for a fast transition is sometimes at odds with the limited (financial) resources available, and this is no different in the hydrogen "sector". The large number of applications where hydrogen has the potential to decarbonise practices or products makes the prioritisation of the most promising ones a critical step. All applications lie in a spectrum between "unavoidable" - where no other alternative exists for a full decarbonisation and "uncompetitive" - with other alternatives that exist and have the potential to be more efficient or cost-effective.

In the Latin American context, and specifically in **Argentina, Brazil and Peru**, this report evaluates many hydrogen applications based on their competitiveness, temporality and regional context. **Competitiveness** refers to the status of technology development, alternative decarbonisation options, and cost prospects. **Temporality** considers the timing of the investment, whether the technology is developed enough to have an impact on the short term and the potential lock-in of equipment or emissions if the investment is delayed. Lastly, the **regional context** considers the relevance of each application in light of the current and expected circumstances of the aforementioned countries.

The reports finds that hydrogen investments in the region should focus on green hydrogen production via electrolysis, making use of the region's vast renewable energy resources and the potential for hydrogen use locally and for trade.

Sectors especially in the **steel and chemical industry** should be prioritsed. The region could benefit from being an early adapter in the steel sector and can do this with a step-wise approach, initially making sure to invest in Electric Arc Furnaces and phase out Blast Furnaces, while prioritising the use of steel scraps and investing in Direct Reduced Iron technology as soon as it is commercially viable in the region. Industries where hydrogen is already used, such as methanol and ammonia production should also be considered for investment, as these products

are already being produced and their "greening" doesn't require new technologies. Green ammonia can be used to produce cleaner fertilisers, which is another large industry in the region.

In the transport sector, direct electrification is preferred in many applications, although heavy duty vehicles present an interesting opportunity. This is especially true in the mining sector, which requires large amounts of energy from fossil fuels and is often performed in remote locations.

An enabling environment will be key for these hydrogen investments to be attractive for international and commercial finance institutions. It will be vital for countries to provide the right policy signals and other financial measures to incentivise technological development and drive the effort towards a decarbonised economy.

About the Annual Investment Reportsin Latin America and the Caribbean

This report is the last of a series of three reports looking into investments needed to meet the climate mitigation objectives of the Paris Agreement in Latin America and the Caribbean (LAC). The report series focuses on private sector investment, and public policy instruments that can incentivise it, as private sector finance will need to be significantly scaled up to meet the investment needs of a transition to net zero emissions.

This third edition focuses on investment opportunities in green hydrogen, analysing hydrogen's role in achieving the objectives of the Paris Agreement and identifying investment opportunities that have the potential for transformational change to net zero emissions.

The report incorporates findings from Latin America—and the Caribbean when it comes to certain data points—and focuses predominantly on three countries of the region: Argentina, Brazil, and Peru. The analysis is mostly conducted for these three countries, but findings from the broader LAC region help provide context and highlight success stories for low and zero emissions developments.

The analysis for this report was mostly conducted between August and December 2022. Developments occurring after this period have mostly not been included.

01 Introduction

Achieving the Paris Agreement's objective to limit global temperature increase to 1.5°C compared to pre-industrial levels, requires that carbon dioxide (CO_2) emissions peak as soon as possible and reach net-zero levels by 2050, with other greenhouse gases (GHG) following a similar trajectory thereafter (IPCC, 2018). Decarbonising the global economy entails transition processes and transformations across all sectors, including energy, industry, buildings, transport, waste, agriculture, forestry, and land use. These rapid transitions and their associated technological, systemic, and socio-behavioural changes, although require higher up-front costs, will bring about long-term gains and benefits by limiting the impacts of climate change (Pathak et al., 2022).

Decarbonising the energy sector remains one of the biggest challenges to international climate targets. In 2019, energy services were responsible for 76% of global GHG emissions (WRI, 2022) and 81% of the primary energy supply was still based on fossil fuels (IEA, 2019b). Thus, building a net-zero energy system requires substantial investments to shift away from fossil fuels. The sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) stresses some common characteristics of future net-zero energy systems, including the reduction and phase-out of fossil fuel consumption, ramped up energy production from renewable and low-carbon sources, higher efficiency, reduced demand, and widespread electrification of end-uses, the use of alternative energy carriers, such as hydrogen, and CO_2 removal to offset residual emissions (Pathak et al., 2022). Some energy services, such as light-duty transport, lightning, heating, and cooling, are relatively easier to decarbonise through electrification and renewables. By contrast, activities such as aviation, long-distance transport, shipping, some chemical processes, carbon-intensive manufacturing industries (for example, steel and cement), and load-following and peaking power plants are more difficult to decarbonise (Davis et al., 2018). Specifically, due to the need for technology development and long infrastructure lifetimes in these 'hard-to-abate sectors', there is an urgent need to invest in their decarbonisation.

Hydrogen is expected to play an important role in future net-zero energy systems, mostly in hard-to-abate sectors where short and mid-term electrification is not viable. To secure energy supplies, which have been affected by the invasion of Ukraine by Russia, one of the world's most important oil and gas producers, the procurement of green hydrogen has become the focus of interest for many governments, especially Western industrialised nations. Presently, however, hydrogen production still relies on fossil fuels and has significant GHG emissions in the process value chains (**see → Chapter 2.1** for further details on hydrogen production technologies) (IRENA, 2019). Alternatives for low-carbon hydrogen, which are not yet widespread, range from green production with renewable electricity such as wind or solar, to hydrogen produced from nuclear energy, biomass, or fossil fuels coupled with Carbon Capture, Utilisation, and Storage (CCUS). Low-carbon hydrogen can then be used as a fuel or feedstock to produce other chemicals and energy carriers (Clarke et al., 2022). Potential applications of low-carbon hydrogen and its derivatives include the decarbonisation of aviation and maritime shipping fuels, ammonia and methanol production, and energy intensive industries such as steel and cement manufacturing. Hydrogen can also help store electricity produced from intermittent solar and wind resources and enable the integration of energy systems based on renewables, and thus contributing to solve issues of demand variability and seasonality (Griffiths et al., 2021).

Scaling up the application of low-carbon hydrogen will require dedicated investment strategies and targeted policies integrated in the overall energy sector to make technologies competitive and cost-effective. Research and development, pilot demonstration, and technology deployment should focus around no-regret industrial and power applications (BloombergNEF, 2020; IEA, 2021f). To de-risk infrastructure projects, governments and private actors, albeit with different roles and functions in this process, need to anticipate changes in energy demand and renewables production (Flis and Deutsch, 2021), create end-use demand, establish commodity markets, build value chains for low-carbon hydrogen (IEA, 2021c), avoid carbon lock-in (Janipour et al., 2020), and consider the social acceptance of hydrogen technologies (Scott and Powells, 2020). Some further challenges to a hydrogen economy include the development of transport and storage infrastructure, potential efficiency losses, the cost of capital, and geopolitical factors that will influence global trade (DNV, 2022; IRENA, 2022b, 2022c). In this sense, countries with supportive policies, long-term certainty, and ambitious decarbonisation targets will be able to create investment opportunities and foster low-carbon development (IRENA, 2022h).

In Latin America and the Caribbean (LAC), hydrogen has the potential to play a major role in the decarbonisation of the energy mix. The region has abundant renewable resources, which account for nearly one quarter of the primary energy supply[1] (OLADE, 2022), and renewable generation has also increased rapidly in the past years. For example, installed capacity of wind and solar photovoltaics (PV) grew more than thirty-fold between 2010 and 2021 (IRENA, 2022g). The estimated potential of renewable resources also exceeds the foreseeable demand for the next century (Vergara et al., 2015; Grottera, 2022), meaning that the region could use excess renewable energy to produce low-carbon hydrogen at competitive prices, contribute to local decarbonisation efforts and energy transitions, and even become a global exporter (IEA, 2021e).

1 Mainly due to the high share of hydropower.

Although renewable energy already represents an important share of the energy mix in some countries in the region, the rapid growth in energy and electricity demand in the region presents LAC countries with the opportunity to shift their energy mix even more towards renewables, which requires ambitious decarbonisation targets, public and private investment throughout the value chain, and institutional and regulatory frameworks. Most LAC countries rely on national and imported oil and natural gas, particularly for sectors such as transport, industry, and power generation (IRENA, 2022g).Thus, hydrogen can potentially help to decarbonise hard to electrify sectors, while at the same time tapping into the region's vast renewable resources and addressing concerns over energy security and increasing climate impacts. Although large-scale low-carbon hydrogen applications are still not commercially available, **investments in initial demonstration and infrastructure deployment in the next decade will be key to expand hydrogen use in a cost-competitive way.** According to the International Energy Agency (IEA) Hydrogen wil play an important role in the post-2030 decarbonisation effort, accounting for between 3% to 20% of final energy consumption by 2050 in net-zero scenarios. In this scenario, hydrogren production in the LAC region alone would need to increase 66% by 2030, and more than triple by 2050 to meet future regional demand (IEA, 2021e).

This report aims to provide recommendations on investment opportunities and needs in the LAC region to support the deployment of low-carbon hydrogen (**see ➔ Box 1** for a definition of low-carbon hydrogen). The analysis builds upon relevant literature and scenarios that describe the expected role of hydrogen in decarbonisation globally and potential applications in various sectors **(➔ Chapter 2)**. This is followed by an analysis of recent trends and the status of hydrogen demand and supply in the LAC region **(➔ Chapter 3)** and an analysis of the regional implications of this future demand for relevant sectors **(➔ Chapter 4)**. In **➔ Chapter 5**, relevant investment opportunities for the region are assessed and presented in a detailed evaluation matrix, with the prioritised applications then described in more detail. In **➔ Chapter 6**, specific insights and recommendations are provided for the LAC region as well as the three focus countries, Argentina, Brazil, and Peru.

02 Role of hydrogen in decarbonisation

Energy carriers – such as electricity, heat, and solid, liquid, and gaseous fuels help to transport energy from where it is produced (primary sources[2]) to where it will be consumed (end-uses). Future net-zero energy systems will require the carbon footprint of energy carriers to be eliminated or minimised. Energy transitions are expected to rely heavily on low-carbon electricity (for example, from solar or wind energy) and electrification of end-uses such as heating and transport. However, **low GHG liquid or gaseous fuels, such as hydrogen, ammonia, biofuels, and synthetic hydrocarbons, will be required to decarbonise applications across a range of different sectors that cannot be electrified easily** (**see ➔ Section 2.2** for further detail). All these fuels can have an important role in decarbonisation depending on technology improvements and deployment (Pathak et al., 2022). Interest in hydrogen is linked to its unique properties, which make it an excellent alternative to carbon intensive energy carriers like fossil fuels but also constrain its production, storage, transport, and usage **(see ➔ Table 1)**.

2
Primary energy refers to energy in its natural state, before it has undergone any human-made conversion process and can be either non-renewable or renewable.

Since hydrogen is not a primary energy resource, it needs to be produced from other renewable and non-renewable sources. Once obtained, it can be used as a fuel to produce heat or electricity in various applications such as combustion engines, turbines, or fuel cells, stored for future use, converted to other chemicals and fuels or used to replace carbon intensive industrial processes, such as steel production (for further details **see ➔ Annex 3**).

Table 1
Key properties of hydrogen

Occurrence	Hydrogen is the most abundant element in the universe and is commonly found on Earth as part of other compounds, especially water or hydrocarbons.
Density	Extremely light density in the gas state gas (0.089 g/L). In the liquid state, density is also very low (70.79 g/L).
Liquefaction	Accomplished by cooling rather than pressurization. At standard pressure (1 bar) hydrogen liquefies at -253°C.
Diffusivity	Able to pass through porous materials and metals, causing embrittlement or cracking. Storage requires special materials to prevent losses from diffusion.

Source: Authors based on (Griffiths et al., 2021; DNV, 2022)

The following sections summarise the different technological pathways for hydrogen production, as well as feasible applications in relation to the decarbonisation of the energy system.

2.1 Hydrogen production technologies

Hydrogen production can be based on fossil fuels, renewables, or other non-renewable energy sources. A colour nomenclature is typically used to label hydrogen depending on the feedstock and technological pathway used for its production, each with a different efficiency, technology readiness level (TRL), cost, and environmental impacts. The carbon intensity[3] of production pathways is useful to determine which technologies can better contribute to decarbonisation efforts. However, emission intensity can vary within pathways due to resource availability, particularities of local supply chains, and country-specific characteristics of energy systems (The Hydrogen Council, 2021; WEC, 2021). Moreover, other factors such as technology maturity, resource depletion, impacts on ecosystem quality, and effects on human health can also be used to assess the impacts of each pathway (Al-Qahtani et al., 2021).

Grey hydrogen is currently the most common form of hydrogen production. Grey hydrogen is obtained from natural gas, or methane, via steam methane reforming (SMR) or autothermal reforming (ATR) but without capturing the greenhouse gases that result from this process (Nikolaidis and Poullikkas, 2017).

Black and brown hydrogen are produced by reacting black coal or lignite (brown coal) with oxygen and steam at high temperatures, a process which is known as gasification (Vidas et al., 2021). Reforming and gasification are currently the most technologically mature and cost-effective processes for large scale hydrogen production but they result in significant GHG emissions either from the energy input or as a by-product, reducing its impact as a tool for decarbonisation (Osman et al., 2021).

Blue hydrogen is produced mainly from natural gas and incorporates carbon capture, utilisation and storage (CCUS) to separate CO_2 from the product stream and compress it for use or storage. Thus, blue hydrogen is sometimes described as 'low-carbon hydrogen'. Some challenges to the deployment of blue hydrogen applications are that CCUS systems are expensive to develop and operate (Griffiths et al., 2021), and concerns exist over upstream emissions of CO_2, for example during transport or storage (DNV, 2022). While blue hydrogen can have reduced emissions, it doesn't address the fossil fuel dependency of current energy systems.

Turquoise hydrogen is obtained by thermal or catalytic decomposition of natural gas (methane pyrolysis); since the process occurs in the absence of oxygen, the products are hydrogen and solid carbon instead of CO_2 emissions. The latter has potential market applications and can be stored more easily than CO_2, reducing capital and operational costs. However, methane pyrolysis is not a mature technology, with only pilot plants in early development stages. Despite these limitations, both turquoise and blue hydrogen are expected to have an expanding role in a net-zero future, particularly as cost-effective transition technologies while the infrastructure and end-use applications for the other types of hydrogen are

3 Expressed in tonnes of carbon dioxide equivalents (CO_2eq) per ton of hydrogen produced.

deployed (Parkinson et al., 2018; Al-Qahtani et al., 2021). However, similar toblue hydrogen, turquoise hydrogen also relies on fossil fuel extraction; methane leakage together with carbon lock-in risks could hinder mitigation efforts and the transition to a fossil-free energy future (Kemfert et al., 2022).

Nuclear power is another large-scale option to deliver low-carbon energy, including electricity to produce pink hydrogen through electrolysis. Concerns over **pink hydrogen** are the same as those for nuclear, namely high investment needs, cost overruns, disposal of radioactive waste, and varying levels of political support and public acceptance (Clarke et al., 2022).

Green hydrogen is produced from renewable electricity (solar, wind, hydropower) via water electrolysis. Electrolysis uses electricity to split water molecules into hydrogen and oxygen and produces the purest hydrogen, which is an advantage for further applications in many supply chains. Currently, there are four major electrolyser technologies with promising applications in large-scale green hydrogen production, each with varying maturity levels and efficiencies: Alkaline electrolysis (AE), Polymer electrolyte membrane (PEM), Anion exchange membrane (AEM) and Solid oxide electrolysis (SOE) **(see → Annex 2)**. Water electrolysis coupled with cheap renewable energy has the potential to become a cost-effective option for hydrogen production (Nikolaidis and Poullikkas, 2017) and is often considered to be the most promising production pathway for low-carbon hydrogen. In this context, the affordability and accessibility to freshwater is a key issue (Osman et al., 2021); availability of renewable energy and freshwater might not coincide in every location and competing uses may raise questions of justice in energy and water allocation and distribution. As this type of hydrogen is produced through the electrolysis of water using renewable energy sources such as wind or solar power, which results in zero GHG emissions and the only byproduct produced being oxygen, green hydrogen is considered one of the cleanest and most environmentally friendly methods to produce hydrogen.

→ Table 2 summarises the hydrogen colour scheme based on production technologies and provides data on their efficiency, carbon intensity, and TRL.

Depending on the source of the electricity, electrolysis can have minimal GHG emissions (associated to the life cycle of materials) and contribute to decarbonisation efforts. However, the high electricity consumption of electrolysers makes them currently less competitive than hydrogen obtained from natural gas through steam methane reforming (SMR) or coal gasification. **To become a more cost-effective option, all electrolyser technologies will need to improve in terms of their efficiency, hydrogen production rate, life span, capital cost, grid balancing options, system integration, and compactness** (Thomas, 2018) . Green hydrogen is also not impacted by fossil fuel price fluctuations, potentially increasing its competitiveness and making it independent of geopolitical changes. Moreover, investments are required to advance technology development, increase manufacturing capacities, standardise large-scale applications, and up-scale deployment of electrolysers (DNV, 2022).

Table 2
Hydrogen colours and production technologies

Base	Colour	Feedstock	Technology	TRL[a]	Efficiency (%)	Carbon intensity (g $CO_2eq/g\ H_2$)
Renewables	Green	Renewable electricity, water	Electrolysis (AE)	9	62-82	1-3 [b]
			Green	7-9	67-84	
			Electrolysis (SOE)	3-5	75-90	
		Biomass	Gasification	5-6	35-50	1-3
			Gasification with CCUS	3-5	35-50	Possibility of net negative emissions
		Biogas	Reforming	-	-	1-3
			Reforming with CCUS	-	-	Possibility of net negative emissions
Nuclear energy	Pink	Nuclear electricity, water	Electrolysis	3-9 [c]	62-90	1
Fossil fuel	Grey	Natural gas	SMR	9	74-85	10-16
			ATR	8	60-75	
	Black	Lignite or brown coal	Gasification	9	74-85	19-27
	Brown	Black coal				
	Blue	Natural gas	Reforming with CCUS	7-8	74-85	1-4
		Blue	Gasification with CCUS	6-7	74-85	4-11
	Turquoise	Natural gas	Pyrolysis	3-5	35-50	1-5

[a] The TRL index was developed by the U.S. National Aeronautics and Space Administration in the 1970s to track progress of technologies, from applied research (1) to successful system operation (9). It has been previously used to assess technological progress in the energy sector (Dawood et al., 2020). [b] Comparable to renewable power production infrastructure (1-20 gCO_2/kWh). [c] Depends on the electrolyser type.

Source: Authors based on (Thomas, 2018; Dawood et al., 2020; Al-Qahtani et al., 2021; Osman et al., 2021; WEC, 2021; DNV, 2022)

Depending on the source of the electricity, electrolysis can have minimal GHG emissions (associated to the life cycle of materials) and contribute to decarbonisation efforts. However, the high electricity consumption of electrolysers makes them currently less competitive than hydrogen obtained from natural gas through steam methane reforming (SMR) or coal gasification. **To become a more cost-effective option, all electrolyser technologies will need to improve in terms of their efficiency, hydrogen production rate, life span, capital cost, grid balancing options, system integration, and compactness (Thomas, 2018).** Green hydrogen is also not impacted by fossil fuel price fluctuations, potentially increasing its competitiveness and making it independent of geopolitical changes. **Moreover, investments are required to advance technology development, increase manufacturing capacities, standardise large-scale applications, and up-scale deployment of electrolysers (DNV, 2022).**

For LAC countries with already relatively high shares of renewables in their electricity mixes, grid-connected electrolysers could contribute to a gradual decarbonisation of the hydrogen supply. In order to be able to produce green hydrogen in the future, it is essential to invest in the complete decarbonisation of the electricity supply. In parallel, investments should be made in expanding the use of electrolysers, even if the electricity is not exclusively green, to help countries phase out the production of hydrogen from fossil fuels, including blue hydrogen pathways.

Hydrogen produced from biomass such as crops and crop residues, wood, and other types of biological waste is also often classified as green hydrogen. Although the process of gasification emits GHG, since biomass absorbs CO_2 during growth, the carbon footprint is considered minimal. This technological pathway has the potential to have net negative emissions if combined with CCUS (Al-Qahtani et al., 2021). Some challenges are that the efficiency of the process differs significantly depending on the feedstock (Iribarren et al., 2014), costs and complexity of biomass gasification are higher than coal gasification due to the need for biomass pre-treatment (Thomas, 2018), and yields are lower due to the limited content of hydrogen in biomass. Thus, scaling up this technology would require incentives and regulatory frameworks to make biomass-based hydrogen competitive with fossil alternatives (Osman et al., 2021). Other green hydrogen options include biogas reforming (Minh et al., 2018; Cvetković et al., 2021) and biomass pyrolysis (Nikolaidis and Poullikkas, 2017). As with other applications of bioenergy, large-scale production may raise environmental and social concerns such as food security and competition with food systems, deforestation, impacts on biodiversity, water consumption, and pollution from fertilisers (Heck et al., 2018; Clarke et al., 2022).

Box 1

Definition of low-carbon hydrogen

Due to the relatively low carbon intensity (per gram of hydrogen), green hydrogen produced on the basis of renewable energy and hydrogen produced with natural gas in combination with CCUS (blue) or pyrolysis (turquoise) can be considered low-carbon (**see → Table 2** for more details on the characteristics of the different production technologies). It should be noted, however, that unlike green hydrogen, blue hydrogen can have adverse climate impacts. While the use of blue hydrogen could, in theory, be close to CO_2 neutral, the efficiency losses that the production implies and the uncertainty around CCUS as well as upstream emissions from production and transport of, for example, natural gas make this technology costly and very risky. The focus for future capacity additions and investments in technological innovations and infrastructure should thus be on green hydrogen.

2.2 Potential applications of low-carbon hydrogen

While hydrogen is likely to play an important role in the global energy transition, the circumstances under which it can contribute to a truly sustainable and cost-efficient decarbonisation in different parts of the world must be carefully analysed. Three key points that should be considered in the expansion of hydrogen are:

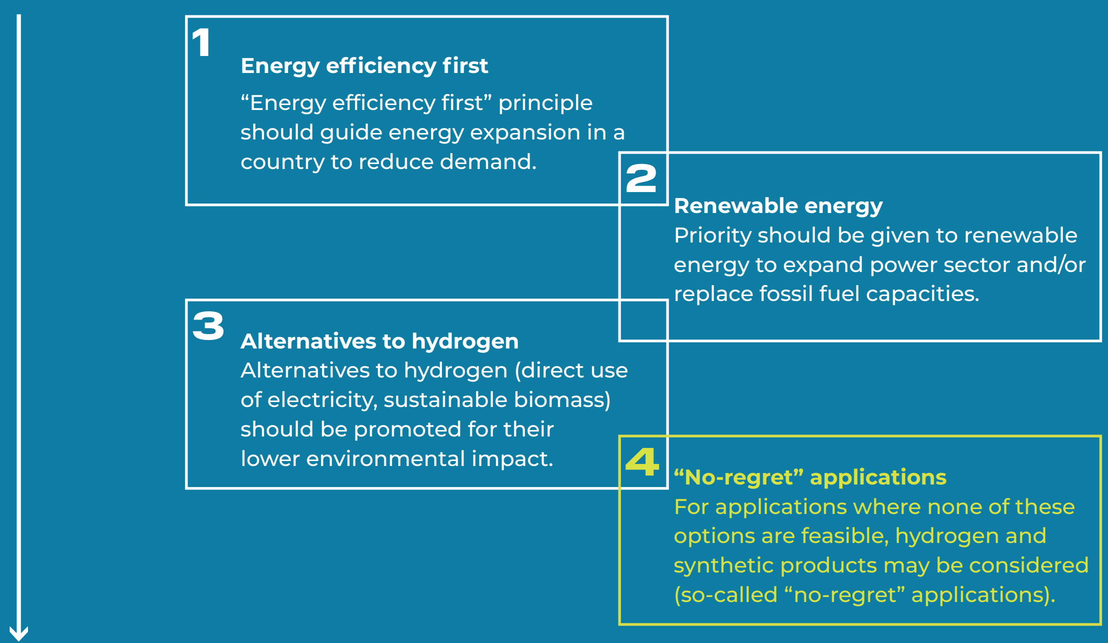
→ **The production of green hydrogen leads to efficiency losses,** which means that the usable energy available after the production process is less than before. Depending on how the fuel is used, additional efficiency losses can occur (e.g. in gas turbines to generate electricity, or in combustion engine vehicles).

→ **Direct use of electricity from renewable energies is in most cases more energy- and cost-efficient** than converting it to hydrogen.

→ **In remote regions with excellent renewable energy potential, power-to-gas technology, such as green hydrogen, can be cost-efficient.** For this technology to be sustainable, however, these regions must also be able to access abundant water resources.

The feasibility, benefits, and risks of hydrogen thus depend largely on the respective context in which it is produced and used. For a hydrogen application to be deemed as "no-regret", a number of conditions should be met, as shown in → **Figure 1**.

Figure 1
Identifying "no-regret" green H_2 applications



Hence, priority setting in the deployment of hydrogen applications is needed (IRENA, 2022f). **Future deployment should focus on no-regret applications where hydrogen is either the only or the most cost-effective decarbonisation option.** Likewise, end uses where better alternatives exist should be avoided. Factors that influence the potential of hydrogen for decarbonisation in particular end uses include:

- **a** **Energy efficiency:** direct electrification is more efficient ("energy efficiency first" principle), since hydrogen production and its further transformation to electricity, heat, or another fuel generates progressive conversion losses (Clarke et al., 2022). In some applications, higher energy requirements can be offset by other considerations, such as the need for energy dense fuels or costs (IRENA, 2022f).
- **b** **Technological readiness and existence of alternative options:** for some end uses, decarbonisation options are already commercially available (for example, heat pumps), while for other sectors alternatives have not been demonstrated at a large-scale use (such as biofuels for long-haul aviation)(IRENA, 2022f).
- **c** **Potential size of hydrogen demand:** supplying hydrogen to large and localised demand centres is more cost-effective than for distributed applications since the former will require less investment in infrastructure for hydrogen storage and distribution (IRENA, 2022f).
- **d** **Existing assets and infrastructure:** hydrogen production and utilisation can have synergies with specific industries and make use of existing skills, jobs, infrastructure, assets, and business models, favouring a more just energy transition (Griffiths et al., 2021). When building on existing systems, hydrogen can 'piggy-back' and become the most cost-effective option. This could include the use of gas infrastructure for hydrogen transport and distribution (Staffell et al., 2019).
- **e** **Country conditions:** political objectives, socio-economic factors, energy and industrial sector conditions, and the size, maturity level, competitiveness, and infrastructure age in specific sectors can influence priority setting.

Various studies have prioritised and quantified the potential of hydrogen applications based on different criteria. One of the most known examples is Liebreich Associates' clean hydrogen ladder, where potential applications are ranked from unavoidable (Category A) to uncompetitive (Category G) in seven levels. **➔ Figure 2** depicts the clean energy ladder and distinguishes use cases by end-use sector where hydrogen is expected to have a role in future decarbonisation efforts.

Industry

Heavy industrial sectors is where low carbon hydrogen is expected to have the most impact on decarbonisation, here grey hydrogen is a key feedstock that cannot be replaced by other chemicals. These sectors are: **Oil and gas refining**, where hydrogen is used to remove impurities (hydrotreating and desulphurisa-

Figure 2

Use cases for clean hydrogen in key end-use sectors

Source: NewClimate Institute elaboration based on the “Clean Hydrogen Ladder” (Liebreich Associates, 2021)

tion) and upgrade oil fractions (hydrocracking); **Ammonia production** through the Haber-Bosch process, which in turn would help decarbonise fertiliser production and other industrial applications (for example, explosives and plastics manufacturing); and **methanol production**, a widely used chemical feedstock and solvent in many industries (IRENA, 2022f). **Iron and steel production** is another sector where technological lock-in and path dependence can hinder energy transitions and where thus the swift application of low-carbon hydrogen can play a key role in the sectoral transformation. **Hydrogen (and carbon monoxide) can be used for Direct Reduction of Iron (DRI), which can then be fed into Electric Arc Furnaces (EAF) that can produce steel with potentially no emissions.** EAFs are currently used but rely on steel scraps for secondary steel production; however, the availability of steel scraps limits the market share of EAFs to 24% (IRENA, 2022f). Currently, 71% of global steel production is made in blast furnace-basic oxygen furnaces (BF-BOFs) (Fan and Friedmann, 2021), where hydrogen can partially substitute coke as a reducing agent. This substitution is not a long-term path to decarbonisation, however, considering it only has the potential to eliminate 21% of process emissions (Yilmaz et al., 2017). **In terms of a long-term transition of iron and steel, new plants using BF-BOF technology are not compatible with the long-term decarbonisation of the sector.**

Hydrogen and hydrogen derivatives can replace fossil fuels in many industrial sectors (e.g. cement, glass, ceramics), where **high-temperature heat** (>400°C) is required. In the case of mid- to low-temperature heat, applications are easier to electrify. However, there are conflicting opinions regarding the feasibility of using hydrogen for high-temperature heat (Liebreich Associates, 2021), since it would require redesigning burners and furnaces, using new materials to prevent corrosion and brittleness of equipment, and finding solutions on safety issues regarding hydrogen handling and combustion monitoring (Staffell et al., 2019; Griffiths et al., 2021). The low maturity of these technologies, uncertain costs, and the slow turnover of existing systems add to the previous issues. Biofuels and electricity-based heating can be more competitive than hydrogen for high-temperature heating, but hydrogen remains an attractive option for large-scale processes hard to electrify (for example, steam crackers and cement kilns) and for geographically fragmented industrial sectors (IEA, 2019a).

Transport

The suitability of hydrogen varies significantly between transport modes. Hydrogen and hydrogen-based derivatives (ammonia and synthetic fuels) are expected to have the highest impact on the decarbonisation of **maritime shipping** and **long-haul aviation**, but technologies are still on a research and development phase (Jaramillo et al., 2022). For **maritime shipping**, green ammonia has received particular attention and could help reduce life-cycle emissions up to 70-80% compared to fuel oil (Bicer and Dincer, 2018; Gilbert et al., 2018). The rollout of new systems could be hampered by the long lifetimes of most vessels (Staffell et al., 2019) and the need for further development of safe storage and handling procedures. For **long-haul aviation**, synthetic fuels are expected to compete with biofuels, while smaller short-haul planes are more likely to be electrified (Sahoo et al., 2020; Jaramillo et al., 2022). Biofuel production through hydrotreatment of vegetable oils (HVOs) is another potential tool for fossil fuel substitution in the short-to-medium term, as hydrogen can be then used to produce both jet-fuel and green diesel (Esposito et al., 2022).

Land transport applications rely on hydrogen fuel cell vehicles (FCEVs), a technology that has improved through research and development but is not yet mature for many transport modes beyond light-duty vehicles (Jaramillo et al., 2022). For short-range and light-duty vehicles (such as passenger cars, urban buses), battery electric vehicles are expected to remain the most competitive decarbonisation option in the foreseeable future. Hydrogen will have a bigger impact on **long-range and heavy-duty vehicles** like trucks, where it will compete with electric haulage systems (Jaramillo et al., 2022). Rail systems are already highly electrified in some countries in the world and decarbonisation via hydrogen will mainly focus on long-range and low-frequency networks, for example for freight in rural or remote areas (IEA, 2019a). Finally, other types of off-road vehicles such as forklifts, tractors, and logistics hub machinery also have a high potential for decarbonisation through fuel cells (Staffell et al., 2019; Liebreich Associates, 2021).

Power

Electrification of end uses is expected to increase electricity demand and the rise of intermittent renewables like solar and wind will impact electricity systems. Balancing supply and demand through **energy storage** capacity or large-scale peak power plants will be necessary to maintain costs and reliability, particularly when there are large seasonal demand imbalances. Hydrogen technologies can help to integrate, expand, and build the resilience of electricity systems based on solar and wind energy (Strbac et al., 2020; Clarke et al., 2022).

Hydrogen production processes based on electrolysis can make use of excess renewable energy generation. The hydrogen produced can then be stored for future conversion to electricity **(re-electrification)** when demand peaks, using either fuel cells or combined-cycle gas turbines that have been repurposed to run on hydrogen (Staffell et al., 2019).

The economic feasibility of flexible power-to-hydrogen (and vice versa) plants and **long-term hydrogen** storage will depend on the location of renewable energy sources, storage sites, and gas, hydrogen, and electricity networks. The distance between producers and consumers of energy carriers (hydrogen, ammonia, synthetic fuels) will determine the characteristics of the distribution and storage infrastructure to be built (Hansen, 2020; Clarke et al., 2022).

Heating

Decarbonising **residential and commercial heating** mainly relies on demand reduction, electrification, district heating, on-site renewables and, to a lesser degree, alternative gaseous fuels such as biogas. Hydrogen could also play a role in the decarbonisation of buildings, but most assessments foresee only a very limited role, since costs would be higher for delivering heat from hydrogen rather than other commercially available options like electric heat pumps (Cabeza et al., 2022). Options for low-carbon heat include hydrogen boilers, fuel cell combined heat and power (CHP), and gas-driven heat pumps. Cost-wise, applications are more attractive for large-scale commercial buildings or residential complexes, and for district energy networks (IEA, 2019a). Shifting to direct hydrogen use in buildings would require large scale appliance retrofitting plus conversion of natural gas grids to hydrogen or widespread power-to-hydrogen-to-power processes (e.g. methanation), the latter being complex, costly, and less efficient (Staffell et al., 2019). Blending hydrogen with natural gas has also been proposed as a short-term solution, but it is not efficient (20% blends by volume reduce emissions by 7%), it prolongs the life of fossil fuel assets, and displaces solutions with higher decarbonisation potentials (Staffell et al., 2019; IRENA, 2021a).

03 Current demand and supply of hydrogen

Interest in hydrogen as an alternative carrier began in the early 60s and 70s due to its potential applications for space travel as well as the oil crisis (Griffiths et al., 2021). Renewed attention in the early 2000s arose due to energy crises that saw peak oil prices (IRENA, 2022b).

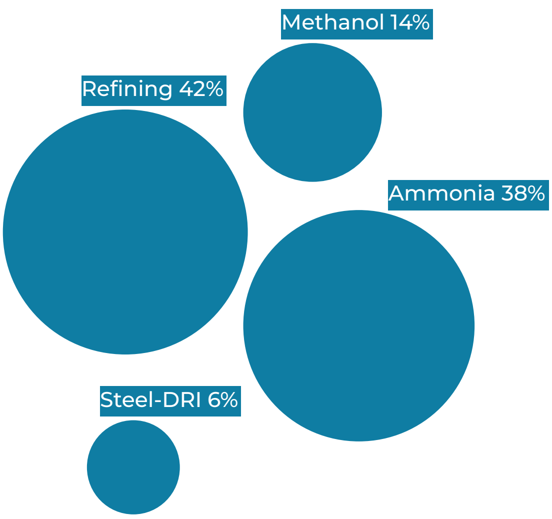
Current demand and supply of hydrogen: The global picture

Global hydrogen demand in 2020 has almost doubled compared to 2000 in light of the energy crises. Oil refining was the single largest consuming sector with 42% of the global hydrogen demand **(→ Figure 3A)**. Ammonia production (38%),methanol production (14%) and direct reduction iron (DRI) in steel (6%) were the remaining prevalent end-uses for hydrogen. Other end-uses, such as hydrogen consumption in transport or power generation, continue to be negligible. Fuel cell electric vehicles (FCEVs) consumed less than 20 kt of hydrogen in 2020 (0.02% of the global demand), while 0.2% of power generation was met with hydrogen, mostly as on-site consumption in the steel industry, petrochemical plants, and refineries.

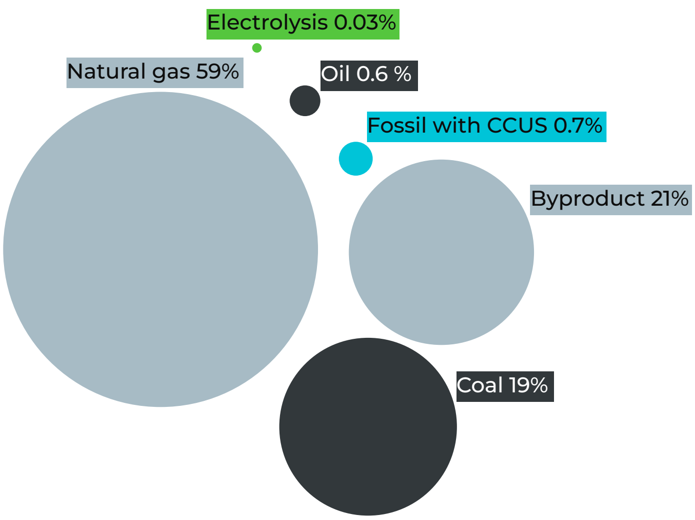
Fossil fuel-based technologies supplied most of the 2020 hydrogen demand (→ see Figure 3A), releasing around 900 Mt of CO_2 into the atmosphere. Steam reforming was the main production pathway (59%), followed by the use of byproduct hydrogen from oil refineries (21%) and coal gasification (19%). Only a

Figure 3
Hydrogen demand by sector and supply by production technology, 2020

A
Hydrogen demand



B
Hydrogen supply
(Grey H_2, Black H_2, Blue H_2, Green H_2)



Source: Authors based on (IEA, 2021c, 2021b, 2021d) small share of hydrogen production can be considered low carbon: around 0.7% was obtained from fossil fuels with CCUS, while electrolysis processes generated 0.03% (IEA, 2021c).

Even if the share is still minimal, the trend indicates that these capacities are being continuously expanded: As of 2022, installed electrolyser capacity (95% through PEM and AE technology) was equal to 0.6 GW and total production capacity amounted to 87 kt H_2/year, doubling the production capacity compared to the previous year (IEA, 2022e).

To date, operational electrolysers are mostly clustered in Europe, Canada, the United States, Japan, and China, accounting for more than 90% of installed capacity (IEA, 2022e). Likewise, announced electrolyser projects are geographically located in regions with developed national hydrogen strategies, like Europe and Australia, highlighting the impact that these policy documents can have in technology deployment. Other regions that have recently received interest for additional investments in electrolysis-based hydrogen production include China and the Arabian Peninsula (IRENA, 2021b). Electrolyser manufacturing capacities are also expected to increase over the next years. In 2018, global manufacturing capacity stood at 135 MW/year and was expected to rise to 3.5 GW/year by the end of 2021. Most announcements concerning the expansion of manufacturing capacities have also occurred mainly in Europe (IRENA, 2021b; Tengler, 2021).

4 Production of urea is based on ammonia.

Current use of hydrogen: The regional picture

The IEA (IEA, 2021e) estimates that in 2019, **hydrogen demand in LAC accounted for 4.1 Mt or 0.5 EJ, which represents 4.6% of the global consumption.** Pure hydrogen demand in the region comes mainly from oil refining and ammonia production, while mixed hydrogen is mainly used for methanol production and DRI in the steel industry. Dedicated hydrogen production or use of the byproduct gas is the most common supply route in the region, with the rest being merchant hydrogen produced within each country. There is currently no hydrogen trade across country borders, and demand equals supply both within the region and inside each country (IEA, 2021e.

The region's five largest economies are also the main demand centres for hydrogen. The exception is Trinidad and Tobago, which accounts for over 40% of the regional demand. In Trinidad and Tobago, the chemical industry drives hydrogen consumption, since the country exports ammonia, urea[4], and methanol. **Oil refineries are the main consumers in Mexico (60%) and Brazil (83%); in Mexico, DRI steel facilities are the second major user, while ammonia-based fertiliser production demands the remaining volume in Brazil. Argentina has a sizeable demand in all four main end uses.** In Colombia and Chile, the application with the largest share of hydrogen consumption is oil refining and methanol production, respectively.

Supply of hydrogen in LAC is mainly based on fossil fuels, namely natural gas. Although some production pathways temporarily capture CO_2 emissions for urea production, these are released into the atmosphere at latter stages of the supply chain. No facilities currently operate with dedicated long-term CCUS. Meanwhile, electrolysis only represented 0.03% of total production in 2020 **(➔ see Figure 3B)**.

In 2021 there were five operating facilities that produce hydrogen from electricity in the region. The largest of these electrolysers, operated by Peru's Industrias Cachimayo, is a 20 MW alkaline electrolyser (AE) that runs on grid electricity (primarily from hydropower) and is used for fertiliser manufacturing. Peru's electrolyser accounts for 96% of the region's installed capacity. The remaining four are pilot projects that generate hydrogen from either dedicated onshore wind or solar energy in Argentina, Chile, and Costa Rica. The IEA's Hydrogen Projects Database lists 11 projects in a feasibility study stage; if completed, they would give rise to a significant increase in hydrogen production capacity by generating 808 kt H_2/year, 200 times more than what can be produced at present. Finally, there are 15 other projects in a concept stage (see complete project list in ➔ **Annex 5**).

Recent trends affecting the use of hydrogen

Nowadays, the foreseen role of hydrogen is more modest and limited to hard-to-abate sectors. However, various trends have once again put hydrogen in the spotlight as an alternative energy carrier that could play a key role in meeting international climate targets and avoiding the worst impacts of climate change. **The following trends are influencing investments in hydrogen production and end-use applications in LAC:**

a **Increased public awareness on climate change and preferences for low-carbon technologies.** Evidence shows that climate change awareness and concern have increased globally over time (Milfont et al., 2021). Public opinion can significantly influence mitigation efforts through the willingness to change energy-related behaviour (e.g. demand-side measures), incur in higher financial costs , or support the adoption and deployment of new policies and technologies, provided that motivation for change is accompanied by interventions that help individuals overcome institutional and market barriers (Drews and van den Bergh, 2016; Boudet, 2019; Creutzig et al., 2022). This change in public perception is key to deploy hydrogen-based applications that are driven or influenced by cultural aspects and user preferences (Griffiths et al., 2021). Given the high vulnerability of the region to climate change and the impacts already being experienced, this awareness and accompanying public response is also evolving in LAC.

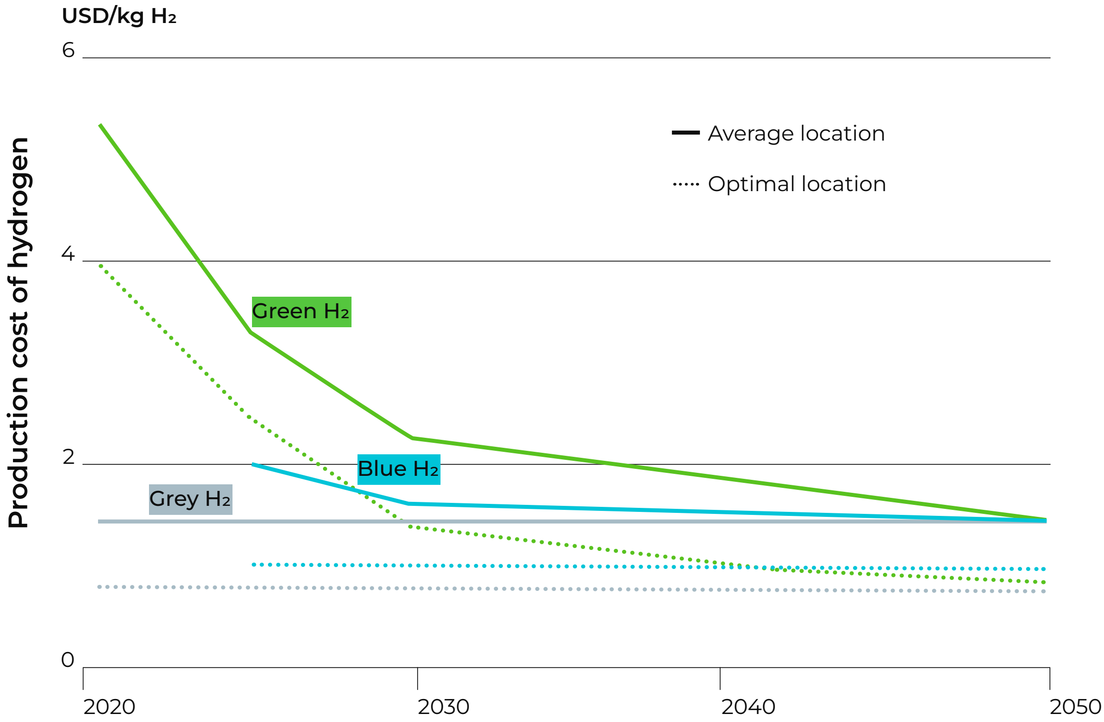
b **New evidence on the magnitude of methane emissions from fossil fuel-based systems.** According to the IEA, global methane emissions from the energy sector have been hugely underestimated by national emission inventories (IEA, 2022f). Recent studies show that actual methane emissions from fossil fuel value chains are 20-60% higher than previously estimated (Schwietzke et al., 2016; Hmiel et al., 2020). Thus, expansion of fossil fuel infrastructure, particularly for natural gas, which is sometimes labelled as a bridge or transition technology, could result in carbon lock-in and hinder decarbonisation efforts (Kemfert et al., 2022). **See → Box 3** for further details on lock-in risks. Investments should therefore shift towards electrification of end-uses, ramping up renewables, and use of alternative carriers, such as hydrogen, in hard to electrify sectors. Moreover, hydrogen can contribute to a just and incremental energy transition since many skills and assets for its deployment are transferable from the oil and gas industry. For example, current infrastructure for natural gas, including pipelines, heaters, and turbines, could be converted for hydrogen use, reducing overall costs of the energy transition (Griffiths et al., 2021). Several countries in the region have recognised these emission sources and developed specific policy instruments to tackle them, such as Mexico (IEA, 2022d) and Colombia (IEA, 2022g).

c **Need for energy supply diversification amidst rising prices and energy security concerns.** Russia's invasion of Ukraine has put pressure on inflation and impacted global commodity prices, including fuels and agricultural products. For LAC countries that are net importers of fossil fuels (e.g. in Central America and the Caribbean) will likely be affected the most (Cárdenas et al., 2022). The region could diversify its energy supply by tapping into its vast renewable resources to produce green hydrogen and strengthen local energy security. To do so, LAC countries must push for hydrogen uptake both from the production and demand sides, while receiving international technical and financial support for technology deployment that is not readily accessible in the region.

d **Expected lower production costs of green hydrogen and increased investments in the sector.** Electrolysis-based hydrogen production costs will likely continue to fall (Glachant and dos Reis, 2021; The Hydrogen Council and McKinsey & Company, 2021b). Capital expenditure (CAPEX) requirements for electrolysers are dropping at the system level and the levelised cost of energy is declining due to cheaper renewable production and better mixes. The deployment or planning of larger hydrogen projects, higher efficiencies of electrolysers, and optimised designs for integrated energy systems will further reduce costs. These factors will allow green hydrogen to become competitive and break even with grey or blue hydrogen production pathways in optimal regions (for example, with high renewable potentials and low cost of capital). Moreover, blue hydrogen may not continue to be a low-cost solution due to the rise in gas prices and potential carbon taxes, questioning policy support for research and deployment. Other critiques towards blue hydrogen include uncertainties regarding methane leakage, carbon capture rates, and the lack of progress in achieving proposed targets over time (Flora and Jaller-Makarewicz, 2022).

→ **Figure 4** show an estimate of the cost evolution for different hydrogen production technologies. Green hydrogen production in optimal locations (with strong renewable energy potential) is expected to reach cost parity with grey hydrogen in 2030 or earlier, as grey hydrogen costs are susceptible to variations on fossil fuels. Investments have also increased rapidly in response to government decarbonisation pledges, targeting the CAPEX of announced or planned projects, research & development, or mergers and acquisitions. Planned investments through 2030 amount to USD 300bn globally, although only one quarter of this spending can be considered mature (e.g. projects in planning, construction, or operational stages).

Figure 4
Hydrogen production costs by technological pathway



Key assumptions: Gas price equal to 2.6 – 6.8 USD/MMBtu*. Levelised cost of energy equal to 25 – 73 USD/MWh (2020), 13 – 37 USD/MWh (2030) and 7 – 25 USD/MWh (2050).

* Forecasts concerning the evolution of blue hydrogen costs do not consider recent increases in gas prices due to geopolitical conflicts (e.g. Ukraine – Russia war) and could be significantly higher.

Source: (The Hydrogen Council and McKinsey & Company, 2021b)

04 Future hydrogen use

Low-carbon hydrogen plays a key role in all future emission scenarios that comply with the Paris Agreement's climate targets. However, the contribution of low-carbon hydrogen in future 1.5°C warming scenarios varies significantly in terms of total volumes and end-uses. Low-carbon hydrogen plays a key role in all future emission scenarios that comply with the Paris Agreement's climate targets. However, the contribution of low-carbon hydrogen in future 1.5°C warming scenarios varies significantly in terms of total volumes and end-uses. Scenarios may not only have different GHG reduction pathways, but they can also differ in their underlying assumptions on future socio-economic developments, energy demand and supply dynamics, technological advances, cost evolution, and behavioural changes. Scenarios that make more optimistic cost assumptions and assume more uses and applications of hydrogen are likely to lead to a larger share of hydrogen in the energy mix as demand and cost efficiency increase. Ultimately, these projections also depend heavily on policy preferences regarding certain measures (such as carbon pricing).

4.1 Future hydrogen demand and supply

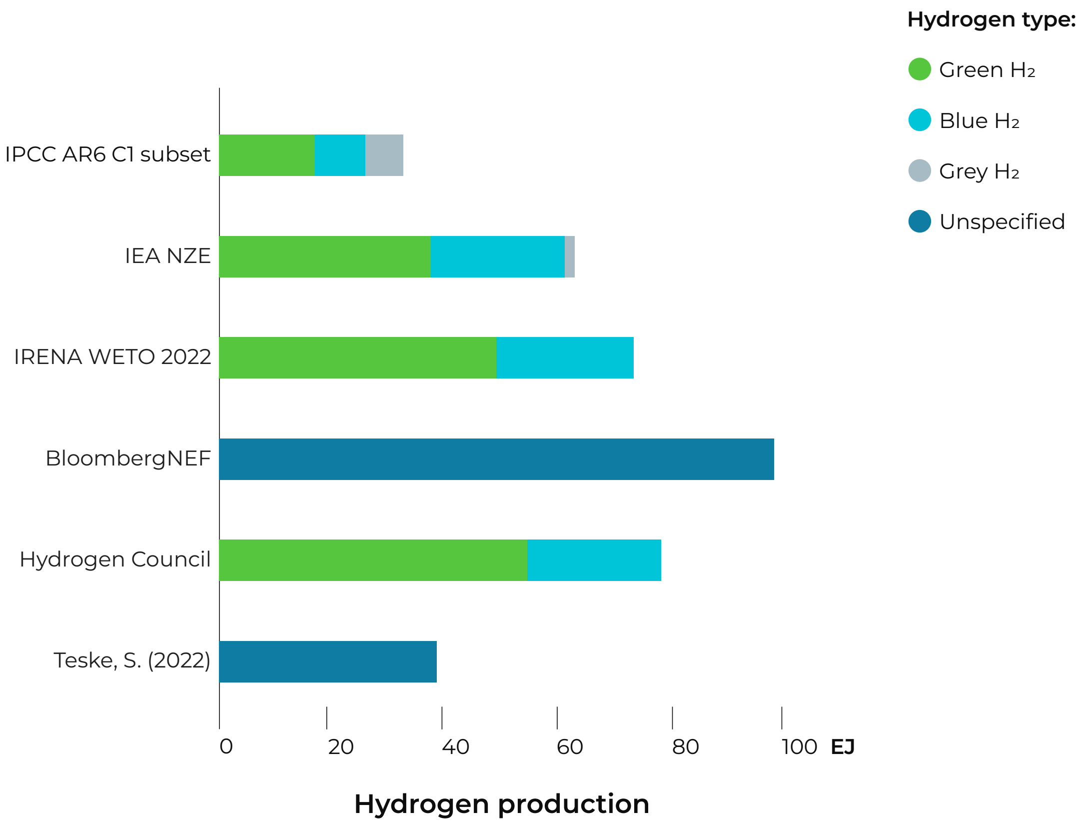
Pathways to net-zero emissions by 2050 require wider use of hydrogen and hydrogen-based fuels in both existing and new applications. Different studies **predict that future hydrogen production in 2050** will range from 30 EJ up to 100 EJ, three to nearly ten times the current global output (**see ➔ Annex 7** for a summary of key indicators for all the reviewed decarbonisation scenarios). In all scenarios, **low-carbon hydrogen makes up almost 100% of the total production in 2050**, with electrolysis from renewables generally representing two thirds of it, and the rest coming from fossil fuels with CCUS **(➔ Figure 5)**. This would require an installed capacity between 3,000 and 5,000 GW of electrolysers and an annual storage capacity of 1 to 3 Gt H_2/year. **To supply green hydrogen from the projected electrolyser demand, a total of 4,800 to 5,400 GW[5] of installed renewable capacity would be required.** These values are more than three times the current global installed capacity of solar PV and wind energy (IRENA, 2022g). This highlights the importance of parallel efforts and investments in the expansion of renewable energy capacity.

The more conservative forecasts estimate that hydrogen will represent about 3% of final energy consumption globally, while more optimistic scenarios project values of more than 20%. Industrial activities call for between 8 to 40 EJ of hydrogen and its iderivatives and is, in many cases, the sector with the largest demand of hydrogen **(➔ Figure 6)**. **Most of the industrial demand is expected to come from existing uses of hydrogen as feedstock in chemical production (44%) and as a reagent for DRI in steel manufacturing (29%) (IEA, 2021d).** These are applications where hydrogen is considered the only feasible decarbonisation option, and the timing of their implementation will mostly depend on policy measures and cost evolution. New applications, particularly for heating in the

5 Considering mean optimal renewables-to-electrolyser capacity ratios of 1.6 for solar PV and 1.8 for onshore wind (Brändle et al., 2021).

Figure 5

Projected hydrogen production by 2050 in 1.5°C decarbonisation scenarios



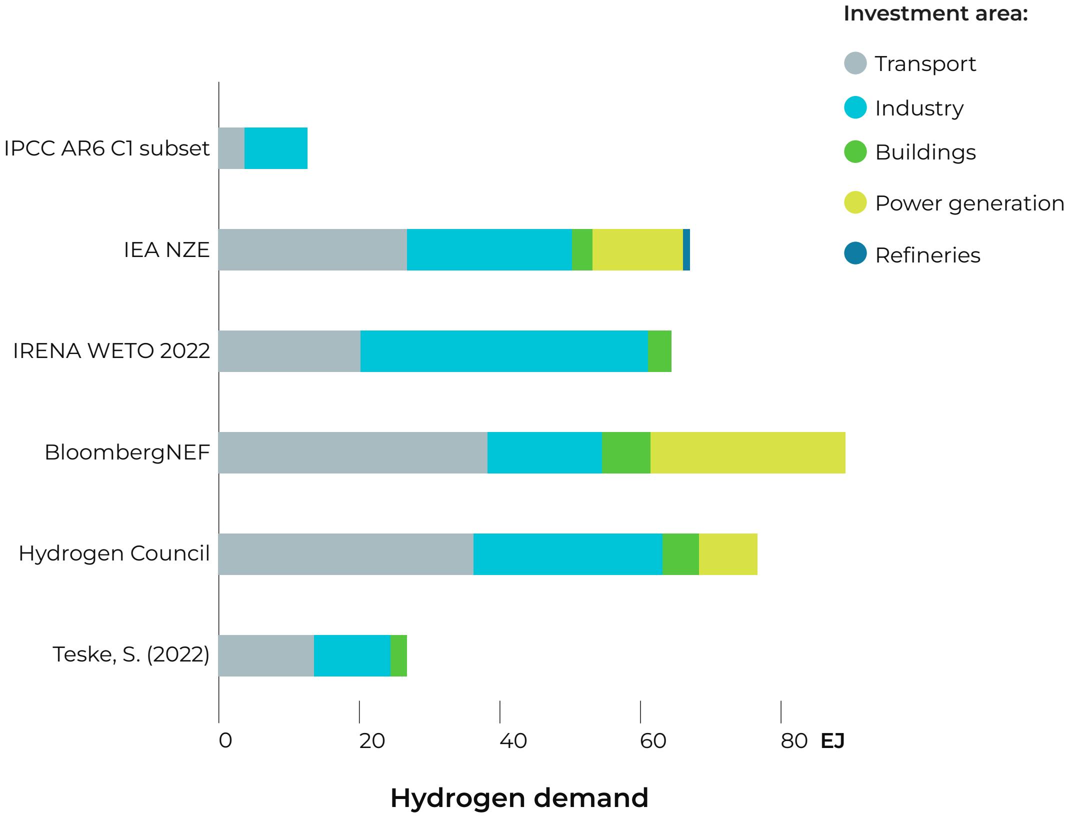
Sources: Authors based on (BloombergNEF, 2020; IEA, 2021f, 2021c; IRENA, 2021c, 2022h; The Hydrogen Council and McKinsey & Company, 2021a; Byers et al., 2022; Teske, 2022)

cement industry, are also expected to play a significant role (6.4%). On-site use of electricity for hydrogen production will be particularly relevant for the industrial sector, representing 6.1% of the sector's final energy consumption. Oil refining will be the only application where future hydrogen demand will decrease since consumption will likely diminish sharply as climate ambition increases.

Around one third of total hydrogen production will likely be used to produce derivatives like ammonia and e-fuels. The use of derivatives will have its biggest impact in the transport sector, where hydrogen and hydrogen-based fuels can replace fossil fuels in the categories where high energy content is necessary and direct electrification is less viable. This is the case for heavy duty and long haul freight transport as hydrogen has a higher energy content than most current batteries. The IEA also estimates that synthetic fuels can represent one third of the final energy consumption of the aviation sector, while half of maritime shipping's demand could be met by using ammonia as a fuel. By contrast, even

Figure 6

Projected hydrogen demand by 2050 in 1.5°C decarbonisation scenarios



Sources: Authors based on (BloombergNEF, 2020; IEA, 2021f, 2021c; IRENA, 2021c, 2022h; The Hydrogen Council and McKinsey & Company, 2021a; Byers et al., 2022; Teske, 2022)

though FCEVs are a mature technology, their deployment is not projected to be significant for light-duty vehicles due to the superior efficiency and cost-competitiveness of electric vehicles, and could represent only 9.3% of the global fleet by 2050. Meanwhile, 31% of heavy-duty trucks will be powered through hydrogen fuel cells by mid-century.

Hydrogen could also help meet between 2.4% and 5% of future electricity demand, as its use for energy storage and grid regulation is scaled up. The NZE scenario of the IEA sees a total generation of 1,700 TWh of electricity from hydrogen by 2050 and a final demand in the power sector of 12 EJ. Forecasts from BloombergNEF and the Hydrogen Council also see a significant share of hydrogen consumption for power generation, with values of 26 EJ and 7.7 EJ. **Finally, hydrogen will have the least use in residential and commercial buildings, accounting for less than 3% of the sector's final energy demand in all scenarios (➔ Figure 6).**

Current project pipelines indicate that anticipated deployment of technologies for hydrogen production and end-use applications do not align with the ambition of decarbonisation scenarios. If all announced electrolyser projects by 2022 were to be completed[6], they would add an annual 3.5 GW/year of installed capacity by 2030. This growth, although it represents a massive increase compared to the current production levels , would need to rapidly accelerate to meet the necessary output. **Manufacturing capacity of electrolysers would need to be scaled up to 130-160 GW/year by 2050 in order to meet the scale-up needs.**

4.2 Role of hydrogen in Latin America and the Caribbean

6
Includes all projects commissioned to 2030 or before, according to the IEA's latest hydrogen project database (IEA, 2022e).

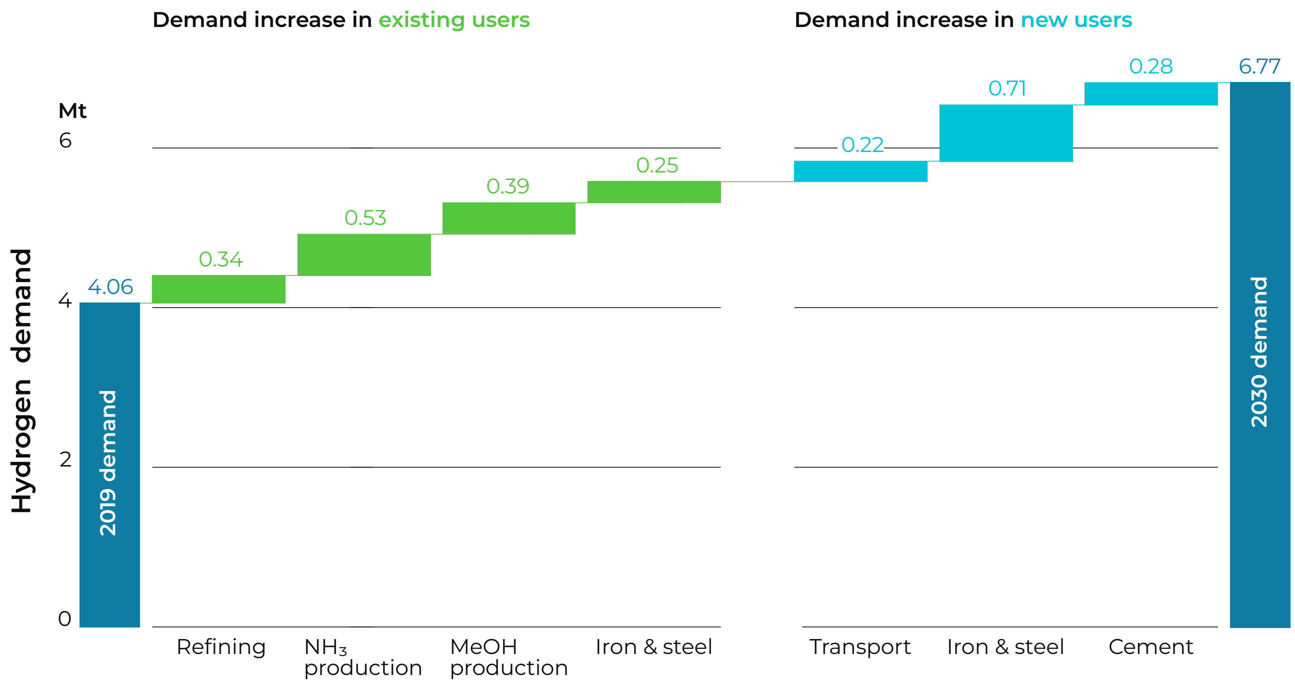
Hydrogen value chains in LAC will need to transform on two fronts if the region is to achieve net-zero emissions by mid-century. First, current hydrogen supply needs to be replaced with low-carbon production technologies and scaled up significantly, and second, hydrogen consumption needs to expand towards replacing carbon intensive end-uses and applications, including value-added products for export markets. The potential evolution of hydrogen demand and supply in LAC is explored in the following section, mostly based on the IEA's decarbonisation scenario and regional forecasts for hydrogen use.

Hydrogen demand forecasts (until 2030)

The IEA estimated hydrogen demand in LAC through an Accelerated case scenario that assumes ambitious energy and climate policies are put in place, along with supporting facilitation mechanisms (IEA, 2021e). The scenario is compatible with the Paris Agreement and long term decarbonisation targets and requires governments and other stakeholders to upscale interventions across entire value chains. The scenario forecasts a demand of 6.8 Mt of hydrogen by 2030 (67% increase). As mentioned for the global case, while this growth is a considerable addition to current efforts, it will need to accelerate at a higher rate in the lead up to 2050 to fully achieve decarbonisation by mid-century. Most of the additional demand will come from existing uses, such as oil refining and chemical production; some new applications in transport, steel production, and direct heat in the cement industry will also play an important role in the next decade **(➔ Figure 7)**.

Hydrogen consumption for oil refining under these scenarios could see an annual growth rate between 1.5% and 3.4%, depending on the adoption of low-carbon mobility options and increases in fuel efficiency, which would likely decrease demand for oil products. Stringent sulphur content requirements in fuels (for example, linked to new air quality standards) and the production of biofuels could also push demand for hydrogen used to increase the quality of hydrocarbons. Since most demand in this sector is currently met through on-site SMR, new opportunities for CCUS or green electrolysis are expected to arise in the near future.

Figure 7
Change in hydrogen demand by sector in LAC (2019 vs 2030)



Source: Based on IEA's Accelerated case for hydrogen demand in LAC (IEA, 2021e, 2021a)

In the industrial sector, demand for ammonia production could increase between 45% and 52% by 2030. The increase in ammonia demand would be driven by the **agricultural sector**, where ammonia is used to manufacture fertilisers. In this sense, increased agricultural and fertiliser efficiency could impact demand changes in LAC. Hydrogen demand for **methanol production** would likely increase 33% to 38% by the end of the decade; this increase will also depend on developments in the transport sector, where methanol is used as an additive for gasoline and during biodiesel production, and thus is linked to blending policies. Hydrogen demand for **steel production** could more than double by 2030, driven by the partial substitution of coke in BF-BOF furnaces, substitution of grey hydrogen with green alternatives in existing DRI plants, and new DRI-EAF applications. Moreover, the **cement industry** could demand around 0.3 Mt of hydrogen in 2030 for direct heat applications in clinker production (IEA, 2021a).

In the **transport sector**, new applications include the use of hydrogen in mining haul trucks, which could be supported by electrolysers in mining locations. FCEVs are expected to have bigger market shares in the future but these could remain relatively low **(→ Table 3)**. Other potential demand uses include blending of hydrogen with compressed natural gas for light duty vehicles, as well as a demand of around 50 kt/year for shipping (IEA, 2021e).

Table 3
Fleet and new sales shares for FCEVs in LAC by 2030

FCEV type	Total fleet share	New sales share
Buses	0.28%	0.45%
Trucks	0.27%	0.78%
Cars	0.02%	0.06%
Light commercial vehicles	0.16%	0.45%

Source: Based on IEA's Accelerated case for hydrogen demand in LAC (IEA, 2021e)

Finally, some **power applications** may materialise by 2030, especially because energy storage is very important to integrate electric systems based on intermittent renewables. Deployment of hydrogen applications in the power sector will vary greatly and most likely will take place beyond 2030. Some short-term opportunities may exist in islands and isolated systems that depend on liquid fuels (IEA, 2021e).

Hydrogen supply forecasts

To meet the projected regional demand future hydrogen supply needs to increase to at least 6.8 Mt by 2030 (IEA, 2021e). Some of the decarbonisation scenarios introduced in section 4.1 also include production forecasts by mid-century **(→ Table 4)**, where production increases to around 15 Mt or 1.8 EJ.

Table 4
Hydrogen supply forecasts in LAC, 2050

Scenario	Hydrogen production in 2050(EJ)	Share of electrolysis	Share of fossil + CCUS
IPCC AR6 C1 subset [a]	1.8 EJ	51%	7%
IRENA	1.7 EJ	Unspecified	

[a] Values correspond to statistical medians.
Source: Produced by authors based on (IRENA, 2021c, 2022h; Byers et al., 2022)

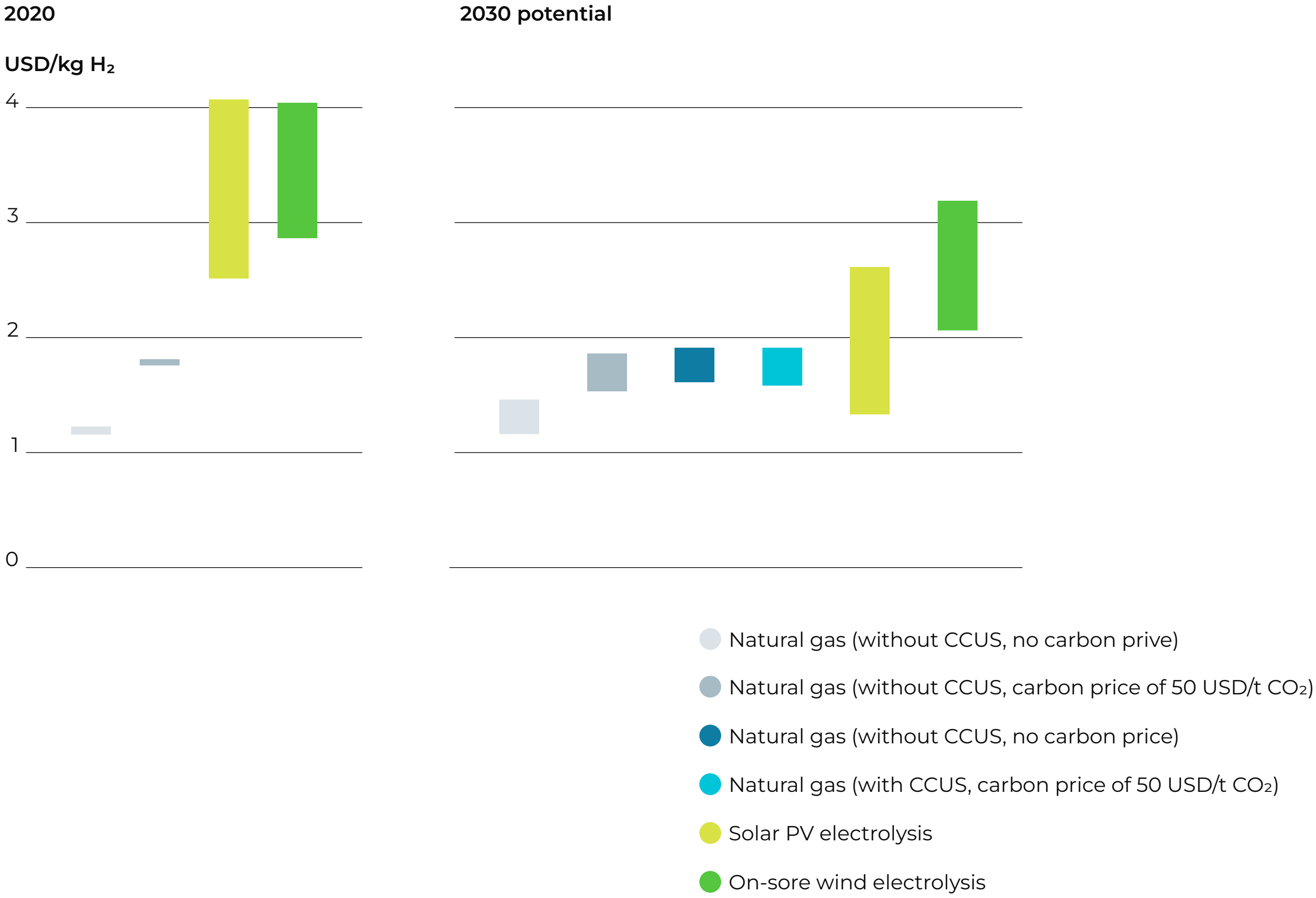
Decarbonising hydrogen production will require the deployment of low-emission supply routes, namely renewables-based electrolysis or SMR with CCUS. The penetration of either technology will depend on each route's levelised cost of hydrogen (LCOH) production **(→ Figure 8)**, which in turn is influenced by factors such as capital costs, availability of primary energy sources and their respective prices (either renewables or fossil fuels), CCUS costs, eventual subsidies and/or carbon pricing effects. The development of supply chains for other hydrogen end-uses (for example, in industry or transport) could also impact the production costs of low-carbon hydrogen.

For the the regional supply to follow global trends, swift action needs to be taken in the short-term, as the current deployment of low-carbon hydrogen production routes in the region is practically non-existent. Plans and strategies are currently being developed by LAC countries to ramp up hydrogen production and use. **The current regional project pipeline[7] will only increase green hydrogen production to 3,065 kt H_2 in 2030, or 45% of the projected necessary demand in order to remain within a 1.5°C warming scenario, (IEA, 2021f, 2021c).** However, 99% of this production potential corresponds to projects whose feasibility is still being evaluated, adding uncertainty to deployment (IEA, 2022e). **Hence, the current project pipeline is insufficient to decarbonise future hydrogen production, and not in line with decarbonisation scenarios that meet global climate targets.**

LAC countries can take advantage of their high renewable generation potential to support electrolytic hydrogen production (IEA, 2021e). A short-term opportunity exists in oil refineries and industrial facilities that produce hydrogen via SMR, where retrofitting with CCUS is more plausible. However, CCUS technologies

7 This includes projects currently operating, in demonstration phase, under construction, awaiting final investment decision, and in a feasibility stage.

Figure 8
Levelised cost of hydrogen production by technology in LAC



Source: (IEA, 2020b)

have not been deployed at scale and are limited by the availability and cost of CO_2 transport and storage. **Despite the renewed interest in CCUS technologies to support decarbonisation efforts, there is limited regional expertise and and a lack of legal and regulatory framework around hydrogen storage.** Brazil has the only commercial CCUS plant in LAC, the Petrobras Santos Basin Pre-Salt Oil Field CCS project, with a capacity to reinject 3.0 Mt CO_2 per year (Iglesias et al., 2015; Godoi and dos Santos Matai, 2021). In the future, deployment of hydrogen production with CCUS could target industrial hubs that allow for shared CO_2 transport and storage infrastructure.

The high renewable potential in some LAC countries means they could supply domestic demand in a first phase and subsequently become net exporters of low-carbon hydrogen with competitive production costs. Green hydrogen could then be used to replace fossil-based production (with or without CCUS). There have been additional efforts to estimate the potential supply of hydrogen for export in South America. A modelling exercise concluded that if South America increases hydrogen production by an additional 20% of their local electricity supply, the region could export up to 800 TWh of green hydrogen (2.9 EJ) by 2050. Most production would come from solar PV in Chile, followed by Argentina and northeast Brazil (Galván et al., 2022).

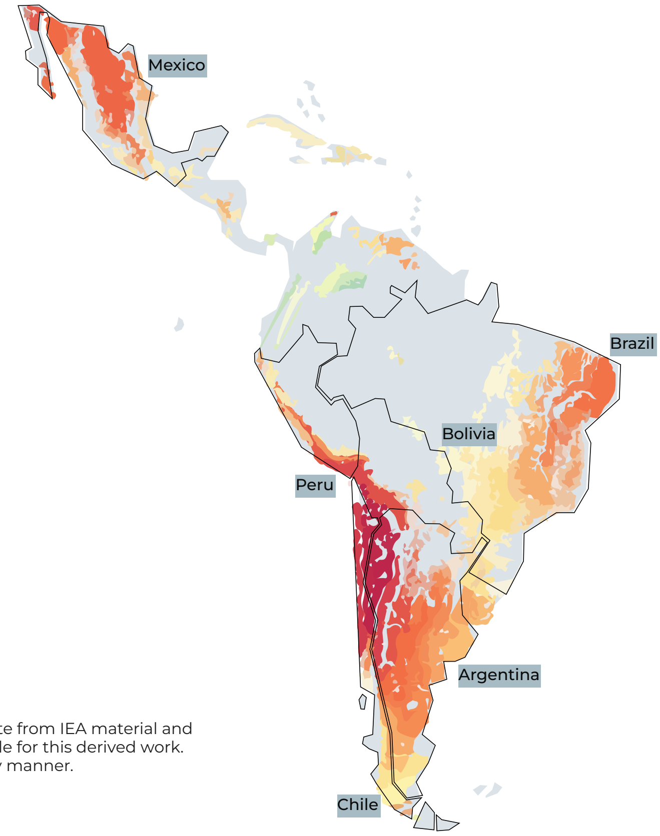
Concerning production costs, the IEA estimates that by 2050, the LCOH via electrolysis could reach values below 1 USD/kg H_2 in 4% of the region's territory **(→ Figure 9)** down from a current regional range between 2.5 and 4 USD/kg H_2 **(→ Figure 8)**. The lowest production costs may be located in the wind-rich Patagonia region in **Argentina** and Chile (Armijo and Philibert, 2020), as well as arid regions with high levels of solar radiation. The latter includes the Atacama region in Argentina, Bolivia, Chile, and **Peru** (Prăvălie et al., 2019; Gallardo et al., 2021). Moreover, **Brazil's** north-eastern region also has high potentials for both solar and wind energy production (Pereira et al., 2012). Since most of these regions are usually far away from current industrial demand clusters, scaling up transport and storage infrastructure also becomes relevant in the long-term.

National hydrogen strategies & roadmaps

The increasing importance of hydrogen can also be seen in many climate-mitigation plans and the development of national government strategies and roadmaps. More than 30 countries have developed hydrogen strategies, mostly in Europe and Asia (The Hydrogen Council and McKinsey & Company, 2021b). **These types of policy documents are important to establish a common vision among stakeholders and across various sectors.** Although hydrogen strategies vary significantly in content, they often identify priorities, define timelines, and set specific targets for hydrogen uptake in both the supply and demand sides. More ambitious countries might also specify policies, regulations, and incentives to achieve the stated ambition.

Figure 9

LCOH via electrolysis (hybrid solar PV and onshore wind) in LAC, 2050



H_2 production costs (USD/kg H_2):

- 0.8-1.0
- 1.0-1.2
- 1.2-1.4
- 1.4-1.6
- 1.6-1.8
- 1.8-2.0
- 2.0-2.2

Source: (IEA, 2021e)

Note: This is a work derived by NewClimate Institute from IEA material and NewClimate Institute is solely liable and responsible for this derived work. The derived work is not endorsed by the IEA in any manner.

In LAC, only Chile has published a National Hydrogen Strategy, while **Brazil** and Costa Rica are currently developing theirs. The governments of Colombia, Paraguay, and Uruguay have all released roadmaps for hydrogen deployment. In other countries, the private sector is playing a vital role in pushing for hydrogen development. For example, the **Peruvian** Hydrogen Association (Asociación Peruana del Hidrógeno) presented a roadmap project to government actors, including the Congress of the Republic, the Council of Ministers, the Ministry of Energy and Mines, and the Ministry of the Environment (H2Perú, 2022a). Progress can also be seen in **Argentina**, where the national government has fostered debate among stakeholders and published documents that state the importance of developing a national strategy and roadmap (Argentina Economic and Social Council, 2021). The Argentinian Secretariat of Strategic Affairs has also commissioned a series of studies aimed to build a roadmap for hydrogen production, demand, regulation and potential for pipeline blending.

The following Box describe the situation with regards to the development of hydrogen strategies or roadmaps in the three focus countries:

Box 2
Status of hydrogen planning in the three focus countries

Argentina's green hydrogen vision

The country's Social and Economic Council has recognised the importance of developing a new national hydrogen strategy fitting to the current market landscape, and which centres around green production routes. The government has launched a process to develop their National Hydrogen Strategy (pending publication), and they are also pushing for a reform to the 26123 law from 2006, which focused on the promotion of hydrogen. With this, Argentina seeks to position itself as one of the main hydrogen exporters in LAC. Forecasts of feasible production levels amount to 500 Mt H_2 per year and an installed electrolyser capacity of 5 GW by 2030. Sector specific targets have not been established, but the steel industry, fertiliser production, oil refining, and transportation are all activities that contribute to national GHG emissions, and could be potentially decarbonised by the deployment of low-carbon hydrogen (Argentina Economic and Social Council, 2021; Diazgranados et al., 2022; GH2, 2022; H2LAC, 2022b; Medinilla, 2022).

Brazil's hydrogen policy

Brazil's approach does not specify targets for hydrogen production or consumption in particular applications. Instead, it emphasises that outcomes will be the result of market dynamics. However, policy documents stress the importance of hydrogen to decarbonise local hard-to-abate industrial sectors and the potential for Brazil to become a green hydrogen export due to its favourable renewable energy potential. The transport sector is also seen as a key source of GHG emissions in which hydrogen could play an important role in decarbonisation efforts. (Brazil Ministry of Mines and Energy, 2021, 2022; Diazgranados et al., 2022; GH2, 2022; H2LAC, 2022b). In 2022, Brazil's National Council for Energy Policy instituted the National Hydrogen Program (PNH2) with the objective of strengthening the role of hydrogen as an energy vector in the country. Moreover, Brazil has developed a set of guidelines for the PNH2, defining six priority axes for the country's hydrogen policy: (1) reinforced research & development and technological bases; (2) capacity building and human capital formation; (3) energy planning; (4) legal and regulatory framework; (5) market development and competitiveness, and (6) international partnerships and cooperation.

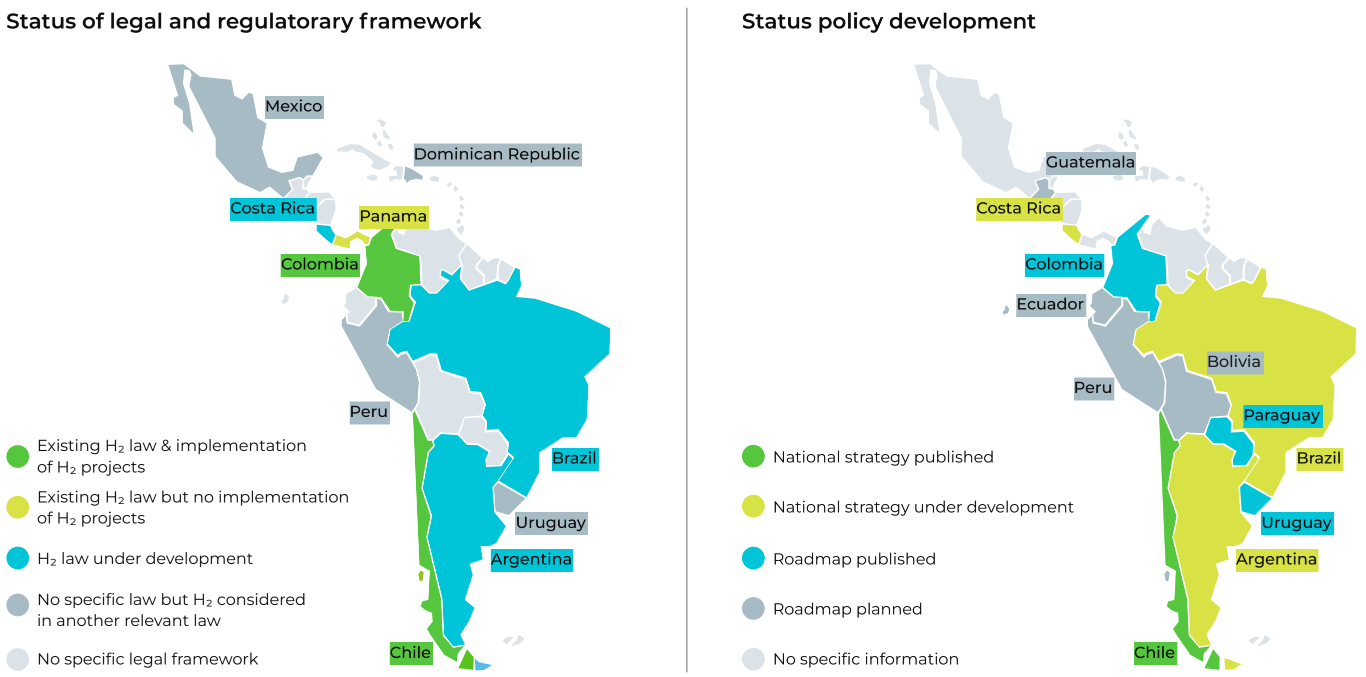
Peru's plans to develop a hydrogen roadmap and a national hydrogen strategy

Various law projects that promote the use of green hydrogen are currently being discussed by the national government. Specifically, a law on investments in renewables (6953/2020-CR) includes provisions to install green hydrogen production plants. The Peruvian Hydrogen Association H2Perú also presented to the national government a proposal for a law to promote the development of green hydrogen. This document foresees the development of a national strategy and stresses the importance of addressing emissions along the entire value chain, including research and development, production, transport, storage, and exports.

H2Perú has also developed a preliminary proposal for a hydrogen roadmap, as well as a list of recommendations for the national strategy. The roadmap forecasts an increase in installed electrolyser capacity of 1 GW to 2030 and 12 GW in 2050. The main end-uses and applications for green hydrogen according to the proposed roadmap are: the steel and cement industry (fossil fuels phased out by 2050) and transport, including light-duty vehicles, public transport buses, trains, forklifts, mining trucks, freight trucks, and maritime transport (Diazgranados et al., 2022; H2LAC, 2022b; H2Perú, 2022b).

Regulatory and legal frameworks are equally important to support future development of hydrogen applications. Countries need to lay down the legal basis to develop programmes and statistics, establish safety standards, and legislate equipment characteristics and installation requirements. → **Figure 10** summarises the current progress in developing hydrogen roadmaps and regulatory frameworks in LAC.

Figure 10
Status of policy development and legal frameworks for hydrogen deployment in LAC



Source: Produced by authors based on (Diazgranados et al., 2022).

LAC countries are also developing bilateral agreements that will shape future hydrogen trade and interdependence patterns. Bilateral deals often offer technology cooperation or building the infrastructure required for international trade in order to secure future green hydrogen supply between partner countries. These agreements can take various forms, including letters of intent, memorandums of understanding, partnerships, or trial shipments (IRENA, 2022b). In LAC, some countries have agreements already in place, or they explicitly mention potential trade routes in their national strategies and roadmaps:

a **Argentina** signed a memorandum of cooperation with the Ministry of Economy, Trade and Industry of Japan (METI) in 2019, with the objective of exchanging information on the development of green hydrogen, developing a roadmap for hydrogen, and increasing production efficiency, among others (Japan Ministry of Economy Trade and Industry, 2019). Bilateral engagement with the government of Germany has led to support under the PtX Hub, providing support with local institution's capacity building, scenario modelling and technical studies related to development of the national strategy.

b **Brazil** has established an energy partnership with Germany, which includes the H2Brazil project lead by the German Agency for International Cooperation (GIZ). As part of this partnership, a study has been developed to map the current status and potential for hydrogen use in the country (GIZ, 2021, 2022).

c **Chile** has actively engaged in hydrogen diplomacy, positioning itself as a potential future exporter of green hydrogen to attract foreign investment. The Chilean Ministry of Energy has signed an agreement and established a taskforce with the German government to support local green hydrogen projects, within the framework of a wider energy partnership. China, Japan, South Korea, and the United States have also been identified as potential markets for green hydrogen produced in Chile (Chile Ministry of Energy, 2020, 2021b, 2021a).

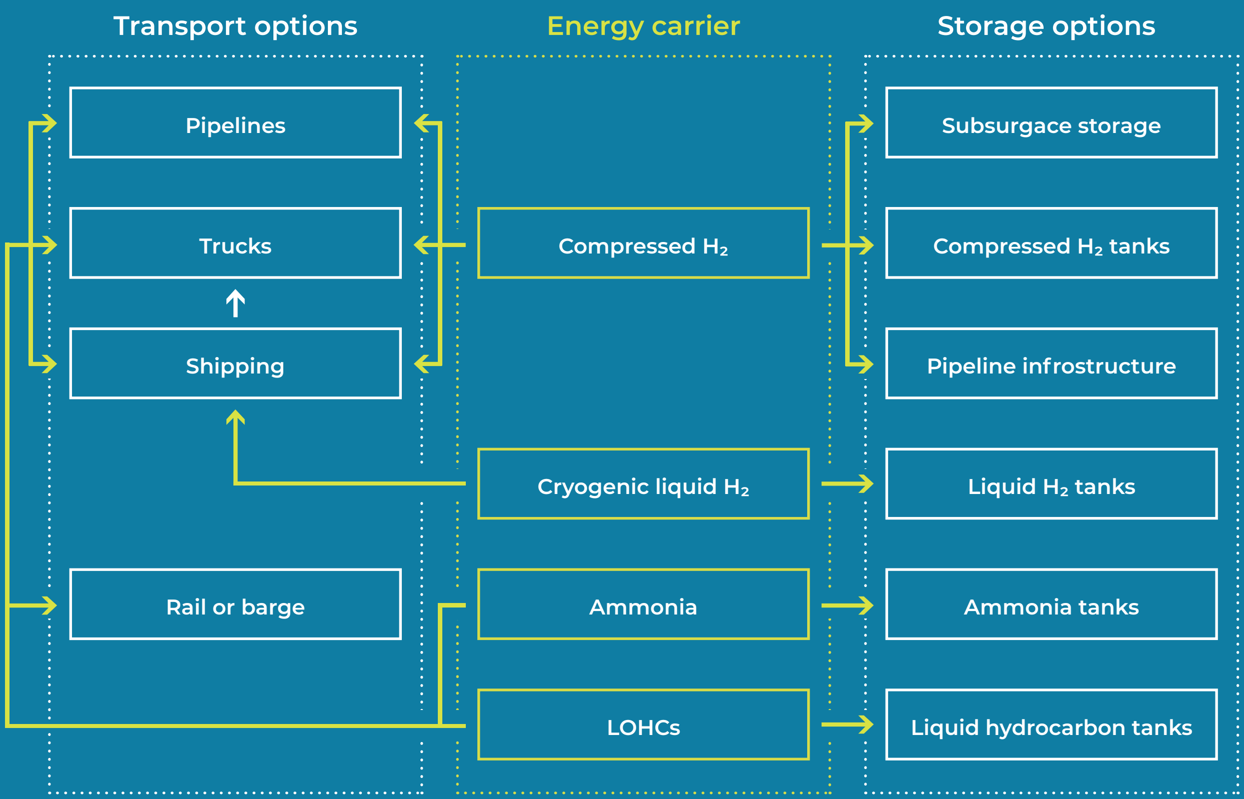
d **Colombia** has signed a memorandum of understanding with the Port of Rotterdam to discuss a potential trade corridor and support the development of the country's national hydrogen strategy (H2LAC, 2022a).

e **Uruguay** and the Netherlands have signed a joint statement on collaboration for the establishment of export-import corridors (The Netherlands Ministry of Economic Affairs and Climate Policy, 2021).

4.3 Infrastructure and trade

Transport and storage infrastructure is essential to integrate hydrogen into the whole energy sector and enable its use in locations far away from optimal production sites, as well as regional and international trade. Infrastructure needs in a net-zero scenario will depend on the extent of the hydrogen economy and its applications in hard-to-abate sectors. Investment in infrastructure will need to be carefully planned; potential risks are linked to the future development of hydrogen demand and supply. Hydrogen's inherent characteristics pose additional challenges for distribution in comparison with other energy carriers like natural gas or fossil fuels. Conversion to other derivatives that can be more easily distributed is possible but energy losses can increase costs significantly, in some cases even more than doubling the original production costs (BloombergNEF, 2020). ➔ **Figure 11** provides an overview of the main options available for hydrogen transport and storage.

Figure 11
Overview of hydrogen storage and transport options



Source: Adapted from (DNV, 2022)

Hydrogen transport

Hydrogen and its derivatives can be transported by pipelines, trucks, ships, or rail systems. Due to its low density, hydrogen must be pressurised or liquified to increase its energy density by volume and make distribution more efficient. Compressed hydrogen can be transported in tanks by truck, tube trailer, or ships, and via new or repurposed pipelines. Liquified hydrogen is more suitable for transport in ships or trucks. Alternatively, hydrogen can be converted to liquid organic hydrogen carriers (LOHC[8]), ammonia, methanol, or synthetic fuels that have higher volumetric energy densities (IRENA, 2021b), and which can be easily transported using existing infrastructure. In general, the suitability and cost-effectivity of each transport option will depend on two factors: 1) the size of production facilities and economies of scale, and 2) the transporting distance.

8 This are organic compounds that can absorb or release energy through chemical reactions. One example is toluene.

Pipelines of compressed hydrogen are an attractive option for high volumes and short to medium distances. When both distances and volumes are small, transport in tanks (usually as ammonia or LOHCs) by trucks or rail might compete with pipelines. Natural gas pipelines can be repurposed to provide low-cost hydrogen transport, particularly for regional trade or within industrial hubs (IEA, 2021c). **However, repurposing may involve the replacement of equipment such as valves, regulators, compressors, and metering devices.** Depending on the material of existing pipelines, complete replacement might be necessary. In LAC, the lack of regionwide natural gas networks limits the possibilities of large scale infrastructure repurposing to enable regional trade. However, IRENA reports that the underutilisation of gas transmission pipelines could make repurposing attractive in some cases, specifically when connecting prime areas for low-carbon hydrogen production with utilisation hubs. This could include pipelines connecting the southern Chile and Argentina with Brazil, as well as Uruguay with Argentina and Colombia with Venezuela (IRENA, 2022c, 2022d).

For the largest volumes and distances, including international trade, ammonia shipping is the most promising option. Global ammonia trade accounts for 10% of the current production and trade infrastructure already exists globally. One key challenge is the reconversion of ammonia to hydrogen, a process that is not energy efficient and increases overall costs by 1.5-2.0 USD/kg H_2 (DNV, 2022) or between 40 and 80% of current production costs of green hydrogen. Large-scale transport is appealing since ammonia can be directly used in many chemical feedstock applications. Moreover, most scenarios forecast an increased role of ammonia as a fuel for shipping, and it could even be used for power generation (IRENA, 2022d). However, the large-scale production of green ammonia (from green hydrogen) still needs to be demonstrated. According to current project pipelines, up to 34 Mt of green ammonia per year could be produced by the end of this decade, with 50% located in LAC (IRENA, 2022d).

Hydrogen storage

Storage options include dedicated tanks and vessels for compressed/liquified hydrogen and its derivatives, as well as subsurface storage of gaseous hydrogen. The latter can include naturally occurring geological formations like salt caverns and aquifers, or engineered sites in depleted oil and gas reservoirs (Griffiths et al., 2021). The suitability of each storing option depends on the required volumes and timeframes, as well as cycling rates. Geographical limitations also play a role in storage dependent on naturally occurring formations. **→Table 5** compares the costs and characteristics of different storage options.

Salt caverns are the most feasible large-scale option for hydrogen storage, but countries may have limited capacities. However, storage potential usually exceeds required volumes in regions with suitable geological formations (IRENA, 2021b). One key challenge for LAC is that expertise in the storage of gaseous compounds

Table 5
Hydrogen storage options

	Gaseous H_2				Liquid carriers in containers		
	Salt caverns	**Depleted gas fields**	**Rock caverns**	**Pressurised containers**	**Liquid H_2**	**Ammonia**	**LOHCs**
Capacity ($Mt\ H_2$)	0.3–10 Mt per cavern	0.3–100 Mt per field	0.3–2.5 Mt per cavern	5–1,100 kg per container	0.2–200 t per tank	1–10,000 t per tank	0.2–4,500 t per tank
Duration/ cycling	Weeks to months	Months (seasonal)	Weeks to months	Daily	Days to weeks	Weeks to months	Weeks to months
Benchmark levelised cost* (USD/kg)	0.23	1.90	0.71	0.19	4.57	2.83	4.50
Possible future levelised cost* (USD/kg)	0.11	1.07	0.23	0.17	0.95	0.87	1.86
Geographical availability	Limited	Limited	Limited	Not limited	Not limited	Not limited	Not limited

* Levelised costs at the highest reasonable cycling rates.

Source: Adapted from (BloombergNEF, 2020; Flis and Deutsch, 2021; Griffiths et al., 2021)

and hydrogen is mainly limited to the United States and Europe (Tarkowski, 2019). The only storage project in LAC is in Argentina, where the company HyChico is considering a pilot project for hydrogen storage in depleted oil and gas reservoirs (HyChico, 2018).

Hydrogen trade

Some LAC countries, due to their abundant and cost-competitive renewable energy resources, could produce more green hydrogen than their local demands and become net exporters. LAC is projected to have a self-sufficient hydrogen market, with most of the trade happening regionally. **Argentina, Brazil, and Chile are three countries that are frequently identified as potential exporters of low-carbon hydrogen and its derivatives (e.g. low-carbon ammonia, synfuels, steel) outside from the region (Berkenwald and Bermudez, 2020; DNV, 2022).** However, other LAC countries are also establishing bilateral agreements that will underpin future international export routes, as described in ➔ **Section 4.2**. Trade could also be meaningful for Panama, which could become a major distribution hub since it already concentrates maritime trade routes (IEA, 2021e).

The main markets for hydrogen trade will be countries that do not have enough land and renewable resources to meet their future hydrogen demand, including most European countries, China, Japan, Korea, and some countries in Southeast Asia (BloombergNEF, 2020; IRENA, 2022c). About one quarter of the global future demand could be satisfied through international trade; around 55% of the global hydrogen trade is expected to occur via pipelines concentrated either in Europe (85%) or in LAC (15%). Based on the scenarios presented in ➔ **Section 4**, this would mean that between 5 and 11 Mt of hydrogen could be regionally traded through pipelines in LAC by 2050. Meanwhile, the remaining share of traded hydrogen will be shipped as ammonia intended for direct use without cracking or reconversion (IRENA, 2022c). Other forecasts estimate that only about 4% of hydrogen demand will come from interregional trade through pipelines and that most trade by 2050 will occur through ammonia shipping, amounting to little more than 150 Mt/year[9](DNV, 2022). For comparison, global ammonia production was 183 Mt in 2020, of which LAC exported around 3.12 Mt to international markets, namely North America (41%), Africa (26%), Europe (21%), and Asia (12%)[10]. An additional 1.24 Mt of ammonia was traded within LAC (IRENA, 2022d).

9
DNV estimates a global production of ammonia equal to 450 Mt/year by 2050.

10
Global ammonia production in 2020 was 183 Mt and required over 32.4 Mt of hydrogen (~5.6 ratio of ammonia to hydrogen).

For hydrogen trade to be cost-effective, the cost of production in the exporter country must be sufficiently less expensive than in the importing region, to compensate for distribution costs and energy losses during conversion steps (e.g., liquefaction, pressurisation, or conversion to other energy carriers or products). **A key challenge for future international trade is the substantial investment required for transport and storage infrastructure.** The benefits of keeping transport distances short and practicable might outweigh trade benefits (DNV, 2022). **Investing in large-scale green hydrogen production for export will thus make sense in areas close to both ample renewable energy resources and port infrastructure, like coastal areas (Bertram, 2022)**, for future trade as ammonia or through regional pipelines.

Another factor that could limit international trade is the weighted average cost of capital (WACC) in potential export countries. Countries with high WACC (e.g. Argentina, Bolivia, Costa Rica, Ecuador) can face tougher challenges to attract investment if this is not directly addressed, therefore delaying potential hydrogen exports or losing out on bilateral agreements with countries with ambitious hydrogen goals. **This means that for countries like Argentina, despite their high potential for renewable energy and green hydrogen production, policy measures to address macroeconomic challenges such as high WACC are needed to, among others, take advantage of the quality of their resources and become exporters of green hydrogen (IRENA, 2022c, 2022e).** Some of these measures are explored in ➔ **Section 5.2**.

05 Assessment and prioritisation of hydrogen applications

Targeted investments, policies, and incentives across all stages of the value chain, from production to demand end-uses, are required for low-carbon hydrogen use to become more widespread. As decarbonisation efforts include a wide range of sectors and technologies, it must be ensured that the available financial resources are invested in the most impactful technologies. Despite its potential, production, conversion, transport and end use of hydrogen can be costly and very energy intensive, therefore potentially drawing resources from other, more impactful, decarbonisation or sustainability efforts. Investment along the entire value chain (from production to consumption) should thus prioritise the most promising applications where hydrogen is the only or most cost-effective option for decarbonisation.

11
Griffiths et al. (2021) and BloombergNEF's Hydrogen Economy Outlook (2020) provide a marginal abatement cost curve (2050) for using $1/kg hydrogen for emission reductions versus low-cost fossil fuels, by sector. The values can be interpreted as the required carbon price to trigger investment in low-carbon hydrogen applications for each sector.

The assessment made in this chapter aims to provide investment guidance on the applications that focuses on the most advantageous use of low-carbon hydrogen, from both a technological perspective as well as their mid- and long-term impact in emissions. To this end, a matrix evaluating a wide range of applications was created, which were assessed under **three dimensions: competitiveness, temporality and regional participation in the value chain (in the LAC region).** To enable transparent priority setting, the following criteria were defined for the quantitative assessment of each dimension in ➔ **Table 6**.

In the evaluation process, **certain criteria were given more weight** to emphasise their critical importance for investment decisions today. These include the criteria **"expected future role"** and **"carbon lock-in risk"**. The former is intended to highlight applications where there are none to very limited alternatives in the decarbonisation process (technology competitiveness). The latter assesses the impact what delaying decarbonisation investments could have in future emissions, and considers both the urgency of the technological shift as well as the long term impact in emissions of the investments in carbon-intensive alternatives (temporality). More context on the definition and relevance of carbon lock-in is provided below in ➔ **Box 3**.

In contrast current technology readiness level (TRL), current "penetration level" and "degree of centralisation" were weighted less strongly, as applications with low TRL are technological innovations that are not yet cost-competititve, which however, does not change their potential role in the long-term. Penetration level is currently very low, or non-existent, for all applications considered, making it less relevant for this assessment. Similarly, the degree of centralisation can be important in the short-term when hydrogen production will be mostly generated close to its offtakers. Once production and utilisation projects are decoupled, this will become less relevant. The criteria and the methodology used for their evaluation is further detailed in ➔ **Annex 5**.

The overall results of the prioritisation of investment opportunities in the low-cabon hydrogen value chain for the LAC region can be seen in ➔ **Figure 12**. The full matrix detailing each investment opportunity and its evaluation can be found in ➔ **Annex 1**.

Table 6

Fleet and new sales shares for FCEVs in LAC by 2030

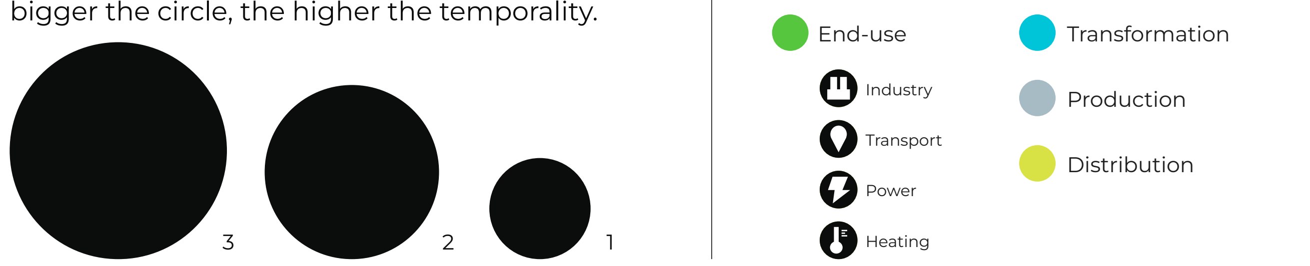
Dimension	Criterion	Description
Competitiveness Describes whether an application is competitive with other decarbonisation options that may already be available. Based on the technological maturity, expected or potential future role in decarbonisation efforts, current market penetration levels, and cost prospects for each application.	Technological Maturity	Describes whether applications are in research, development, or deployment stage (global values based on available literature). The indicator was evaluated using values for Technology Readiness Levels (TRL) by the IEA (2022a).
	Expected future role	Describes whether alternative decarbonisation options exist for a specific application (for example, electric vehicles vs FCEVs) and if the hydrogen application is expected to play a significant role in future decarbonisation efforts. Based on the revision of decarbonisation scenarios and the role they assign to different hydrogen production technologies and end uses **(→ see Section 4)**, as well as assessments by the IEA (2022a) and Liebreich Associates' Hydrogen Ladder (2021), to classify each application in a scale from unavoidable (no alternatives exist) to uncompetitive (alternatives to hydrogen are likely to be the most competitive option for decarbonisation).
	Penetration level	Market penetration levels of applications, using current values available in literature (global or regional-wide values, if available).
	Cost prospects	Considering current and forecasted levelised costs of hydrogen production, storage, and distribution in USD/kg H_2 For end use applications that rely on grey hydrogen or fossil fuels, the carbon price required to trigger investment in low-carbon hydrogen applications[11] was used to grade cost prospects.
Temporality Describes the urgency of investment in specific applications. Based on the expected deployment timeframe of specific applications (e.g. in the short, medium, or long-term) and the risk of carbon lock-in, understood as path dependencies, stranded assets, and the persistence over time of carbon-intensive technological systems and, if there is little investment in alternative decarbonisation options.	Deployment timeframe	Describes whether an investment opportunity is likely to take place in the short, medium, or long-term, tied to expectations on technological development. Global values were based on available literature.
	Lock-in risk	Describes whether an investment opportunity moves away from BAU activities that have carbon lock-in risks due to equipment lifetime, financial barriers, over-committed emissions, and techno-institutional effects (Erickson et al., 2015). More detail on the importance of this criterion is provided in **→ Box 3**.
Regional participation in value chain Describes whether specific applications are relevant for the three focus countries of the report. Based on the potential market size of low-carbon hydrogen technologies and the economic relevance of hard-to-abate sectors where hydrogen is a potential decarbonisation option. This dimension also considers whether hydrogen applications in the focus countries will represent centralised production or demand centres, requiring minimal additional steps (e.g. conversion, storage, transportation) to reach end users, or if the applications have a higher degree of spatial distribution; more centralised applications are likely to be more competitive sooner than those requiring greater infrastructure for distribution or storage.	Market size (potential)	Weighs the size and importance of the different sectors in the region and/or the focus countries, based on available literature.
	Degree of centralisation	Assesses large demand centres vs distributed applications in the LAC region and/or the focus countries. Highly centralised applications (e.g. large industrial hubs, ports with potential for renewable generation) enable economies of scale and more cost-effective options.

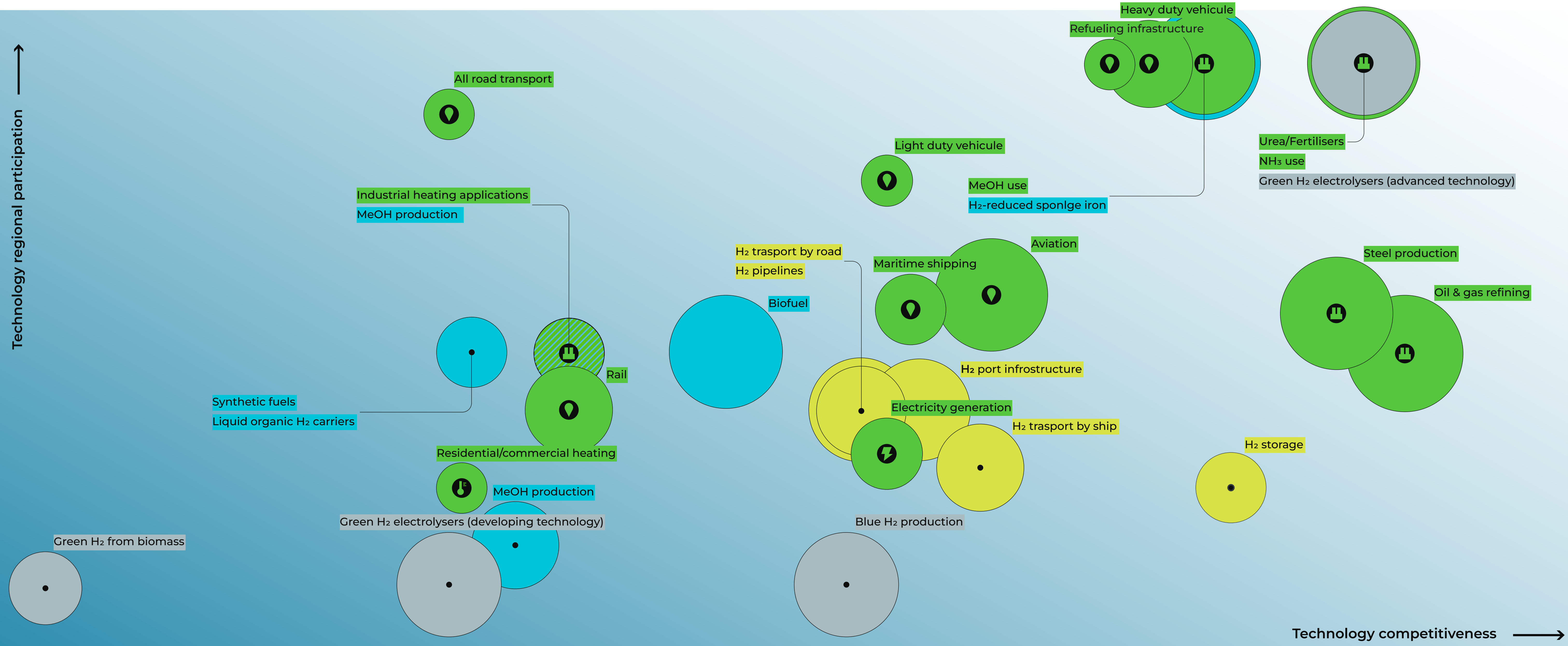
Figure 12
Relative prioritisation of investment opportunities in the low-carbon hydrogen value chain for the LAC region

How to read this chart:
This chart represents relative prioritisation of investment opportunities in the low-carbon hydrogen supply chain. **Regional participation** describes whether specific applications are relevant for the three focus countries of the report. **Competitiveness** describes whether an application is competitive with other decarbonisation options that may already be available. The closer the circle is to the top right side of this chart, the more attention the investment opportunity should receive, as it is both competitive and regionally appropriate.

Circle size = Temporality. Temporality describes the urgency of investment opportunities. The bigger the circle, the higher the temporality.

Color of the element = Investment area





Source: Produced by authors based on own prioritisation methodology. Relevant information sources include (Erickson et al., 2015; The Hydrogen Council, 2020; IEA, 2020b, 2020a; Schemme et al., 2020; IEA, 2021e; IRENA and Methanol Institute, 2021; Liebreich Associates, 2021; Gomes et al., 2021; IEA, 2022a, 2022c; IRENA, 2022d; Clarke et al., 2022; IRENA and AEA, 2022; Nurdiawati and Urban, 2022; IEA, 2022e)

The evaluation shows three main categories of hydrogen investments that should, according to this assessment, be prioritised in the LAC region, and in particular the three focus countries. These are analysed in more detail in the following sections, and include:

- **a** **Production of hydrogen** through electrolysis is the main priority for investment. As described in previous sections, hydrogen is poised to play an important role in decarbonisation efforts and reducing production costs is a key milestone for widespread application. Spurring technological learning and lowering the perceived risk of hydrogen investments are the main objectives of the technology's early adoption.
- **b** **Industrial applications** in the chemical and steel sectors also achieved high scores, especially to substitute grey hydrogen in refining processes, producing low-carbon methanol and ammonia, and to introduce low-carbon steel production through direct reduced iron (DRI).
- **c** In the **transport sector**, only remote off-road, heavy-duty mining vehicles were prioritised, as the direct electrification of most other transport applications is seen as a preferred option due to its better efficiency and further technology development.

All these applications show significant risk of carbon lock-in if not implemented in the near-term, and are considered the main alternative to decarbonisation of each sector applications, as feasible low-carbon alternatives do not currently exist nor fully address the current reliance on fossil fuels.

Some hydrogen applications were also deemed unsuitable for the region, and others were regionally compatible but other alternatives (direct electrification, for example) are expected to play a larger role in the future. Green hydrogen from biomass, for example, has been proposed in Brazil due to the country's current biomass use at large scale. However, the technology is still under development and its higher expected costs when compared to the current use (biofuel production) lands it in the bottom left side of the chart. Issues around deforestation and land use can also make biomass use without proper certification contentious in some regions.

Technology competitiveness against other decarbonisation alternatives combined with the long-term nature of the investments worked against other applications, such as residential and commercial space heating, electricity generation, rail transport and road transport infrastructure (to transport hydrogen).

Investment in hydrogen storage scored high in technology competitiveness, and does not pose a risk of locking-in additional carbon emissions, however, it was also not identified as a necessary investment in the short to mid-term. From the evaluated storage technologies, pressurised hydrogen and ammonia tanks were the technologies that achieved the highest scores.

Box 3

Path dependence and lock-in effects

Path dependence, a concept first introduced in 1989 (Arthur, 1989), refers to the idea that the choices taken and actions implemented in the past can shape and constrain future options and outcomes for a given system (Geels F, 2002) and partially explains the difficulty of transitioning away from established technologies and systems (Grubler, 1998)

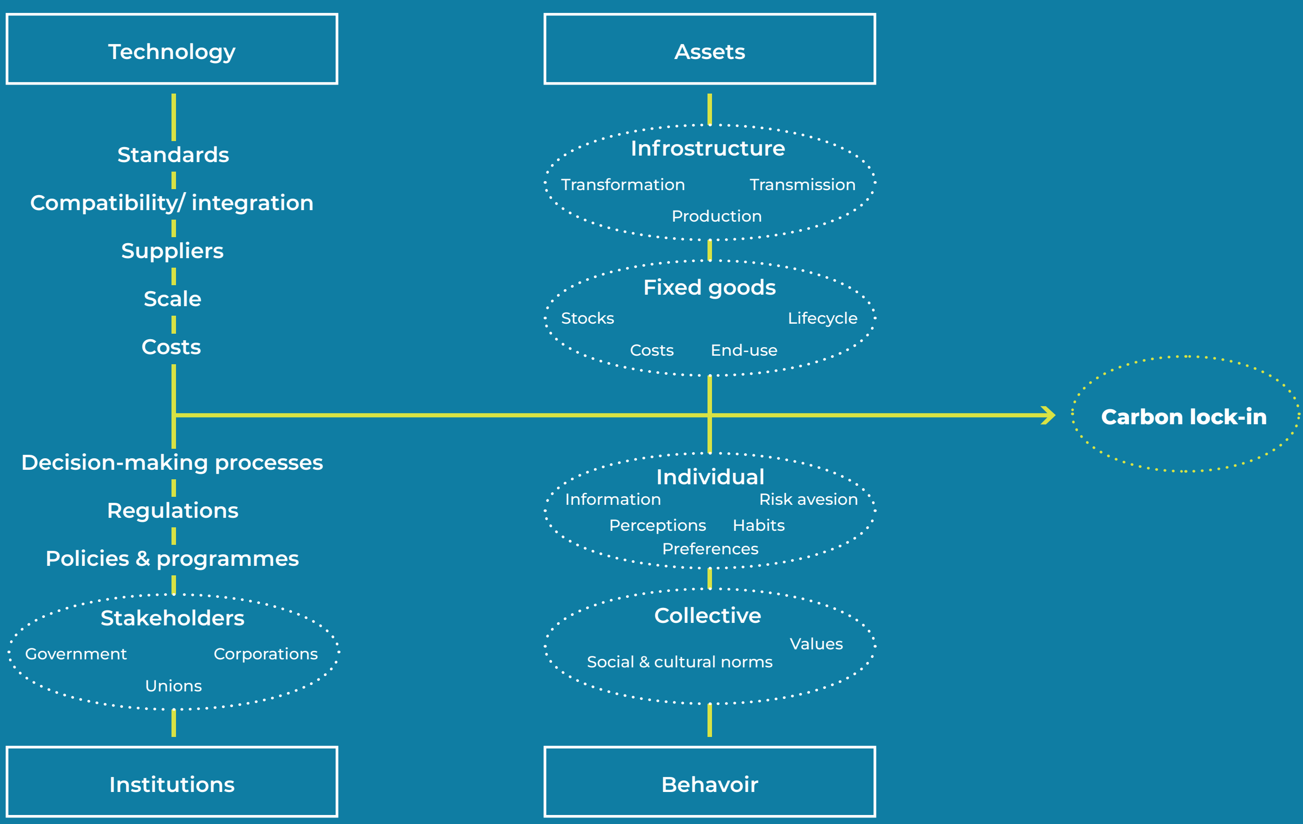
The lock-in effect further compounds this issue, as it refers to the difficulty of transitioning away from established and prevalent technologies and systems (Arthur, 1989; Seto et al., 2016). This can be due to the financial costs of transitioning to new technologies, as well as the difficulties of coordinating and aligning the actions of multiple actors within the energy system.

In particular, carbon lock-in refers to the long-term reliance on fossil fuel-based infrastructure and technologies, which makes it difficult to transition to low-carbon alternatives. This phenomenon can occur at various levels, including individual behaviours, firms, and the entire systems.

Carbon lock-in can be categorised in three types: Infrastructure and technological, corresponding to technological and economic forces leading to inertia, long lead times, large investments and

Figure 13

Carbon Lock-in factors or clusters



Source: Adapted from (Elementos para una Estrategia Climática de Largo Plazo (FTDT, 2022), based on Seto et al. (2016), Janipour et al. (2019), Unruh (2000) and Erickson et al. (2015))

A practical approach to assess carbon lock-in risks in the power, buildings, industry, and transport sectors, can be based on four dimensions (Erickson et al., 2015):

- Technical equipment lifetime, relating to how long a given technology or asset may continue to operate, and emit;
- Scale of increase in CO_2 emissions, based on the use of CO_2 accounting for the future emissions of the assets under full normal operation, which can be contrasted to the carbon budget resulting from the analysis of a given emissions scenario;
- Financial barriers to the replacement of an asset with low-carbon alternatives, often quantified as the necessary carbon price for the early retirement and/or replacement of an asset with its predominant low-carbon alternative; and, finally,
- System-wide Techno-institutional mechanisms that further strengthen high-carbon technologies at the expense of low-carbon alternatives, mostly linked to the economic, political and social advantages that incumbent technologies have (e.g. higher market share, cumulative production and cumulative investments).

Hydrogen has a two-way relationship with the lock-in effect: on one hand, the dominance of incumbent technologies hinders the possibilities of development of green hydrogen through several of the mechanisms described above. Conversely, certain hydrogen pathways, particularly those based on fossil fuels, may further contribute to carbon lock-in (Rosenow and Lowes, 2021; Oh and Yeon, 2022) by delaying the phase out of existing natural gas plays and infrastructure. This can contribute to a failure to reduce or can even increase fugitive methane emissions and could also reinforce reliance on long-lived carbon capture assets where “green” hydrogen can replace fossil-based hydrogen in the short- to medium terms.

5.1 Key investment opportunities

After evaluating and prioritising hydrogen applications, this report looks at specific investment opportunities in the target countries of Argentina, Brazil and Peru. By detailing the investment opportunities, it aims to provide additional insights for investors looking at the best ways to support ambitious decarbonisation efforts.

The following sections present more details on the prioritised investment opportunities, offer a description of local and regional context and, when possible, identify specific investment needs. Additionally, the section also provides recommendations on overarching policy and financial instruments required to drive low-carbon hydrogen use across the entire value chain.

Policies and investment decisions taken between now and 2030 will shape the long-term potential of hydrogen to become a cost competitive option to reduce GHG emissions in the region and contribute to global mitigation efforts.

Addressing the current hydrogen supply is the starting point to ramp up low-carbon hydrogen production. Increasing supply of low-carbon hydrogen will help to unlock new uses and applications in other sectors. Efforts should thus target the production of low-carbon hydrogen and its use in sectors that already require significant amounts of hydrogen, including oil refining, steel production, and the chemical industry. This can ensure that low-carbon hydrogen has an immediate impact in decarbonising industrial processes, and can help reduce production costs. Moreover, production and consumption should ideally be deployed in centralised locations or in close proximity of industrial hubs, minimising the need for distribution infrastructure such as pipelines or storage facilities. Heavy transport, shipping, and aviation are other end uses where hydrogen is expected to play an important role in the long-term, and initial investments could target pilot-scale projects, technology demonstration, and infrastructure development.

The next section explores in more detail the four applications that were considered most promising for the region:

- Green steel, where the section includes an added focus on financing projects
- Green hydrogen production through electrolysis
- Green chemicals such as methanol and ammonia, as well as fertilisers
- Heavy-duty mining vehicles in remote locations

Green steel

Steel productions is one of the applications that achieved high scores in all three evaluated dimensions. The high share of global emissions coming from steel production, and the fact that **hydrogen technology is the most feasible decarbonisation**

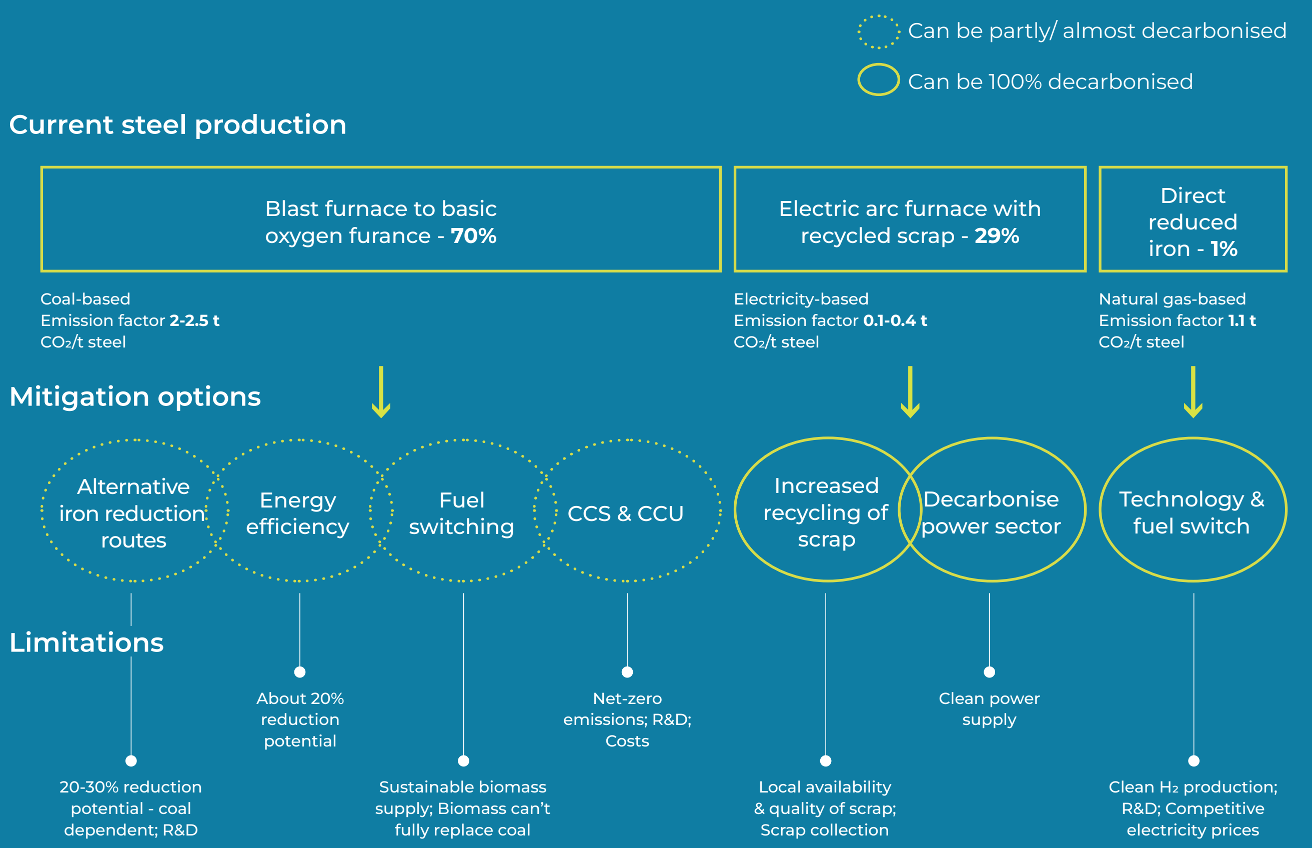
option that ranked the sector high in the temporality dimension. It is one of the technologies labeled as unavoidable in ➔ **Section 2.2**. Partial replacement of coke in the reduction process should only be seen as an short-term solution considering the limited potential to reduce emissions and the high risk of carbon lock-in if the practice is perpetuated. DRI coupled with EAFs, however, has the potential to fully decarbonise a sector often categorised as “hard-to-abate”. The long lifetime of steel plants and the region’s ageing infrastructure makes **investment in the short-term critical to avoid emissions lock-in**. Brazil being the largest producer of the region and Argentina with EAF plants in the majority of its production sites means the application is highly relevant for this report’s target countries.

Steel can be produced in two main routes: BF-BOF relies on coal and has only limited potential to reduce emissions (beyond using CCUS technology), and therefore should be eventually phased out to fully decarbonise the sector; EAF is a fully electrified process that currently relies on the limited supply of steel scraps to produce new steel. The use of hydrogen for the Direct Reduction of Iron (DRI) can substitute BF technology and decarbonise the most carbon intensive part of the steel making process. The only way to fully decarbonise the steel sector is to use EAF technology on steel scraps or DRI produced with green hydrogen. Therefore, the path forward must phase in the right combination of clean power, green hydrogen, scrap steel recycling and technology improvements, coupled with Electric Arc Furnaces to increasingly reduce the carbon intensity of the sector. ➔ **Figure 14** shows the different production pathways and their decarbonisation potential.

Recycling of steel scraps should be maximised as part of efficiency and circular economy strategies, but recognising its limited availability makes the **introduction of hydrogen in DRI technologies unavoidable if the sector aims to achieve its full decarbonisation.** EAF are widely used globally, while the combination with hydrogen-based DRI is not yet at a commercial stage. **The long lifetime of steel plants and industrial inertia puts the sector at high risk of carbon lock-in.** All investments in the sector, from new furnaces to upgrades and refurbishment needs to be geared towards an eventual total shift to EAF (including the phase-out of all BF furnaces) and the introduction of low-carbon DRI. Global steel demand is expected to keep increasing, from 1.9Gt in 2019 to over 2.5Gt in 2050 (IEA, 2022b), increasing also the risk of locking-in carbon intensive technologies if a transition to cleaner production processes is not started soon. Low-carbon hydrogen production needs to be scaled up in parallel so that hydrogen sourcing doesn’t become a limiting factor when deciding the technology choice. Currently proposed hydrogen projects in the steel sector consider this, as half of them include plans to produce the necessary hydrogen on-site (De Villafranca Casas and Nilsson, 2022).

Brazil has the largest steel industry, with over 55% of the production in the region (36.2 Mt of crude steel produced in 2021 (World Steel Association, 2022). Notably, none of the 27 iron/steel plants operating, proposed or mothballed use DRI and less than 17% of the country’s capacity relies on EAF technologies (Global Energy

Figure 14
Steel production and its decarbonisation options



Source: Adapted from (CAT, 2020)

Monitor, 2022). Being a net exporter of steel scraps, Brazil has the potential to ramp up the use of EAFs using local inputs (U.S. International Trade Administration, 2019). The current reliance on BF-BOF plants makes decarbonisation pathways reliant on short term improvements through fuel switch (charcoal and/or hydrogen) while the mid-term needs to focus on larger changes towards DRI-EAF steel production[12].

While many plants have been expanded or retrofitted, 15 out of the 22 operating plants in Brazil are over 35 years old (with 8 of them being over 60 years old). This means these plants will soon need to be replaced or retrofitted, providing an opportunity for early decarbonisation investments in the sector to avoid long-term carbon and technological lock-in.

12 All steel production values reported by the World Steel Association and plant data by the Global Steel Plant Tracker.

Argentina has 4 operating plants, with a total output of 4.9 Mt of crude steel in 2021. While 3 of them use EAF technology, the remaining BOF plant, accounting for almost half of the country's steelmaking capacity, has been in operation for over 60 years, the last furnace installed in 1974 (Global Steel Plant Tracker, 2022). This again provides the opportunity to invest in decarbonisation-compatible EAF technology when this plant reaches the end of its useful life, or even earlier if the right incentives can be brought in to place. Investments to prepare the remaining EAF plants to incorporate DRI technology as soon as feasibly possible also presents an investment priority and necessity.

Peru has the most limited steel production capacity of the three countries (1.23 Mt of crude steel in 2021), and both plants in the country use EAF technology (one fully electric and one integrated BF-EAF process).

Financing hydrogen applications: the case of green steel

Green steel is considered an early technology bet[13], as it is a technology largely unproven at commercial scale. Developing green steel at the pace and scale required is therefore challenging. In addition, due to its significant incremental production cost, estimated at around +20-50%, and in the absence of strong demand and/ or enabling policy environment, there is no strong business case yet to significantly invest in green steel (Mission Possible Partnership, 2022).

The majority of investment for green steel is currently coming directly from steel producers **(➔ Table 7)**. Their incentive to invest depends on a number of factors. This includes company size and strategy, the geography and policy environment it is located in and whether the incremental production cost can be passed on. Currently, in Latin America there are limited incentives for steel producers to invest in green steel development. **In the absence of more stringent domestic policies and fiscal incentives smaller steel producers with a focus on domestic markets might be less inclined to invest in green steel.** Looking ahead, for a large steel producer that is exporting a significant share of its product, the incentive will be larger due to more stringent climate regulation in many importing markets. For example, the EU Carbon Border Adjustment Mechanism (CBAM), planned to be gradually introduced in October 2023, will encourage imports of industrial products, such as steel, from non-EU companies that fulfil the (more ambitious) European climate standards (Council of the European Union, 2022). Additionally, robust green steel certification schemes can create a market for companies with serious net zero commitments, therefore creating a demand that can incentivise private investors (Glasgow Financial Alliance for Net Zero and UNFCCC Race to Zero, 2021).

13
Early technology bets are those technologies that come with high but uncertain potential returns, requiring enabling policy frameworks (UNFCC Race to Zero, 2021).

To counteract these barriers, governments and companies could investigate and proceed with a few targeted interventions. For example, on the company side, early bilateral offtake agreements between green steel producers and their offtakers in the automotive and manufacturing sectors can help secure demand and provide necessary business guarantees to the producer, which in turn increases investment appetite by commercial financial institutions (Mission Possible Partnership, 2022). **Current corporate target evaluations, however, do not show companies taking a serious approach to their net-zero commitments,** therefore hindering potential investments in this and other sectors (Day et al., 2022)

While we currently see that most green steel investments are made by companies, this will be nowhere near enough to meet the investment needs at the pace and scale required. Targeted policy interventions will be essential to drive forward green steel development and mitigate investment risks. Regulatory certainty is one way to achieve this. Governments could for example set up a sufficiently high carbon price or work with new Paris-aligned emissions standards to level the playing field. Tax credits or other financial incentives, in particular for those smaller steel makers catering domestic markets, could be another instrument to further analyse. Demand could further be improved through green procurement commitments by public authorities (Glasgow Financial Alliance for Net Zero and UNFCCC Race to Zero, 2021).

Other measures and instruments could include the development of taxonomies or the introduction of international carbon contracts for difference (CCfDs) (Glasgow Financial Alliance for Net Zero and UNFCCC Race to Zero, 2021). “Traditional” CCfDs are a financial instrument which can be used to de-risk green steel investments by covering the incremental production costs of green steel and work in jurisdictions that have introduced a price for carbon. In a developing country context, CCfDs could be used as an international finance instrument that can help donors and recipient countries foster green steel projects (The German Institute for Economic Research - DIW Berlin, 2022).

More generally, international finance as well as the increased usage of blended finance can play an important supporting role to help de-risk investments and mobilise private capital for green steel in Latin America **(➔ Table 7)** (Leadership Group for Industry Transition (LeadIT), 2022). Just Energy Transition Partnerships (JETPs), multilateral agreements aimed at supporting the phase out of fossil fuels in developing countries could provide another boost for green steel development.

Table 7
Overview of finance providers for green steel development

Type of financial provider	Relevance	Role in green steel development	Challenges
Private companies	Highly relevant. Currently largest provider of green steel development.	Investment or co-investment throughout all financing phases, often through the set up of special-purpose vehicle (SPVs) for project financing.	Lack/ uncertain business case (depending on company and geography); Lack of internal resources.
Governments	Highly relevant	Funding of RD&D. Provide risk absorption guarantees, e.g. credit guarantees to lower transaction risks, for commercial financial institutions and/or DFIs. Creating enabling policy framework.	Limited resources; Unlikely to directly invest in greenfield steel development in LAC.
Development finance institutions	Highly relevant	Technical assistance and grants for scoping/ (pre)feasibility studies. Concessional loans and other blended finance instruments.	Currently insufficient funding for industrial decarbonisation, additional private finance mobilisation required.
Multilateral climate funds	Relevant, especially for project finance. Not yet systematically leveraged.	Technical assistance and grants for scoping/ (pre)feasibility studies.	Currently insufficient funding for industrial decarbonisation, additional private finance mobilisation required.
Commercial finance institutions	Potentially highly relevant, not yet directly leveraged (with a few exceptions). Important also for its finaning role for steel companies.	Debt financing (commercial banks), mostly for construction/ implementation phase.	Require risk absorption support; Need certainty on returns given liabilities; reserve and liquitidy requirements can stand in the way of long-term infrastructure projects (commercial banks).
Infrastructure funds	Potentially highly relevant, not yet directly leveraged.	Mostly for construction/ implementation phase.	Require risk absorption support.
Private equity	Less relevant for early technology bets.	-	More relevant for mature markets.

Source: Glasgow Financial Alliance for Net Zero and UNFCCC Race to Zero, 2021; Leadership Group for Industry Transition, 2022)

If investment barriers are tackled, and the right incentives are put in place (carbon pricing, CCfDs, fiscal incentives or [public] procurement strategies) **greenfield steel development could successfully be financed.** A case in point is H_2 Green Steel, a Swedish company, that in late 2022 secured funding for the construction of one of the world's first large-scale green steel plants. It is set to start production in 2025, with an initial yearly capacity of 2.5 million tonnes (Institute for Energy Economics and Financial Analysis, 2022). **The main success factors that enabled the deal are:** 1) the company had pre-sold a large part of its planned annual produced steel, including to carmakers and manufacturers who came in to decarbonise their supply chain, 2) multilateral and public finance providers came in to mitigate investment risks, by providing credit guarantees and senior debt capital, 3) financial support from commercial lenders who had built a business case and could count on the guarantees from multilateral and public finance providers, and 4) the country's access to cheap renewable energy. Examples such as the green steel plant that will be built by H_2 Green Steel are important to demonstrate the bankability of green steel (Rocky Mountain Institute, 2022).

These success factors can, at least partially, be replicated in the region. Both Argentina and Brazil have a sizeable car manufacturing industry[14] with plants from the largest carmaking companies, which are expected to commit to serious decarbonization efforts and could potentially pre-purchase steel to provide market certainty. Brazil produces a large share of its electricity from hydropower, and while clean energy is still a small share of Argentina's electricity mix, wind capacity has seen the largest growth of all sources in the last 5 years (Our World in Data, 2022b, 2022a). While Argentina may face challenges securing international finance, both from multilateral providers and international commercial lenders; Brazil has the potential to lead the steel decarbonization efforts, making it an interesting recipient of international and development finance.

14 Brazil is the 8th largest car manufacturing country with close to 2.25 million vehicles in 2021, while Argentina ranks 23rd with almost 435,000 vehicles. Source (2021 Statistics | www.oica.net)

Electrolysers for hydrogen production

As mentioned in ➔ **Section 2.1****, most of the hydrogen used today is blue hydrogen produced with fossil gas.** While current production costs make this the obvious choice to scale up hydrogen production and use, an effective long-term decarbonisation will require that most of the hydrogen used comes from electrolysers using clean energy. To this end, investment in hydrogen production in this report, prioritises green hydrogen routes. Currently, Alkaline Electrolysers (AE) and Polymer Electrolyte Membrane (PEM) electrolysers are the most advanced technologies for green hydrogen production. Their evaluation is high for the technology competitiveness criteria, as their technology readiness level (TRL) is considered at the highest level (9), and already been successfully demonstrated at the plant level. **These are also both considered "unavoidable" technologies, as only clean energy-derived hydrogen will deliver the maximum possible emissions reductions,** and these technologies are leading all new green hydrogen projects. Cost prospects are also reaching competitive level, with AE expected to reach production costs between 1.2 and 1.8 USD/kg H_2 by mid-century with PEM production costs slightly above at 1.8-2.5 USD/kg H_2 (IEA, 2020b). While AE is the most mature electrolyser technology, it presents challenges when coupled with intermittent RE. Considering the large share of hydropower in the LAC region, there is still vast potential for increasing AE capacity without compromising on the low-carbon nature of the hydrogen produced. PEM electrolysers being less challenging to couple with RE is the main reason behind this technology being the most common one in the pipeline of projects at a regional level.

The temporality dimension achieved the highest scores, as it evaluates both the urgency of the deployment and the risk of carbon lock-in if the technology is not scaled up in the short term. Considering that the uptake of hydrogen in end-use application depends on a steady supply, it is imperative that the electrolyser capacity is increased in the short term. While currently a lot of the electrolyser capacity is tied to a specific source of RE and projects are often developed in parallel, electrolyser capacity connected to the grid will be more common in the future. This can **allow to decouple the construction of RE and electrolyser capacity,** and take advantage of the existing electricity transmission infrastructure.

A high level of regional relevance was also considered, as the potential for low-carbon hydrogen production in the region is considered to be much larger than the potential demand, particularly in the short and medium terms. High RE potential is also reflected in the expected production costs, as the region could produce up to 49 Mt of hydrogen per year at costs below 1.2 USD/kg H_2, and up to 913 Mt at costs below 1.8 USD/kg H_2. (IEA, 2020b)

While this section mostly focuses on AE and PEM electrolysers, Anion Exchange Membrane (AEM) and Solid Oxide (SO) electrolysers are very promising technologies. However, the lack of large-scale demonstration and longer-term expected deployment means they will likely only become economically feasible technologies in the mid-to-long term.

Green chemicals (ammonia & methanol)

The chemicals sector is one where low-carbon hydrogen could have an immediate use and impact. Currently 32% of the hydrogen demand in the LAC region is used in oil refineries (IEA, 2021d), but considering the decarbonisation focus of this study, this application is omitted as oil refining is expected to decrease as fossil fuel reliance fades.

Ammonia and methanol production account for almost 60% of the region's hydrogen demand, with more than 90% of it being produced from fossil gas (IEA, 2021c). Increasing demand for low-carbon hydrogen in these applications is the fastest way to signal the need of an increased supply of low-carbon or green hydrogen. The large fertiliser industry, which uses ammonia as one of its main inputs, would also be impacted by these improvements. Methanol is a widely used feedstock for chemicals and materials production, and is also used to produce fuels for a number of applications. All three of these low-carbon hydrogen applications (use in ammonia and methanol as well as fertiliser production using this "low-carbon ammonia") are considered unavoidable, as it has the potential to fully decarbonise an important part of the production of globally used products. Cost prospects are also good, and mostly associated with the higher costs of green versus grey hydrogen. It is estimated that a carbon price between 60 and 135 USD/tCO_2 would be enough to drive investments in the sector. If this carbon price was to be established in a region with large RE potential (able to produce green hydrogen below 2.2 USD/kg H_2), cost parity with grey ammonia could be achieved as early as 2024 (Systemiq, 2023).

The temporality dimension of these investments also receives the highest scores, as **there is no real technological challenge to switching the source of hydrogen in the methanol and ammonia production** processes. This switch can avoid the large carbon lock-in effect associated with increasing capacity of grey hydrogen production, which would still rely on fossil gas.

There is also a strong regional relevance for green chemicals. Although Trinidad & Tobago and Mexico account for more than 55% of the hydrogen demand for the region, Brazil and Argentina follow them with close to 10% each (IEA, 2021c). Although Brazil only uses roughly 17% of the hydrogen for fertiliser production (the main use is in oil refineries), Argentina has "sizeable demand" for all three uses as well as the DRI process of steel production.

Heavy duty EFCVs for the mining industry

Mining requires moving enormous volumes of minerals across large distances in an almost continuous way and currently uses only fossil fuels (diesel) to power the necessary vehicles. As mining is often done in remote location, the cost of purchasing and transporting the fuel has mining companies looking for innovation in this sector. While electrification of transport is widely seen as the more straightforward solution, the large amount of power needed by mining vehicles poses a challenge due to the weight of the batteries and the recharging times. Electric Fuel Cell Vehicles (EFCV) can be powered by batteries when requiring "low" amounts of energy and be supported by hydrogen-powered fuel cells to deliver the remaining power. The emissions avoided by drastically reducing a mine's diesel use can be very large (Nilsson et al., 2021).

Although not yet widely commercially available, companies have tested EFCVs for mining applications with positive results. Fully electric vehicles are also being developed and tested, which makes this hydrogen application "very competitive" although not necessarily "unavoidable". **In remote locations with high RE potential where the needed electricity (and hydrogen) could be produced in place, EFCVs are cost competitive as a carbon price below 60 USD/tCO_2 would be enough to**

directly compete with diesel vehicles (Nilsson et al., 2021). Additional cost benefits such as the potential elimination of underground ventilation systems are often not considered in these calculations. Implementation could mean that renewable energy production and electrolyser capacity would be needed on site, or the fuel would need to be transported either as hydrogen or electricity.

Considering the large investments needed for these vehicles, companies often use them beyond their estimated useful life. **This application can be implemented in the short term, and therefore eliminate the carbon lock-in** associated with the high level of emissions coming from mining vehicles purchased in the near future.

As for the regional dimension, this application is particularly relevant in the Peruvian context due to their large industry. Mining exports in Peru accounted for over 60% of total exports in 2019 (the World Bank Group, 2021).

5.2 Overarching policy and financial measures

Latin American governments are not expected to use public finance to directly invest in electrolyser capacity or industry uses of hydrogen. But they will play an important role in providing the private sector with the right signals and incentives to direct private sector and international development finance into the development of the hydrogen economy.

The following section provides examples of actions that governments can choose to follow to spur investment.

National strategies and programs

An official hydrogen national strategy, supported by targets and long-term roadmaps is one of the most effective signals a government can send to incentivise investment. These strategies should include actions along the whole value chain, ideally including (IEA, 2021e):

- → Targets, for both installed electrolyser capacity and shares of low-carbon hydrogen in key sectors.
- → Creation of a future marketplace for hydrogen, whether for domestic industrial use or for export to other countries.
- → Clear alignment to other policy documents, as decarbonisation strategies, NDCs, sectoral programs, etc.
- → Mechanisms to effectively track the progress of the strategy over time, increasing the reliability of market formation.
- → Creation of coordination mechanisms between governments (national and regional) and private sector stakeholders.
- → Considerations for accompanying incentives, as described in the following sections.

Incentives and finance needs

To support the implementation of a robust national strategy, financial incentives might be necessary to elevate interest while hydrogen technologies achieve cost parity with current alternatives. The vision of a decarbonised economy requires to make higher investments, and governments can facilitate these by implementing strategies to reduce investment risk and improve returns. While interest in hydrogen technologies has been steadily growing and investment has increased, costs and profitability continue to be pressing concerns.

These concerns can be at least partially addressed by the development of frameworks for public-private partnerships and the prioritisation of concessional loans from development institutions (both national and multilateral) to fund the initial projects that can support national learning and set the sector on track.

Favourable taxation frameworks, like tax incentives and carbon pricing; market approaches to monetise byproducts or cobenefits (oxygen resulting from water electrolysis, or flexibility for power systems) and derisking tools or other instruments that address initial high-cost barriers can also become powerful tools to incentivise investment and create and grow a market for hydrogen (IEA, 2021e).

As currently most of the hydrogen applications have come at a premium when compared to current (fossil-based) alternatives, these incentives are seen as necessary for the initial growth of the hydrogen economy. In the short to mid-term, though, many of these technologies are expected to become the leading alternative to achieve decarbonisation, and therefore present a clear business case for private investors without the need for consessional finance or other types of public support. Therefore all these concessional instruments and support measures should include an exit strategy that gradually phases out the role of both development banks and governments. As the perception of risk decreases and cost parity of hydrogen technologies comes within reach, shift towards catalysing private investment rather than providing direct financial support should be envisioned and implemented.

R&D and capacity building

To develop a sustainable market that goes beyond pilot projects, a robust foundation based on strong capacities and local knowledge must be established. While most of the hydrogen-related technology currently comes from more developed countries, applications tailored to local contexts and a skilled labour force are key to a successful implementation of new technologies.

Collaboration between governments, research institutions and the private sector can accelerate the adaptation of applications to the region’s needs. At the same time, focusing on skills development for the most promising applications can avoid future bottlenecks in human resources when the industry develops.

International partnerships should be established when bi- or multilateral agreements are made. To have a lasting impact, these partnerships should go beyond investment in technological applications and include capacity building components that support the creation of local capacities and markets. Countries can then continue developing their markets and deploying technology long after the end of these partnerships.

Lastly, private sector initiatives as national hydrogen consortia and associations (e.g. H2Perú, H2LAC), can play an important role aligning the efforts of individual companies and government strategies, while also identifying future commercial opportunities (IEA, 2021e).

Certification schemes

Certification and guarantees of origin schemes are likely to become a powerful tool to decarbonise end-use sectors (IRENA, 2022a), ensure implementation of low-carbon technologies and applications, and encourage future innovation (IEA, 2021e). Initiatives that do this transparently can make low-carbon hydrogen more attractive to potential consumers, such as companies seeking to reduce their emissions to contribute to industry or sectoral targets, as well as their own ESG commitments or corporate energy and climate goals.

The same kind of initiatives can be applied to products made with low-carbon hydrogen technologies, such as iron, steel, cement or fertilisers. As demand for clean materials increases, aligning developing markets with upcoming international certification schemes can make these products more interesting for markets in sectors with ambitious climate goals. These low-carbon products are also likely to be able to be sold at a premium, providing additional financial incentives at the end of the value chain.

Carbon pricing

Carbon pricing can be a valuable instrument to promote clean energy transitions and increase the speed in which low-carbon hydrogen is deployed (IEA, 2021e). Countries are increasingly implementing some form of carbon pricing as part of the policy toolkit to promote clean technologies and meet their climate targets. Carbon pricing can be introduced as a carbon tax, emissions trading systems, or hybrid systems that combine the two.

The sectoral coverage of carbon pricing mechanisms and the value assigned to each ton of CO_2 are two of the key details. The carbon price needs to be high enough to trigger investment in low-carbon technologies, but not too high that it could actively harm industry in the short term. Currently, all existing carbon pricing initiatives in Latin America cover hydrogen-related sectors, but pricing levels are too low to trigger investment in low-carbon hydrogen. While these mechanisms can be used specifically to promote hydrogen technologies, they are more generally valuable to accelerate the phase out of fossil fuels or promote energy efficiency measures or technologies.

Currently, many countries still have direct or indirect subsidies for fossil fuel production and use. This fact often sends mixed signals about the commitment for decabonisation and decreases the effectiveness of incentives for decabonisation alternatives. The phase-out of support for fossil fuels is a long-standing debate, but an important step towards achieving climate targets.

Beyond carbon taxes and emissions trading systems, innovative pricing mechanisms are being considered in some sectors. One example is the EU's carbon contracts for difference, which has the potential to reward investors in low-carbon hydrogen by paying CO_2 price higher than the EU ETS one for low-carbon products, effectively bridging the difference in costs due to the introduction of low-carbon hydrogen technologies. Another example are tariffs for products with high carbon intensity, as recently proposed by the US for the steel and aluminium industries (Lawder, 2022). This would effectively benefit lower-carbon alternatives (green steel, in this case) over current, more carbon-intensive products trying to engage in international trade.

06 Conclusion

Hydrogen is expected to play an important role in the decarbonisation effort to keep global warming at 1.5 degrees. Net-zero models foresee its share in final energy consumption ranging between 3-20% by 2050. For hydrogen technologies to fulfil this role, sizeable investments need to be made to reduce production costs and improve end-use applications.

The rapid expansion of renewable energy generation capacity is key to clean the global energy matrix, and to ensure that **hydrogen future use does not rely on the same fossil fuels expected to be phased out.**

Investment in hydrogen applications needs to be carefully prioritised to focus the limited existing resources in promising technologies that don't undermine global electrification and other alternative technologies. While most applications are not yet cost-effective compared to current alternatives, investment is needed to reduce production and end-use costs, increase learning and avoid carbon lock-in that can ultimately undermine decarbonisation efforts.

In order to identify the most promising investment opportunities for the region, and specifically for the focus countries Argentina, Brazil and Peru, this report has analysed different hydrogen applications across the value chain based on three main dimensions: **technology competitiveness, temporality of the investment and regional considerations.**

As a result of this exercise, four **key investment opportunities** were identified:

→ Green steel production

The iron and steel sector is attracting international attention due to its large emissions and relatively available solutions. While the technology to fully decarbonise steel production through hydrogen is still not cost-competitive with current production methods, this is expected to change in the short-term. In the meantime, a lot can be done to prepare the industry in the region, with technologies widely available and cost-competitive. Substitution of BF-BOF plants for EAF is a first step to decarbonise the sector and avoid risky carbon lock-in. Maximising scrap recycling and preparing for DRI reduction process can get the industry a step ahead.

The first hydrogen-based steel plants will soon begin production in Europe, providing technical expertise and examples of potential financing. Early adopters can also benefit from advantages in international trade as consumers increase their demand for low-carbon products. Specific measures like carbon contracts for difference or robust certification schemes could be a starting point to develop green steel markets that mitigate this invesntent's risk. With the largest production capacity in the region, this is an especially interesting opportunity for Brazil.

→ Green hydrogen production through electrolysis

Most green hydrogen capacity additions are currently directly coupled with their industrial offtakers. As demand grows, investment in stand-alone electrolyser projects will be needed to fulfil the increasing demand. **Electrolyser costs are declining at a fast pace, and substitution of the current hydrogen demand with green hydrogen added to the expected growth of other applications will require even more production capacity than what is currently in the project pipeline.** The region has the potential to reach low production costs due to its large renewable energy potential.

The electrolysis project pipeline in Latin America is constantly growing, although a large amount of potential capacity to be added is still in the early stages of planning. Even considering these planned additions, **the region needs to more than double the planned capacity additions by 2030 to fulfil the hydrogen production envisioned at that stage in all 1.5-compatible scenarios.**

→ Green chemicals - methanol and ammonia, as well as fertilisers

The chemical industry offers another interesting opportunity for the region, as ammonia and methanol are emerging clean fuels, and green ammonia is necessary for the production of low-carbon fertilisers. This sector offers a short-term opportunity as hydrogen is already used in the production process, and substitution of fossil-based hydrogen can jump start the low-carbon hydrogen production in the region.

→ Heavy-duty mining vehicles in remote locations

Hydrogen can also be a cost-effective solution to replace a large amount of diesel used in heavy-duty mining vehicles, especially in remote locations. It is the most attractive application in land transport due to the large power and range these vehicles need. Costs related to the purchase and transport of fuel can be avoided with local hydrogen production, and further savings on ventilation needs can make the business case for EFCV more interesting in the sector. To fully avoid fuel logistic costs, the opportunity lies in developing parallel projects for on-site renewable electricity and hydrogen generation capacity. This application is cost-competitive with a carbon price of around 60 USD/tCO_2, which make policy interventions key for its successful implementation

The Latin American region is in an excellent position to become a front-runner and eventually play a key role in a fast-approaching hydrogen economy. Beyond the discussed decarbonisation benefits, this could have additional positive effects in the region's wider economy. To take advantage of this opportunity, however, the right policy signals need to be in place. **Clear strategies with a long-term vision for hydrogen and its applications need to be coupled with the right incentives for low-carbon products to attract international finance.** A wide range of measures including fiscal incentives, certification schemes and carbon pricing methods are available to countries in order to accelerate this energy and industrial transition.

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Annex

Annex 1
Evaluation Matrix of investment opportunities

Investment area	Subsector	Investment opportunity	Details	Degree of centralisation	Temporality	Regional participation	Final score
Production	Green hydrogen (electrolysis based)	Electrolyser capacity	Alkaline electrolysers (AE)	2.88	5.00	3.00	**3.63**
			Polymer electrolyte membrane (PEM) electrolysers	2.63	5.00	3.00	**3.54**
			Anion exchange membrane (AEM) electrolysis	1.50	1.25	1.13	**1.29**
			Solid oxide electrolysis (SOE)	1.63	2.00	1.88	**1.83**
	Blue hydrogen	NG infrastructure	Extraction and distribution	2.50	2.00	3.00	**2.50**
		Production plant	From NG with CCS via SMR (partial capture)	1.75	2.00	2.25	**2.00**
			From NG with CCS via SMR (high capture rates)	2.13	1.25	2.25	**1.88**
	Other green hydrogen	Production from biomass with CCS	Gassification or pyrolysis plants	1.00	1.25	1.50	**1.25**
Transformation	Fuels	Synthetic fuels / e-fuels	Fischer–Tropsch process: for use as fuel	1.63	3.13	1.50	**2.08**
		Green ammonia	For use as fuel (applications other than shipping)	1.88	3.13	2.25	**2.42**
			For use as fuel (co-firing in coal power plants)	1.75	1.25	1.50	**1.50**
			Cracking (reconversion to hydrogen)	1.38	1.25	1.50	**1.38**
		Biofuels	Hydrotreatment of biofuels to increase quality	1.75	3.13	3.00	**2.63**
		Methanol	For use as fuel	1.75	3.13	1.50	**2.13**
	Intermidiary products	Liquid Organic Hydrogen Carriers	For storage	1.63	3.13	1.50	**2.08**
		Sponge iron	Produced through DRI (100% electrolytic based)	2.50	5.00	3.00	**3.50**
Distribution	Local/ regionalw/ international trade	Ships	Liquid hydrogen tankers	1.50	2.00	2.25	**1.92**
			Liquid organic hyrogen carriers (LOHCs) tankers	2.31	3.13	1.50	**2.31**
			Ammonia tankers	2.63	2.00	2.25	**2.29**
		Road transport	Compressed H_2 trucks	2.13	2.75	1.88	**2.25**
			Liquified hydrogen trucks	1.88	2.75	1.88	**2.17**
		Port infrastructure	For liquified hydrogen shipping	1.63	2.75	2.25	**2.21**
			For ammonia shipping	2.44	2.75	2.25	**2.48**
		Pipelines	New hydrogen transmission pipelines	2.50	3.13	1.13	**2.25**
			Refurbished NG pipelines	2.38	3.13	1.88	**2.46**
			Deblending technology (gas permeation, pressure swing adsorption, cryogenic separation)	1.63	2.00	1.13	**1.58**
		Storage	Subsurface storage (depleted gas fields)	2.13	2.00	1.00	**1.71**
			Subsurface storage (salt caverns)	3.13	2.00	1.00	**2.04**
			Pressurised tanks	2.94	2.75	1.88	**2.52**
			Cryogenic liquid tanks	2.19	2.00	1.88	**2.02**
			Ammonia tanks	2.88	2.75	1.88	**2.50**
			Liquid organic hyrogen carriers (LOHCs) tanks	2.00	2.00	1.13	**1.71**
End use	Industry	Refineries	Replace hydrogen source (grey to blue, with CCS)	2.50	2.00	3.00	**2.50**
			For use as fuel	3.13	4.25	3.00	**3.46**
		Methanol	Replace hydrogen source (grey to green)	2.50	5.00	2.25	**3.25**
		Ammonia	Replace hydrogen source (grey to green)	2.75	5.00	3.00	**3.58**
		Urea/ fertilisers	Replace feedstock with ammonia from green hydrogen	2.75	5.00	3.00	**3.58**
		Steel	Partial replacement of coke with green hydrogen in BF/BOF furnaces	2.63	2.00	3.00	**2.54**
			DRI Based on natural gas with high levels of electrolytic hydrogen blending (in existing furnaces)	2.63	3.88	3.00	**3.17**
			DRI Based on 100% electrolytic hydrogen (new furnaces integrated with EAF)	2.88	4.25	3.00	**3.38**
		Cement	Use of hydrogen for direct heat applications in cement clinkers	1.88	3.13	2.63	**2.54**
		Other industries	Other high temperature heat applications	1.88	3.13	1.13	**2.04**
			Low to middle temperature heat applications	1.50	3.13	1.13	**1.92**
	Transport	Infrastructure	Refuelling stations	2.38	5.00	0.75	**2.71**
		All road transport	Hydrogen fuelled engines	1.50	3.50	0.75	**1.92**
			Methanol fuelled engines	1.63	4.25	0.75	**2.21**
		Heavy duty vehicules	Mining vehicles (EFCVs)	2.63	5.00	2.63	**3.42**
			Freight transport (EFCVs)	2.25	5.00	1.50	**2.92**
		Light duty vehicles	Electric Fuel Cell Vehicles (EFCVs)	2.00	4.25	0.75	**2.33**
		Maritime shipping	Hydrogen powered engines	1.88	3.50	1.50	**2.29**
			Methanol powered ships	1.94	3.50	1.50	**2.31**
			Ammonia powered ships	2.38	3.50	2.25	**2.71**
			Fuel cell powered ships (smaller ships)	2.00	3.13	1.50	**2.21**
		Aviation	Long-haul aviation	2.13	3.50	3.00	**2.88**
		Rail	Hydrogen trains	1.75	2.75	1.88	**2.13**
	Buildings	Residential/ commercial heating	Hydrogen blending in NG network	1.75	2.75	1.50	**2.00**
			Hydrogen boilers and hydrogen driven heat pumps	1.50	2.00	0.75	**1.42**
			District energy applications	1.50	2.00	0.75	**1.42**
	Power generation	Electricity generation	Gas turbines (pure hydrogen)	2.00	2.38	1.50	**1.96**
			Gas turbines (hydrogen rich syngas or mixed with NG)	2.13	2.00	1.50	**1.88**
			Hybrid fuell cell - gas turbine systems	1.88	2.38	1.50	**1.92**
			Grid-connected fuel cells (for grid balancing). Molten carbonates and solid oxid fuel cells	2.00	3.13	1.13	**2.08**

Annex 2
Main electrolyser technologies

Major electrolyser technologies with promising applications in large-scale green hydrogen production, each with varying maturity levels and efficiencies, include (Thomas, 2018; Miller et al., 2020; Vidas et al., 2021; DNV, 2022; U.S. Department of Energy, 2022):

- **a** **Alkaline electrolysis (AE)** is the most widespread and mature technology. Commercially available electrolysers using a solution of potassium or sodium hydroxide as electrolyte have been available for many years. These electrolysers usually operate at low temperatures and pressures. One key disadvantage is that AE does not work well with intermittent power sources, such as renewables.
- **b** **Polymer electrolyte membrane (PEM)** electrolysers using a solid plastic material as electrolyte are developing quickly and are already commercially available. Advantages of this technology include its compact design and its performance, stability, and compatibility with intermittent renewable energy sources. Disadvantages include the need for rare metal catalysts such as platinum or iridium.
- **c** **Anion exchange membrane (AEM)** electrolysis is a promising technology that combines characteristics of PEM and AE, but with cheaper materials. However, AEM electrolysers that use a solid alkaline exchange membrane as an electrolyte have only been developed at a lab-scale.
- **d** **Solid oxide electrolysis (SOE)** uses a ceramic material as an electrolyte and usually operates at high temperatures (700-800°C) as opposed to AE and PEM electrolysers. SOE is a promising technology since it has the potential to produce hydrogen with the highest efficiency. However, electrolysers are only available at smaller scales. Future scaling needs to consider that the source of heat for the process must also come from renewables to consider the resulting hydrogen as green.

Annex 3
Main applications of hydrogen

The three main applications of hydrogen (Hiltbrand et al., 2021) are:

a **Fuel:** hydrogen can be used in fuel cells, combustion engines, and turbines to generate either electricity and/or heat, which can then be used to power vehicles, in industrial processes, for residential or commercial heating, etc.

b **Feedstock:** hydrogen is used in various sectors not as an energy carrier but as a feedstock or reagent used to obtain other high-value products in the oil and gas, chemical, and construction material industries (IRENA, 2022f). Hydrogen can potentially be used to produce synthetic hydrocarbon fuels or e-fuels . Derivatives such as ammonia or e-fuels can then be used for energy storage or other applications in the energy system (Kobayashi et al., 2019; Ueckerdt et al., 2021).

c **Energy storage and balancing:** hydrogen technologies can support the resilience and reliability of electricity grids. Electrolysers and fuel cells offer flexible, controllable, and ancillary options to convert and produce electricity on demand. Green hydrogen also has the potential to provide long-term and large-scale storage to overcome challenges of renewables intermittency and demand seasonality (Staffell et al., 2019).

Annex 4
Applications of clean hydrogen by end-use sector

Industry

Low-carbon hydrogen's most substantial impact on decarbonisation is expected to occur in heavy industrial sectors where grey hydrogen is a key feedstock that cannot be replaced by other chemicals. These sectors are: 1) oil and gas refining, where hydrogen is used to remove impurities (hydrotreating and desulphurisation) and upgrade oil fractions (hydrocracking); 2) ammonia production through the Haber-Bosch process, which in turn would help decarbonise fertiliser production and other industrial applications (for example, explosives and plastics manufacturing); and 3) methanol production, a widely used chemical feedstock and solvent in many industries (IRENA, 2022f).

Iron and steel production is a sector where technological lock-in and path dependence can hinder energy transitions. Blast furnace-basic oxygen furnaces (BF-BOFs) have evolved slowly and are dependent on coke to produce steel from iron ore (Karakaya et al., 2018). Hydrogen can help to reduce GHG emissions from BF-FOFs by partially replacing coke as the reducing agent. However, this is insufficient since BF-FOFs make up 71% of the global steel production (Fan and Friedmann, 2021) and hydrogen injection only reduces process emissions up to 21% (Yilmaz et al., 2017). Electric arc furnaces (EAFs) use steel scraps for secondary steel production and the process emissions are relatively close to zero; however, the availability of steel scraps limits the market share of EAFs to 24% (IRENA, 2022f). In the absence of steel scraps, direct reduction of iron (DRI) can be used to feed EAFs; with this technology, iron ore is reduced using syngas (a mixture of hydrogen and carbon monoxide) obtained from fossil fuels (natural gas or coal) or other reducing agents like elemental carbon. Low-emissions steel could thus be achieved through DRI-EAF systems based on low-carbon hydrogen for iron reduction and clean sources of electricity to power the furnaces.

Hydrogen and hydrogen derivatives can replace fossil fuels for the provision of high-temperature heat (>400°C) in many industrial sectors (cement, glass, ceramics, etc.), while mid to low-temperature heat applications are easier to electrify. However, there are conflicting opinions regarding the feasibility of using hydrogen for high-temperature heat (Liebreich Associates, 2021), since it would require redesigning burners and furnaces, using new materials to prevent corrosion and brittleness of equipment, and solving safety issues regarding hydrogen handling and combustion monitoring (Staffell et al., 2019; Griffiths et al., 2021). The low maturity of these technologies, uncertain costs, and the slow turnover of existing systems add to the previous issues. Biofuels and electricity-based heating can be more competitive than hydrogen for high-temperature heating, but hydrogen remains an attractive option for large-scale processes hard to electrify (for example, steam crackers and cement kilns) and for geographically fragmented industrial sectors (IEA, 2019a).

Power

Electrification of end uses is expected to increase electricity demand and the rise of intermittent renewables like solar and wind will impact electricity systems. Balancing supply and demand –through energy storage capacity or large-scale peak power plants– will be necessary to maintain costs and reliability, particularly when there are large seasonal demand imbalances. Hydrogen technologies can help to integrate, expand, and build the resilience of electricity systems based on solar and wind energy (Strbac et al., 2020; Clarke et al., 2022).

Hydrogen production processes based on electrolysis can make use of excess renewable energy generation. The hydrogen produced can then be stored for future conversion to electricity (re-electrification) when demand peaks, using either fuel cells or combined-cycle gas turbines that have been repurposed to run on hydrogen (Staffell et al., 2019). Seasonal long-term storage in geological formations is possible but still poses challenges associated with site availability and technical requirements. Hydrogen could also be stored as other energy carriers, such as ammonia or synthetic fuels, although this option is costly due to the energy demand required for hydrogen conversion or release (Andersson and Grönkvist, 2019; Clarke et al., 2022). Hydrogen also enables the spatial redistribution of energy through trading and distribution networks, which in turn helps overcome variability in seasonal demand or differences in production capability among countries or regions (Clarke et al., 2022). Other storage options, such as pumped hydro and batteries, do not facilitate storage and redistribution on week-month time scales as hydrogen does (Staffell et al., 2019).

The economic feasibility of flexible power-to-hydrogen (and vice versa) plants and long-term hydrogen storage will depend on the location of renewable energy sources, storage sites, and gas, hydrogen, and electricity networks. The distance between producers and consumers of energy carriers (hydrogen, ammonia, synthetic fuels) will determine the characteristics of the distribution and storage infrastructure to be built (Hansen, 2020; Clarke et al., 2022).

Transport

The suitability of hydrogen varies significantly between transport modes. Hydrogen and hydrogen-based derivatives (ammonia and synthetic fuels) are expected to have the highest impact on the decarbonisation of maritime shipping and long-haul aviation, but technologies are still on a research and development phase (Jaramillo et al., 2022). For maritime shipping, green ammonia has received particular attention and could help reduce life-cycle emissions up to 70-80% compared to fuel oil (Bicer and Dincer, 2018; Gilbert et al., 2018). The rollout of new systems could be hampered by the long lifetimes of most vessels (Staffell et al., 2019) and the need for further development of safe storage and handling procedures. For long-haul aviation, synthetic fuels are expected to compete with biofuels, while smaller short-haul planes are more likely to be electrified (Sahoo et al., 2020; Jaramillo et al., 2022). Phasing out fossil fuels from aviation would require the expansion of low-carbon electricity sources for hydrogen production and scaling technologies that are currently not mature; costs also represent a barrier, since synthetic fuels are 4 to 6 times more expensive than fossil kerosene (Scheelhaase et al., 2019).

Land transport applications rely on hydrogen fuel cell vehicles (FCEVs), a technology that has improved through research and development. FCEVs are not yet mature for many transport modes, except for light-duty vehicles (Jaramillo et al., 2022). For short-range and light-duty vehicles (such as passenger cars, urban buses), battery electric vehicles are expected to remain the most competitive decarbonisation option in the foreseeable future. For some light-duty and long-range requirements, such as taxis and sport utility vehicles, FCEVs can be more competitive and might represent a bigger market share. However, this will require cost reductions in the price of FCEVs and will also depend on the cost of hydrogen production and the expansion of refuelling infrastructure (IEA, 2019a; Staffell et al., 2019; The Hydrogen Council, 2020). Hydrogen will have a bigger impact on long-range and have-duty vehicles like trucks, where it will compete with electric haulage systems (Jaramillo et al., 2022). Rail systems are already highly electrified in some countries and decarbonisation via hydrogen will mainly focus on long-range and low-frequency networks, for example for freight in rural or remote areas (IEA, 2019a). Finally, other types of off-road vehicles such as forklifts, tractors, and logistics hub machinery also have a high potential for decarbonisation through fuel cells (Staffell et al., 2019; Liebreich Associates, 2021).

Heating

Decarbonising residential and commercial heating mainly relies on demand reduction, electrification, district heating, on-site renewables and, to a lesser degree, alternative gaseous fuels such as biogas. Hydrogen could also play a role in the decarbonisation of buildings, but most assessments foresee only a very limited role, since costs would be higher for delivering heat from hydrogen rather than other commercially available options like electric heat pumps (Cabeza et al., 2022). Options for low-carbon heat include hydrogen boilers, fuel cell combined heat and power (CHP), and gas-driven heat pumps. Cost-wise, applications are more attractive for large-scale commercial buildings or residential complexes, and for district energy networks (IEA, 2019a). Shifting to direct hydrogen use in buildings would require large scale appliance retrofitting plus conversion of natural gas grids to hydrogen or widespread power-to-hydrogen-to-power processes (e.g. methanation), the latter being complex, costly, and less efficient (Staffell et al., 2019). Blending hydrogen with natural gas has also been proposed as a short-term solution, but it is not efficient (20% blends by volume reduce emissions by 7%), it prolongs the life of fossil fuel assets, and displaces solutions with higher decarbonisation potentials (Staffell et al., 2019; IRENA, 2021a).

Annex 5
Evaluation methodology

	Criteria	Category 1	Category 2	Category 3	Category 4
Technology competitiveness	**Technology readiness level (TRL) [Weight = 0.5]**	**Very low (TRL 1-4) [1]:** Basic technology research and development. Includes: TRL 1 Basic principles observed and reported; TRL 2 Technology concept and/or application formulated; TRL 3 Analytical and experimental critical function and/ or characteristic proof-of-concept; TRL 4 Technology basic validation in a laboratory environment, experimental scale, early prototype.	**Low (TRL 5-6) [2]:** Technology development and early demonstration. Includes: TRL 5 Technology basic validation in a relevant environment, bench scale, large prototype; TRL 6 Technology model or prototype demonstration in a relevant environment, pilot scale.	**Moderate (TRL 7-8) [3]:** Large-scale technology demonstration. Includes TRL 7 Technology prototype demonstration in an operational environment, engineering scale, pre-commercial demonstration; TRL 8 Actual technology completed and qualified through test and demonstration (commercial).	**High [4]:** System test, launch, and operation. TRL 9 Actual technology qualified through successful operational plant.
	Expected future role [Weight = 1.5]	**Uncompetitive [1]:** Alternative decarbonisation options exist, and these will likely be the preferred decarbonisation options. Clean Hydrogen Ladder Levels F & G. The technology is expected to have a low contribution to decarbonisation efforts.	**Somewhat competitive [2]:** Alternative decarbonisation options exist but hydrogen applications are expected to have a medium to low share in decarbonisation efforts. Clean Hydrogen Ladder Levels D & E. The technology is expected to have a moderate contribution to decarbonisation efforts.	**Very competitive [3]:** Alternative decarbonisation options exist but hydrogen applications are expected to have a high share in decarbonisation efforts. Clean Hydrogen Ladder Levels B & C. The technology is expected to have a high contribution to decarbonisation efforts.	**Unavoidable [4]:** No alternative decarbonisation options exist; low-emissions hydrogen is the only option (e.g., applications where hydrogen is an end use). Clean Hydrogen Ladder Level A. The technology is expected to have a very high contribution to decarbonisation efforts.
	Penetration level (market share) [Weight = 0.5]	**Low [1]:** No current penetration level (<0.1%)	**Medium [2.5]:** Small penetration level (0.1-2%)	**High [4]:** Share >2%	**Non-existent [0]**
Temporality	**Expected deployment (technology readiness) [Weight = 1]**	**Short-term [4]:** Before 2025	**Medium-term [2.5]:** Before 2030	**Long-term [1]:** Before 2050	
	Lock-in risks [Weight = 1.5]	**Low [1]:** Indicates that investment opportunity barely helps to move away from BAU activities that have carbon lock in risks, or that it addresses a sector with a very low carbon lock-in risk.	**Medium [2.5]:** Indicates that investment opportunity helps to move away from BAU activities that have a medium carbon lock in risk.	**High [4]:** Indicates that investment opportunity helps to move away from BAU activities that have high carbon lock in risk.	**N/A [0]:** Investment opportunity continues to expand / make use of / perpetuate fossil assets and increases the risk of carbon lock-in.
Regional participation	**Potential market size/ share [Weight = 1]**	**Low [1]:** Focus countries have no potential for a particular market share (no current use of hydrogen or end-use). Alternatively, potential is ranked as low based on relevant literature.	**Medium [2.5]:** Focus countries account for <50% of total LAC production/activity. Alternatively, individual sectors have medium shares in each focus country (each application <25%), or are deemed somewhat relevant in the available literature.	**High [4]:** Focus countries account for >50% of total LAC production/ activity. Alternatively, individual sectors have a high share of total hydrogen consumption/production in each focus country (each application >25%), or are deemed relevant in the available literature.	No info [0]
	Degree of centralisation [Weight = 0.5]	**Distributed [1]:** Widespread distribution infrastructure required to deploy application. Infrastructure coordinated through regional markets. Demand-side management and distribution grids play a key role in deployment of the application.	**De-centralised [2.5]:** Application require distribution infrastructure but various nodes concentrating applications can be identified either close to resources for production or demand centres. Alternatively, distribution infrastructure can be mostly retrofitted or refurbished from existent infrastructure.	**Centralised [4]:** Technologies/applications near both resources for production and demand centres. Distribution infrastructure not required or minimal. Infrastructure controlled by international / national markets. Few nodes where activities are concentrated can be identified in the focus countries (e.g., industrial hubs, ports, pipelines).	

Note: For the cost prospects, the following benchmark costs were considered:
1) For production: costs are compared to the current levelised cost of hydrogen production via SMR without CCS in LAC, equal to 1.2 USD/kg (→ **see Figure 12**).
2) For transformation to intermediary energy carriers (ammonia, syn-fuels, and methanol for use as fuel), costs are compared to the production values of hydrogen since use of these carriers will require to first produce hydrogen and then account for the costs of conversion, distribution and reconversion to hydrogen if needed.
3) For storage/transport: the levelised costs are compared to a benchmark production cost of 1.2 USD/kg. Considering storage and transport are expected to represent significant shares of the future cost of hydrogen deployment, the "very good" prospect considers that storage/transport account for an increase of 50% or less in comparison to production costs.
4) For end-uses, carbon prices are based on the IPCC's worldwide marginal abatement costs for 1.5°C-consistent pathways, which are 135–5500 USD/tCO_2 in 2030 and 245–13000 USD/tCO_2 in 2050. The $60 USD/t$CO_2$ benchmark is a low-end 2030 and mid-range 2020 and is consistent with a slow decarbonisation scenario (OECD, 2021). The 135 USD/t CO_2 is similar to the OECD benchmark of 120 USD/tCO_2 for carbon costs in 2030, and is in line with recent estimates of overall social carbon costs (Kaufman et al., 2020).

Annex 6
List of green hydrogen production projects in LAC

Project name	Country	Technology, electricity source	End use	Capacity (t H_2/year)
In operation				
Hychico	ARG	AE, onshore wind	Power	140
Cerro Pabellón	CHL	Electrolysis, solar PV	Power	9
H2V Las Tortolas	CHL	PEM, solar PV	Mobility	1
Promigas	COL	PEM, solar PV	Grid injection	3
Transportation Ecosystem Project	CRI	PEM, dedicated renewables	Mobility	1
Industrial Cachimayo	PER	AE, grid hydropower	Ammonia	3,300
Demonstration				
Ecopetrol	COL	Electrolysis	Refining	10
Under construction				
EDP Pecem pilot	BRA	PEM, solar PV	Unspecified	450
Walmart Quilicura forklifts	CHL	PEM, solar PV	Mobility	60
Haru Oni, phase 1	CHL	PEM, onshore wind	Methanol and synfuels	190
Transportation Ecosystem Project II	CRI	PEM, dedicated renewables	Mobility	2
CEOG	GUF	AE, solar PV	Power	2,700
Awaiting final investment decision				
Unigel, phase 1	BRA	Electrolysis, dedicated renewables	Ammonia	10,200
Coquimbo	CHL	Electrolysis, dedicated renewables	Grid injection	30
Feasibility study underway				
Fortescue Metals - Rio Negro, phase I	ARG	Electrolysis, dedicated renewables	Unspecified	100,000
Port of Pecem - Base One	BRA	Electrolysis, Hydropower	Unspecified	600,000
Porto do Acu Fortescue Ammonia Project	BRA	Electrolysis, dedicated renewables	Ammonia, steel, synfuels	52,000
Unigel, phase II	BRA	AE, onshore wind	Ammonia	31,000
Renewstable	BRB	PEM, solar PV	Power	2,200
HyEx - phase 1	CHL	Electrolysis, solar PV	Ammonia, synfuels	4,500
HyEx - phase 2	CHL	Electrolysis, solar PV	Ammonia, synfuels	130,000
AES Gener ammonia project	CHL	Electrolysis, solar PV	Ammonia	
Haru Oni, phase 2	CHL	PEM	Methanol	31,000
Hidrógeno Verde Bahía Quintero	CHL	AE, solar PV	Mobility, grid injection	1,700
H_2 Magallanes	CHL	Electrolysis, onshore wind	Ammonia	1,400,000
Proyecto Faro del Sur	CHL	Electrolysis, onshore wind	Synfuels	42,000
HyPro Aconcagua	CHL	Electrolysis, dedicated renewables	Refining	3,500
Antofagasta Mining Energy Renewable	CHL	Electrolysis, dedicated renewables	Methanol	13,900
Green Steel - H2V CAP	CHL	Electrolysis, dedicated renewables	Steel	3,500
Atacama Hydrogen Hub, phase 1	CHL	Electrolysis, solar PV	Mobility	1,700
ACH-MRP	CHL	Electrolysis, dedicated renewables	Ammonia	180,000
H1 Magallanes	CHL	Electrolysis, onshore wind	Ammonia	170,000
San Pedro de Atacama Project	CHL	Electrolysis, solar PV	Power, synfuels	380
Cartagena refinery	COL	Electrolysis, dedicated renewables	Refining, mobility, grid injection	6,900
Barrancabermeja refinery	COL	Electrolysis, dedicated renewables	Refining, mobility, grid injection	10,400
Energía Los Cabos	MEX	PEM, solar PV	Power	3,700
Delicias Solar	MEX	Electrolysis, solar PV	Unspecified	6,000
Mmex Resources Corporation	PER	PEM, dedicated renewables	Unspecified	20,000

Source: Authors based on (IEA, 2022d).

Annex 7

Role of Hydrogen in reviewed 1.5 compatible scenarios

Indicator / Scenario	IPCC AR6 C1 subset [a]	IEA NZE	IRENA
Scenario description	Ensemble of 97 scenarios with warming below 1.5°C (>50% chance) by end of the century, with no or limited overshoot. Net zero CO_2 emissions are reached by 2050. Part of the IPCC's scenario database for the AR6.	Scenario consistent with warming below 1.5°C without a temperature overshoot (50% probability). Energy related and industrial process CO_2 emissions reach net zero levels by 2050. Part of IEA's World Energy Outlook 2022.	Scenario compatible with a 1.5°C climate target. CO_2 emissions reach net zero by 2050. Part of IRENA's World Energy Transitions Outlook 2022.
Total final energy consumption	**410 EJ (370 – 448 EJ)**	**344 EJ**	**348 EJ**
Share of hydrogen	3% (1.9% – 4.4%)	10% – 13% [c]	12%
Demand per sector [b]			
Transport	C3.6 EJ (0.9 – 6.1 EJ), 3.6%	25 EJ	19 EJ, 20% of TFEC [d]
Industry	8.4 EJ (5.9 – 11.5 EJ), 5.3%	22 EJ	38 EJ, 21% of TFC
Buildings	0.04 EJ (0.0 – 0.1 EJ), 0.03%	2.8 EJ	3.2 EJ, 3% of TFEC
Power sector	-	12 EJ	-
Refineries	-	1.0 EJ	-
Use in the power sector			
Generation (share of total)	-	1,700 TWh (2.4%)	-
Storage	-	-	2,000 TWh
Total hydrogen production	**C33 EJ (25 – 41 EJ)**	**63 EJ**	**74 EJ**
Share of low-carbon hydrogen:	-	98%	100%
from electrolysis	66%	62%-77%	66%
from fossil fuels with CCUS	34%	23%-38%	33%
Installed electrolyser capacity	3,600 GW	3,600 GW	5,000 GW
Required electricity generation for hydrogen production (share from total)	-	12,300 – 14,500 TWh (20%)	20,770 TWh (~20%)
CCUS capacity	0.7 $GtCO_2$/year	1.5 – 1.8 $GtCO_2$/year	3.4 $GtCO_2$/year
Share of hydrogen converted to derivatives	-	~30%	-
Share of hydrogen traded globally	-	50% of ammonia 33% synthetic fuels	25%
Required investment	USD 80bn/year (by 2050)	USD 270bn/year (by 2050)	USD 133bn/year (2021-30) USD 176bn/year (2031-50)
Scenario description	Analysis and forecasts carried out by BloombergNEF for their Hydrogen Economy Outlook.	Scenario in line with a trajectory that limits global warming to 1.5-1.8°C.	Sectoral pathways that limit global warming to 1.5°C on a low/no-overshoot basis. Net-zero emissions reached by 2050.
Total final energy consumption	**410 EJ**	-	**374 EJ**
Share of hydrogen	24%	22%	
Demand per sector [a]			
Transport	36 EJ	34 EJ	13 EJ (29%)
Industry	15 EJ	25 EJ	10 EJ (5.7%)
Buildings	6.4 EJ	4.8 EJ	2.0 EJ (1.8%)
Power sector	26 EJ	7.7 EJ	-
Refineries	-	-	-
Use in the power sector			
Generation (share of total)	-	-	(5%)
Storage	-	-	-
Total hydrogen production	**99 EJ**	**79 EJ**	
Share of low-carbon hydrogen		100%	
from electrolysis		60-80%	
from fossil fuels with CCUS		20-40%	
Installed electrolyser capacity	-	3,000-4,000 GW	-
Required electricity generation for hydrogen production (share from total)	31,000 TWh	-	11,000 TWh
CCUS capacity	-	~2.2 $GtCO_2$/year	-
Share of hydrogen converted to derivatives	-	-	-
Share of hydrogen traded globally	-	-	-
Required investment	USD 11tn	-	-

Note: [a] Indicators correspond to median values; ranges indicate the 25th and 75th percentiles of the IPCC scenario ensemble. [b] Percentages correspond to shares in final consumption within sectors. [c] Considering on-site production. Other scenarios do not make this distinction. [d] 12% from direct hydrogen use, and 8% from synthetic fuels and derivatives. Sources: Authors based on (BloombergNEF, 2020; IEA, 2021f, 2021c; IRENA, 2021c, 2022h; The Hydrogen Council and McKinsey & Company, 2021a; Byers et al., 2022; Teske, 2022).

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