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BRAINSHORING SERVICES

Hydrogen market overview:

The role of clean hydrogen in decarbonization

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Introduction

Hydrogen has a longstanding history in the energy ecosystem, particularly in the production of industrial chemicals. H2 has many valuable properties compared to other fuels in the era of decarbonization. It can be produced from different energy sources (including renewables, nuclear, natural gas, coal, and oil), has a high energy content per unit mass, and produces little to no emissions at the point of use. However, as hydrogen mostly exists in molecular forms, such as in water and organic compounds (primarily hydrocarbons), pure H2 requires energy processes to be produced in that form. Additionally, while it does not contribute to GHG emissions at the point of use, the current dominant production pathways for hydrogen are carbon intensive as they primarily rely on the use of fossil fuels.

Low-carbon Hydrogen is a clean energy carrier that can be produced using low carbon methods such as electrolysis, or with carbon capture and storage (CCS)/ carbon capture usage and storage (CCUS). It has generated considerable interest in the past, but its impact has been limited. However, **three significant factors set the current situation apart**:

- Firstly, **governments worldwide have united in their commitment to achieving net zero emissions by 2050**, as outlined in the 2015 Paris Agreement. Reaching net zero emissions is crucial to limiting global temperature rise to 1.5°C and averting severe climate change. This requires emission reductions across all sectors, including industrial sectors and long-distance transportation, where viable solutions are currently lacking. **Hydrogen has emerged as a promising option for reducing emissions in these sectors**

- Secondly, **the declining costs of renewable energy sources and electrolyzers have greatly improved the economic viability of "green" hydrogen**, which is produced through water electrolysis and can be powered by renewable electricity. The growing reliance on variable renewables like wind and solar power also creates a demand for flexibility and energy storage, which hydrogen can help address

- Thirdly, hydrogen can be a **substitute for clean electrification in some sectors** where direct electrification is not feasible or cost-effective. For instance, hydrogen fuel cells can replace internal combustion engines in transportation

Consequently, low-carbon hydrogen is expected to play a significant role in meeting a substantial portion of global energy demand by 2050, compared to its negligible contribution today. This report will delve into this growing demand for hydrogen in both established and emerging applications, exploring the implications of this surge on low-carbon hydrogen production, advancements in hydrogen transportation and storage, interregional trade, and policy developments.

Executive Summary (1/2)

HYDROGEN DEMAND

In 2021, global hydrogen demand hit a record high of **94 Mt,** most of which was concentrated in the **refining** and **chemical** sectors

By 2030, hydrogen demand is expected **to reach 180 Mt** in line with the Net Zero scenario, requiring a steep increase in demand from new applications

Hydrogen will play an important role in decarbonizing various sectors where reducing emissions has been challenging.

The readiness to transition to clean hydrogen varies across sectors:

Transition from grey to clean hydrogen:

Refining, Ammonia, Methanol, Iron & Steel

Long-term development needed:

Shipping, Aviation, Power generation

Low potential compared to electrification

LDVs, Residential and Commercial heating

HYDROGEN PRODUCTION

To meet the increasing demand, low carbon **hydrogen production** must be developed. 99% of global demand in 2021 was met with hydrogen produced from non-renewable sources, with clean hydrogen accounting for less than 1% of total production

In the NZE scenario by 2030, **hydrogen forecasts** predict that grey hydrogen will remain dominant while blue and green hydrogen gain momentum. Looking ahead to 2050, green hydrogen is forecast to predominate with a consensus of 60-70%

Factors that can affect the forecasts:

- Low carbon intensity adoption
- Cost reduction increasing affordability
- Wider technological innovation and adoption

Between 2021 and 2023, there is a **significant increase in the announced expansions** of CCS and electrolyzer capacities with an **influx of new participants**. However, the current deployment levels **still fall short of the required capacity** to achieve 2030 NZE forecasts

Executive Summary (2/2)

HYDROGEN INFRASTRUCTURE

The development of infrastructure is crucial to facilitating the transportation, storage, and global trade of hydrogen. As large-scale applications emerge, there will be a **need for efficient transportation methods and geological storage**, necessitating further research and development efforts and **prompting the increase in global hydrogen trade.**

- **Hydrogen Transportation** requires conditioning (Compression , liquification, or the usage of carriers like ammonia and LOHC) for more efficient transport
- Currently, **trucks and pipelines** are the most common means of transportation for hydrogen, given their costs compared to shipping
- However, to meet the larger future demand, transportation means will involve other factors such as **volume, distance, the final energy demand, and the end use**

- **Hydrogen storage** relies on pressurized containers, which are considered the most efficient in terms of costs for smaller-scale projects.
- **However,** it will require a shift to more affordable underground storage to meet the estimated required capacity equal to cover **15%** to **20%** of annual future hydrogen use.
- **Further R&D and testing** is needed to use underground storage for hydrogen.

Hydrogen trade is expected to rise with:

- **The Americas** have a high potential for **blue and green H2 exporting**
- **Germany and the Netherlands** are among the **largest H2 importers worldwide**
- **More than 42 governments are** releasing **national hydrogen strategies** to unlock hydrogen trade potential

Hydrogen Overview

Current hydrogen demand is almost exclusively met by grey hydrogen, obtained from fossil fuels

Hydrogen is an **energy vector** that can be produced from different energy sources. Despite being a colorless gas, the **various types of hydrogen** are distinguished by **different color codes** that are used in the energy industry. The assigned colors depend on **the method of hydrogen production utilized**. However, color names might evolve with time.

Our focus

Grey Hydrogen*

Steam methane reformation (SMR) using natural gas/Fossil fuels

*Most produced type of hydrogen

Blue Hydrogen**

Steam methane reformation (SMR) using natural gas/Fossil fuels with CCUS

Green Hydrogen**

Electrolysis using renewable energy

**Two main routes under consideration to replace grey hydrogen

Other types of hydrogen

Brown Hydrogen

Extracted from coal using Gasification

Yellow Hydrogen

Electrolysis using solar power

Pink Hydrogen

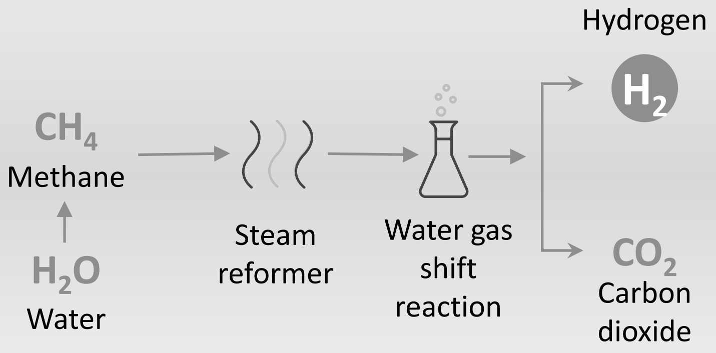
Electrolysis using nuclear energy

Sources: *Press Search*

Blue and green hydrogen are the two main routes under consideration to replace grey hydrogen, resulting in fewer CO2 emissions

Grey hydrogen

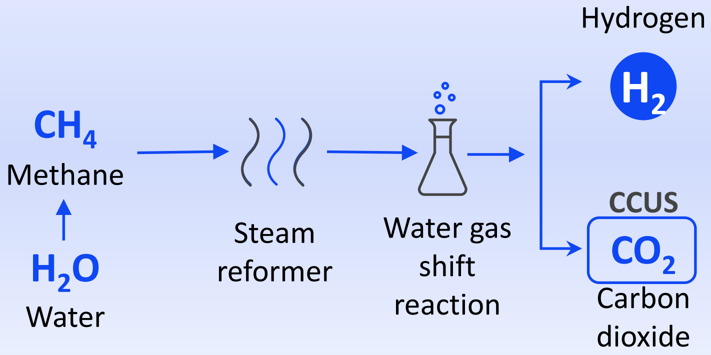
Grey hydrogen is **derived from fossil fuels**, usually **natural gas**, and constitutes **approximately 95% of global hydrogen production**. The most common technique used to generate grey hydrogen is steam methane reforming



Steam Methane Reforming (SMR) **mixes natural gas with very hot steam**, in the presence of a catalyst, where a chemical reaction creates hydrogen and carbon monoxide

Blue hydrogen

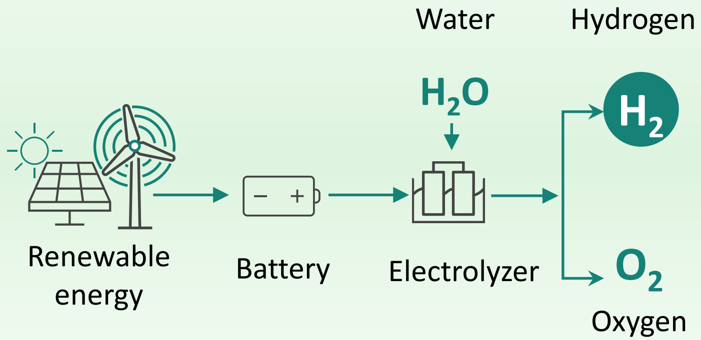
Blue hydrogen is **produced from natural gas** with **carbon capture** technology. The **CO2 generated** during the manufacturing process is **captured and stored permanently underground using Carbon Capture and Storage (CCS) or bound in a solid product and utilized (CCUS)**



Although blue hydrogen is produced similarly to grey hydrogen, the use of **carbon capture technology** in blue hydrogen production results in **significantly lower emissions**

Green hydrogen

Green hydrogen is produced by **splitting water into hydrogen and oxygen using renewable electricity**. As the IEA points out, this method of obtaining green hydrogen would save ~**830 million tons** of CO2 that are emitted annually



During electrolysis, two electrodes are immersed in **water filled with salts and minerals** to conduct electricity, and **a direct current is applied,** causing the **dissociation of hydrogen and oxygen** to occur

Sources: *Press Search*

The demand for hydrogen

The demand for hydrogen

1 Demand overview

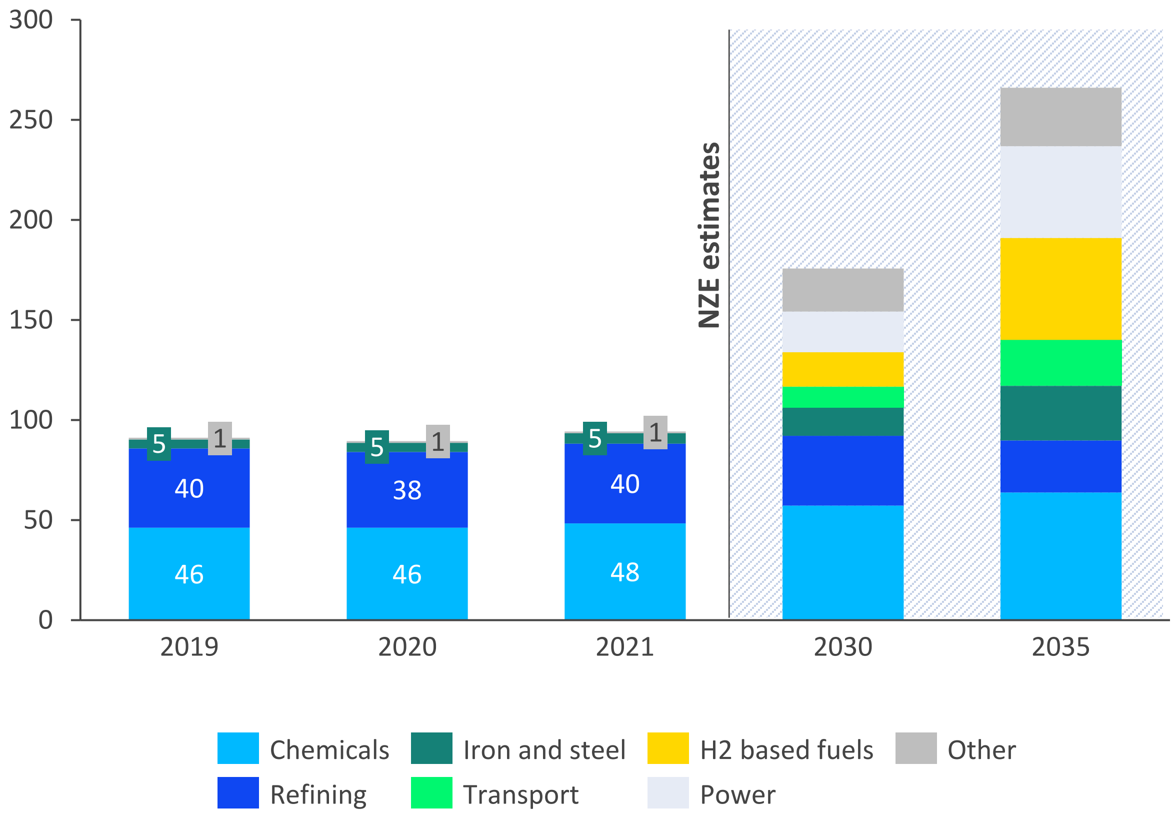
- Global hydrogen demand reached a record high of **94 Mt** in 2021, driven by the recovery of the chemical and refining sectors
- Demand for hydrogen in new applications grew by **60%** in 2021, indicating promising growth potential
- The Net Zero Scenario projects that hydrogen demand will reach approximately **180 Mt by 2030**, necessitating significant increases in heavy industry, power generation, and hydrogen-based fuel production
- **China**, which currently holds the position of the world's largest consumer of primary energy, is **anticipated to be the most significant market for clean hydrogen, with an estimated demand of around 200 MT in 2050**

2 Hydrogen potential

- Hydrogen is traditionally used as a feedstock in numerous industrial processes, including refining, chemicals, and iron and steel
- Traditional hydrogen applications are considered **easier to decarbonize**, they are **less challenging** and don't present high technical challenges
- Emerging applications will play a large role in achieving the Net Zero scenario, mainly through heavy-duty vehicles, due to their higher mileage and heavier weight compared to FCEVs

Global hydrogen demand reached 94 Mt in 2021, driven by the chemical and refining sectors (more than 90% of hydrogen demand)

Global hydrogen demand by sector in the Net Zero scenario (in Mt)



- Global hydrogen demand reached **94 Mt in 2021**, **surpassing the historic high** of 91 Mt in 2019. This growth was mainly driven by the **recovery of the chemical and refining sectors**
- Demand for hydrogen in new applications such as **transport, high-temperature heat in industry, hydrogen-based DRI, power, and buildings** is still **very limited** in 2021 at only 40 kt (representing 0.04% of global demand), although it grew by 60% in 2021
- According to the Net Zero Scenario, **demand should double in 2030 and triple by 2035 to reach around 266 Mt**, which **requires a sharp increase from new applications** including heavy industry, long-distance transport, power generation, and the production of hydrogen-based fuels

[1] *Forecast values used are approximative estimates*

Sources: *IEA "Towards hydrogen definitions based on their emissions intensity" (2023), Goldman Sachs "Carbonomics, the clean hydrogen revolution" (2022)*

Achieving the Net Zero scenario relies on significant uptake from emerging applications

Traditional applications

Hydrogen is traditionally used as a feedstock in numerous industrial processes, including:

Refining: In oil refining, hydrogen is **primarily used in hydrosulfurization and hydrocracking** processes.
In the near term, **tightening sulphur regulations** and **rising oil demand** can support hydrogen demand. Longer term, **increasing demand for biofuels and synthetic fuels** can further support hydrogen demand.

Chemicals: The chemicals industry consumed ~51% of global hydrogen in 2021, mainly as **feedstock for ammonia and methanol production**. Decarbonization of existing ammonia and methanol production facilities and growth in demand for both chemicals are expected to support hydrogen demand in this sector.

Iron and Steel: Steel **represents a small percentage** of global hydrogen demand, accounting for **5 Mt in 2021**. In the NZE scenario, the sector has the potential for significant transformation, shifting from coal blast furnace to electric arc furnace routes using natural gas or clean hydrogen

Emerging applications

Emerging applications will start gaining momentum by 2030 and 2050:

Transport: In 2021, demand in the sector amounted to **30 kt**, accounting for only **0.03% of total hydrogen demand**. Trucks and buses, are **the primary drivers of hydrogen demand in transport** due to their higher mileage and heavier weight compared to FCEVs

Power generation: Hydrogen plays only a small role as a fuel in the power sector today. It accounts for **less than 0.2% of global electricity generation** but may grow as the industry aims for net-zero. It could become a crucial interconnecting component in this field

Building heating: Hydrogen accounts for **a negligible share of energy demand** in the building sector. Low-carbon options such as electricity, district heating, and distributed renewables are expected to be **prioritized over hydrogen technologies** in buildings due to higher energy efficiency, existing infrastructure compatibility, and the avoidance of additional investments

Sources: *Goldman Sachs "Carbonomics, the clean hydrogen revolution" (2022) , IEA "Global Hydrogen Review" (2022)*

Hydrogen has significant potential in heavy industry (especially chemicals and refining) and long-distance transport

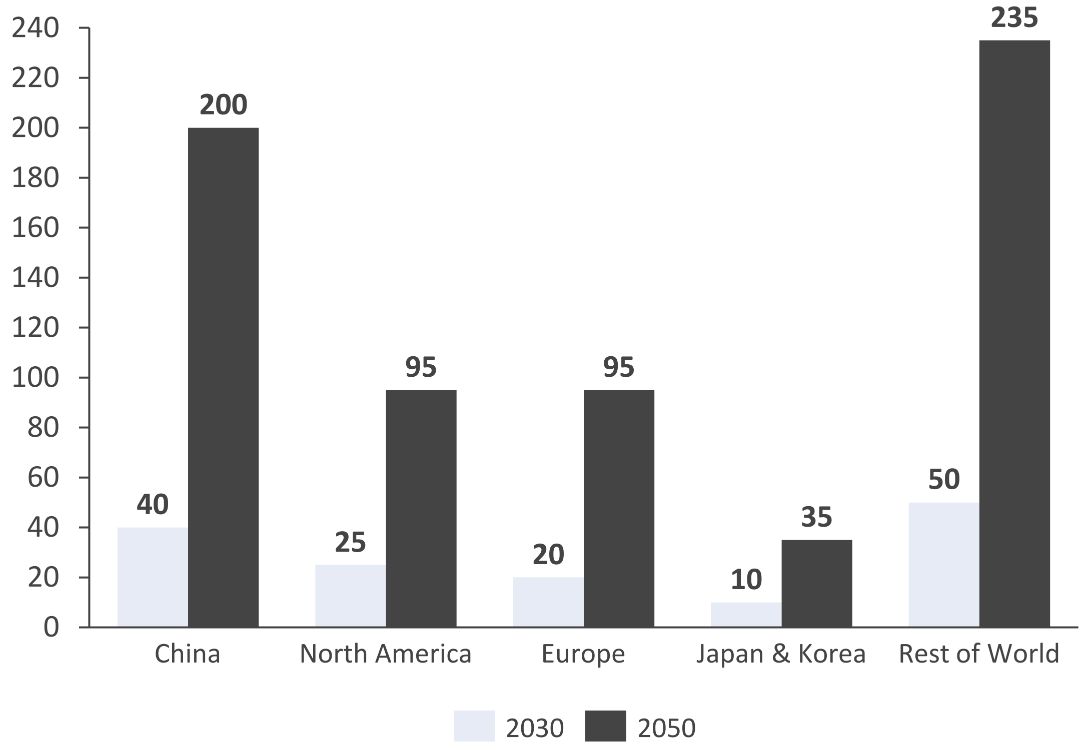
Sectors		2030	2050	Assessment of clean hydrogen potential
Industry	Methanol	High	High	**Increase in hydrogen demand for methanol** due to the **potential development of technologies** such as methanol-to-olefins and methanol-to-aromatics used to produce plastics in the future
	Ammonia	High	High	The analysis of planned future projects indicates **an increase in the production of low-emission ammonia** in the coming years, as it is crucial for nitrogen fertilizers and other industrial applications
	Steel	Medium	High	**High potential** for radical technological transformation in the Net Zero scenario, going from coal blast furnace routes to electric arc furnace routes (NG or clean hydrogen)
Refining		High	High	**Promising hydrogen potential for refining** to replace unabated fossil fuel-based hydrogen with low-emission hydrogen presents relatively low technical challenges
Transport	LDVs	Low	Low	Electrification is considered the key to decarbonizing low-duty vehicles, as it is **a cheaper option** than decarbonizing through clean hydrogen
	HDVs	Medium	High	Clean hydrogen is **a viable technology** for long-haul heavy transport due to its high energy content per unit mass (being lighter) and faster refueling time
	Aviation	Low	Medium	The potential for hydrogen as a fuel source in aviation is **limited** due to the high energy density required, which is better provided by biofuels or synthetic hydrocarbons
	Shipping	Medium	Medium	The industry is still undecided on the fuel and technology that will replace fossil fuels, but **hydrogen is considered a promising option** due to its high energy density
Building	Residential	Low	Medium	While hydrogen has **limited potential** compared to electricity-based options due to lower efficiency, it can still play a role in regions with established gas infrastructure where retrofitting buildings for electricity-based solutions is challenging
	Commercial	Low	Medium	
Power		Low	Medium	Flexibility services have **a niche potential** to store excess renewable electricity as peak capacity and for transport, particularly when pipelines are more cost-effective than cables despite conversion losses

Sources: *Goldman Sachs "Carbonomics, the clean hydrogen revolution" (2022), Deloitte "Creating a viable hydrogen economy - A Future of Energy point of view" (2021)*

China, the world's biggest primary energy consumer, is expected to be by far the biggest market for clean hydrogen in 2050

- North America, a major energy consumer, has **favorable conditions in terms of carbon storage** and leads in planning and implementing CCUS capacity additions. In contrast, Europe will meet future demand through **imports and fast expansion efforts in the production and implementation of clean hydrogen**
- By 2030, regions such as Southeast Asia, Oceania, the Middle East, and Latin America are expected to account for about **50 MT** of hydrogen demand. Additionally, Latin America, the Middle East, and Africa are expected to produce a significant amount of electrolytic hydrogen, surpassing **4 MT by 2030**
- **The largest market for clean hydrogen** is expected to be China, which is currently the world's biggest consumer of primary energy, with an estimated demand of around **200 MT in 2050**. Europe and North America will trail behind, with each accounting for **95 MT** of clean hydrogen demand

Global hydrogen demand forecast by region (in Mt)



Sources: *Hydrogen Council "Hydrogen For Net-Zero" (2021), IEA "Hydrogen in Latin America" (2021), Press search*

The production of hydrogen

The production of hydrogen

1 Production overview

- **99% of global demand** in 2021 will be met with hydrogen produced from **non-renewable sources**
- **Low-emission hydrogen represents less than 1% of total production.** However, the rise in hydrogen generated through water electrolysis in 2021 indicates its growing popularity

2 Production forecasts

- **NZE scenario 2030**: Forecasted paths for hydrogen production differ, but they agree that grey hydrogen will remain dominant, while blue and green will gain momentum
- **NZE scenario 2050**: Green hydrogen is forecast to be predominant **(60-70% consensus)**

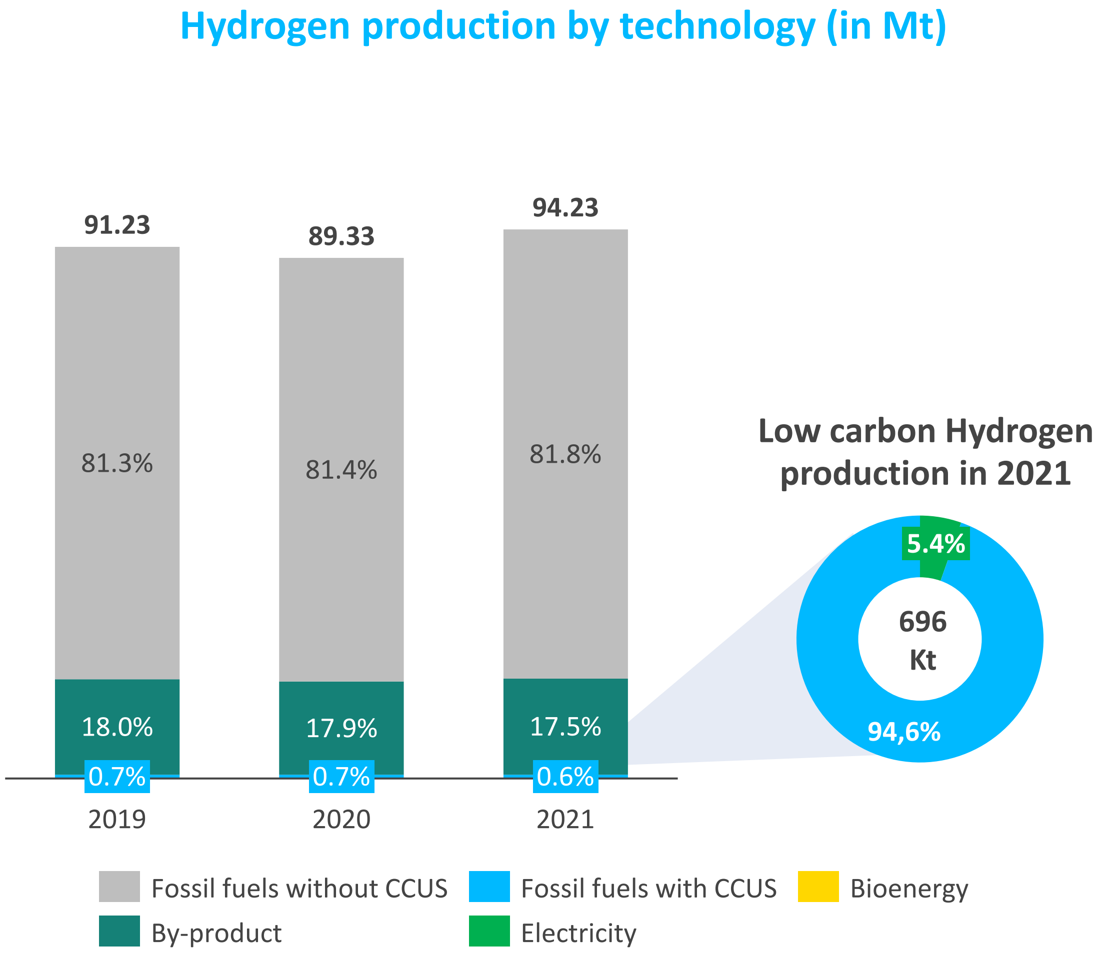
3 Blue and green hydrogen projects

- Announced expansions for CCS and electrolyzer capacities are increasing significantly from 2021-2023
- Both markets for CCS and electrolysers are still **maturing** and **expecting a surge of new entrants.**
- However, deployment still **falls short of the NZE's required capacity in 2030**

4 Market drivers

- By 2050, **technological innovation and economies of scale** will make **green hydrogen cheaper** than blue and grey hydrogen in **regions with low-cost renewable energy**
- **The low carbon intensity** of hydrogen from renewable electrolysis, compared to other production means, makes it a **competitive production method for the NZE Scenario**

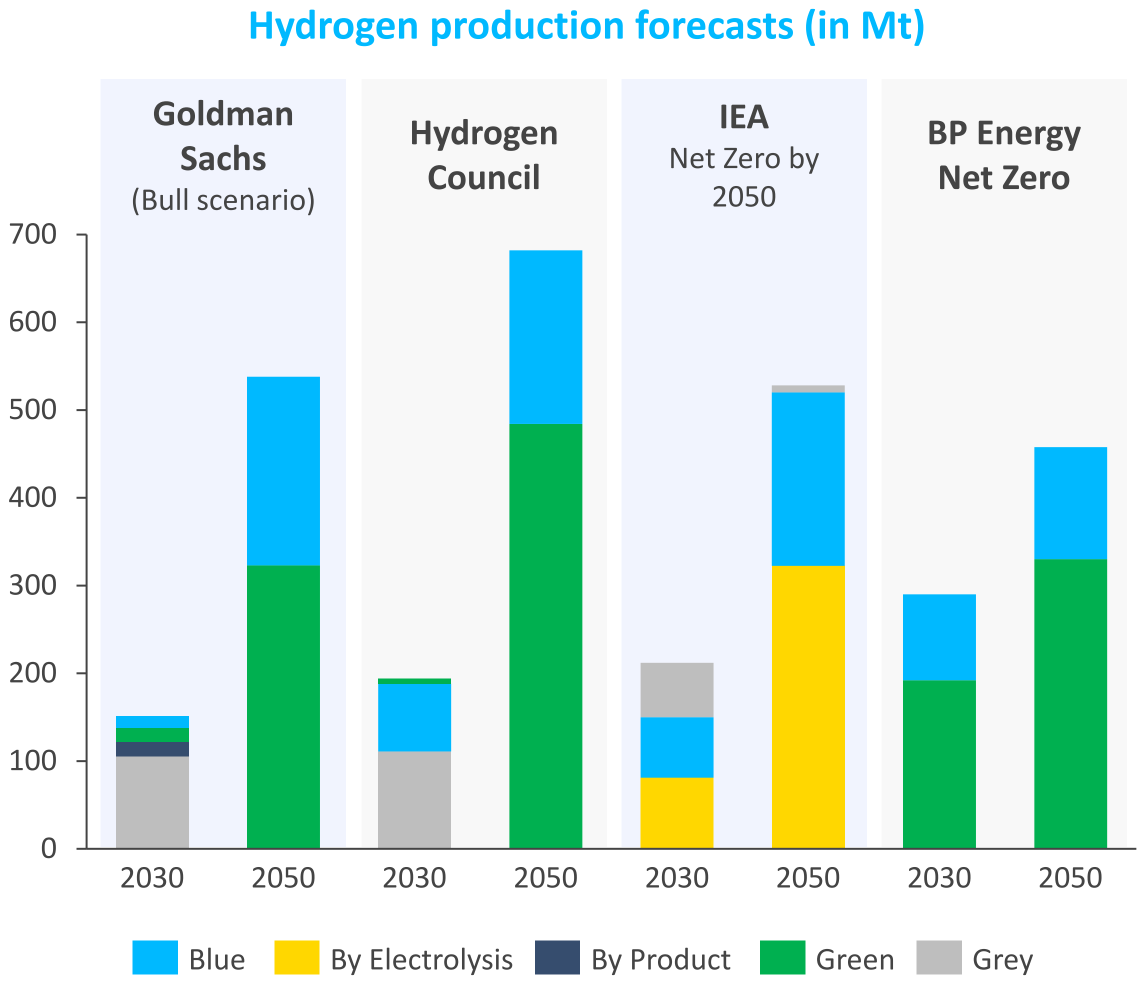
While low-emission hydrogen represented less than 1% of global production in 2021, hydrogen generated through electrolysis has increased by~20% YoY



- Most of the world's hydrogen demand from 2019 to 2021 was met through hydrogen from non-renewable sources like **natural gas without CCS, coal, and by-product of naphtha reforming**, accounting **for 62%, 19%, and 18% of production**, respectively
- **Less than 1% of hydrogen** was generated using low-emission processes, with most of it produced from fossil fuels with CCS. Nevertheless, there was an **almost 20% increase in the amount of hydrogen generated through water electrolysis compared to 2020**
- The 2020 – 2021 growth of renewable electrolysis in hydrogen production **demonstrates an increasing adoption of electrolyzers**. In fact, **more than 200 MW of electrolysers started operating in 2021**, with China accounting for 160 MW thanks to the deployment of the 150 MW Ningxia Project, which currently holds the distinction of being the largest operational electrolyzer

Sources: *IEA "Global Hydrogen Review" (2021,2022)*

Blue hydrogen is expected to act as a steppingstone in the transition to a low-carbon economy, while green hydrogen will dominate by 2050

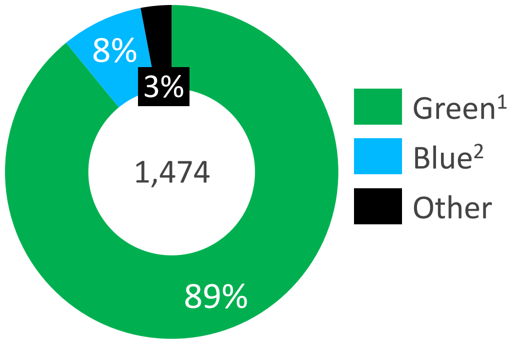


- **Hydrogen production forecasts** to achieve NZE by 2050 **vary significantly** from one source to another, both **in terms of total production estimates** (ranging from 150 Mt to 290 Mt in 2030) and **production pathways**
- Despite these differences, most sources agree that **grey hydrogen will still play a role in production in 2030, noting that blue and green hydrogen production will gain momentum.** The increase in production of blue and green hydrogen is expected to be driven by **capacity expansions and gradual cost reductions**
- All sources agree **that in the Net Zero scenario in 2050, green hydrogen will be the predominant type of hydrogen produced,** varying from approximately 60% to 70% of total production, depending on the forecast source. This growth will require a significant increase in renewable energy and electrolyser capacity

Notes: *1) Forecast values used are approximative estimates, 2) Electrolysis can refer to green, yellow and pink hydrogen*
Sources: *IEA "Global Hydrogen Review" (2021), Goldman Sachs "Carbonomics, the clean hydrogen revolution" (2022), Hydrogen Council "Global Hydrogen Flows" (2022), Bp "Energy Outlook" (2023)*

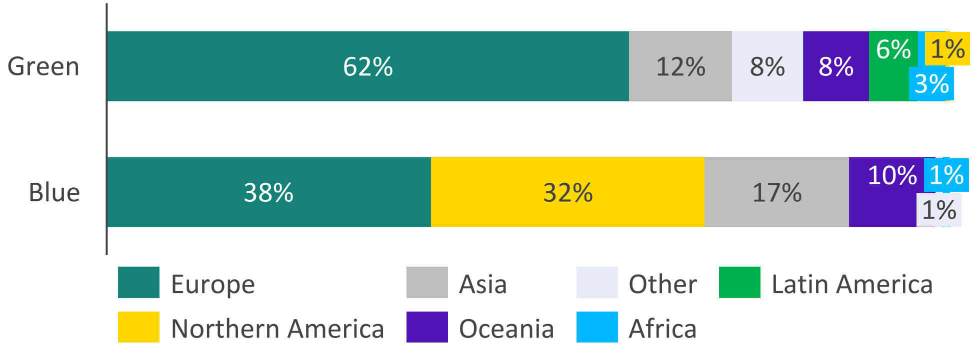
Green hydrogen projects are dominating the project pipelines, further highlighting green hydrogen as the preferred low-carbon option

Number of hydrogen projects by type as of Oct. 2022



- Most of the announced hydrogen projects around the world are **green hydrogen projects**, accounting for **~80%** of the **announced capacity**
- Although blue hydrogen represents only 8% of the number of projects**, it contributes 20% of the total capacity** and will be especially important in regions where renewable energy is limited
- Most hydrogen projects announced are in the **feasibility study** stage **with 33% of green and 58% of blue hydrogen projects, whereas 23% of green and 21% of blue hydrogen projects,** are in the **higher-risk pre-feasibility stage.** Although the risk of some of these projects not being realized exists, **only 3 out of 1,477 projected** projects have been **decommissioned since 1975**

Announced hydrogen projects by region as of Oct. 2022



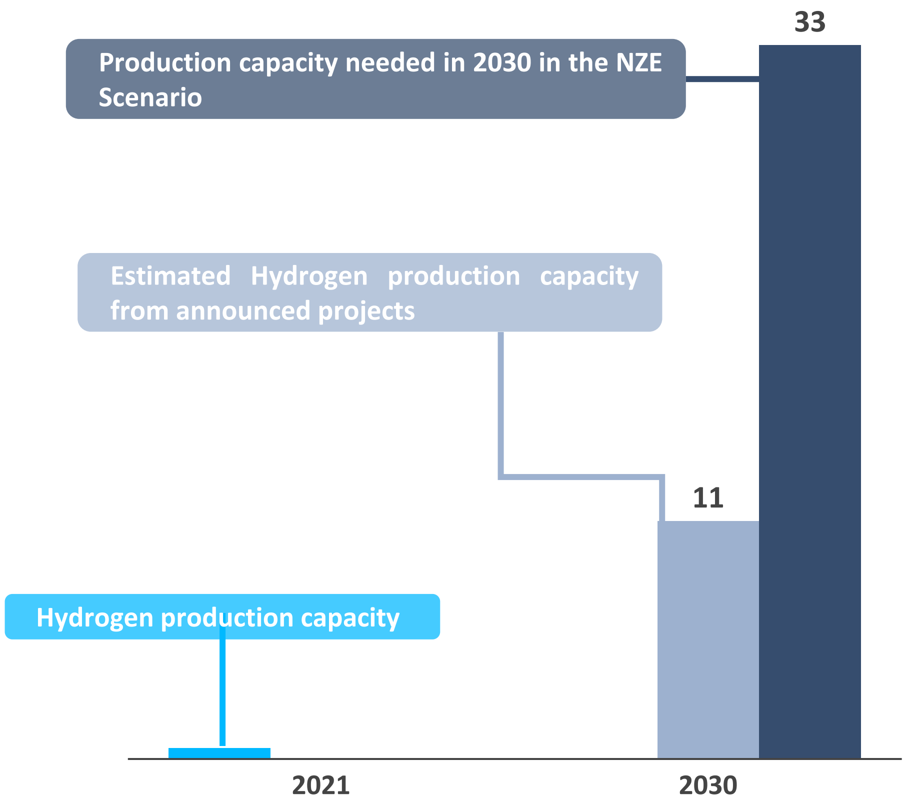
- Most of the on-going and completed hydrogen projects are in **Europe, followed by Asia and Oceania**, while North America is home to a significant number of blue projects
- **Europe and Oceania host some of the largest projects,** including the **HyDeal Ambition (11,608 kT/year)**, producing green hydrogen for France, Spain, and Germany, and **the Western Green Energy Hub project (3,601 kT/year) in Oceania**, focusing on producing green hydrogen for various industries in Australia

Notes: 1: Considering projects from electrolysis to be green hydrogen, 2: Considering projects from fossil fuels with CCS to be blue hydrogen

Sources: *IEA – Hydrogen Project Database – Oct 2022*

Current blue hydrogen production projects announced will not cover the expected NZE 2030 capacity and require additional backing to be realized

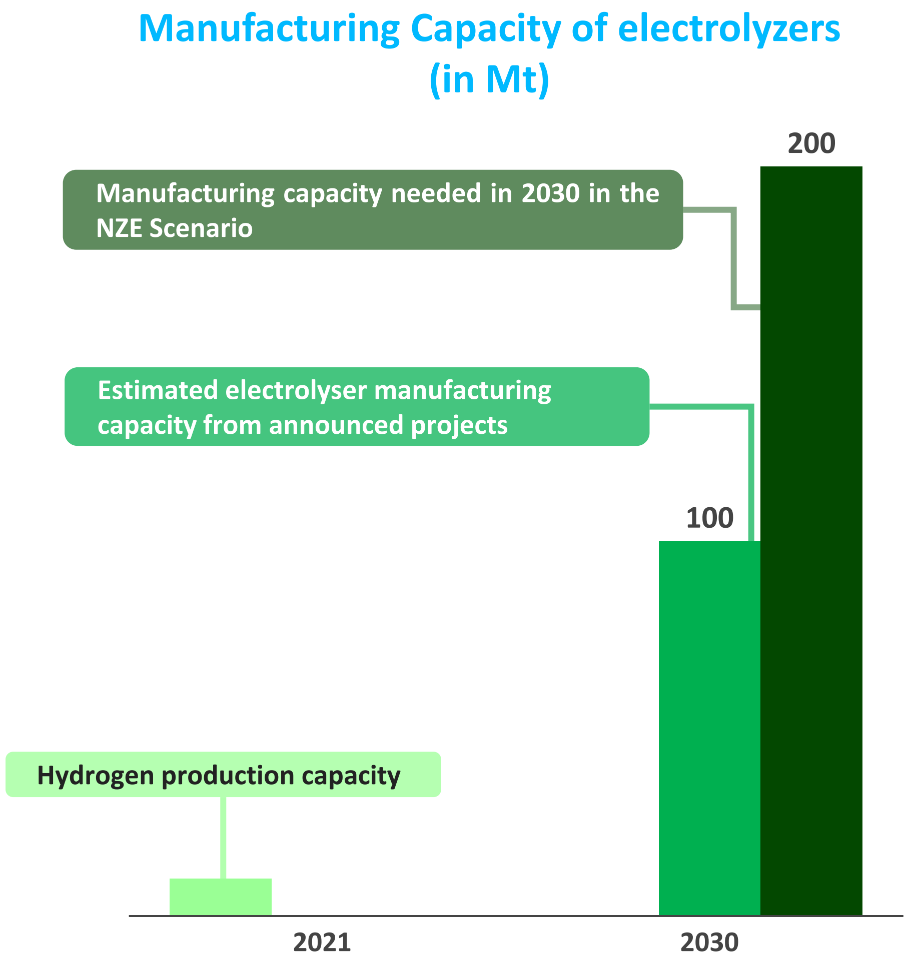
Capacity of hydrogen production from natural gas with CCS (in Mt)



- The production capacity of hydrogen from gas reforming with CCS is expected to increase from 0.5 MT/year in 2021 to 11 MT/year by 2030 if all planned projects succeed, with 1/3 of CO_2 capture projects being built or planned involving hydrogen or ammonia production
- However, **this falls short of the required 33 MT production capacity in 2030** as per the NZE Scenario
- **A surge of new entrants** in the hydrogen from fossil fuels with CCS production is expected, as from the announced projects with a timeline, 37.5% of the projects are expansions for companies already developing hydrogen from natural gas with CCS, whereas **62.5% of the projects announced are from new entrants**
- For these projects to be completed, **additional policy and financial backing may be required for certain projects.** So far, only a small number of projects have been given the final investment decision (FID), and the recent increase in gas prices, particularly in Europe, may cause scheduled projects to be postponed

Sources: *IEA "Energy Technology Perspective" (2023)*

The electrolyzer market's announced capacity showcases significant growth in 2030, yet not enough to cover the estimated capacity to reach NZE

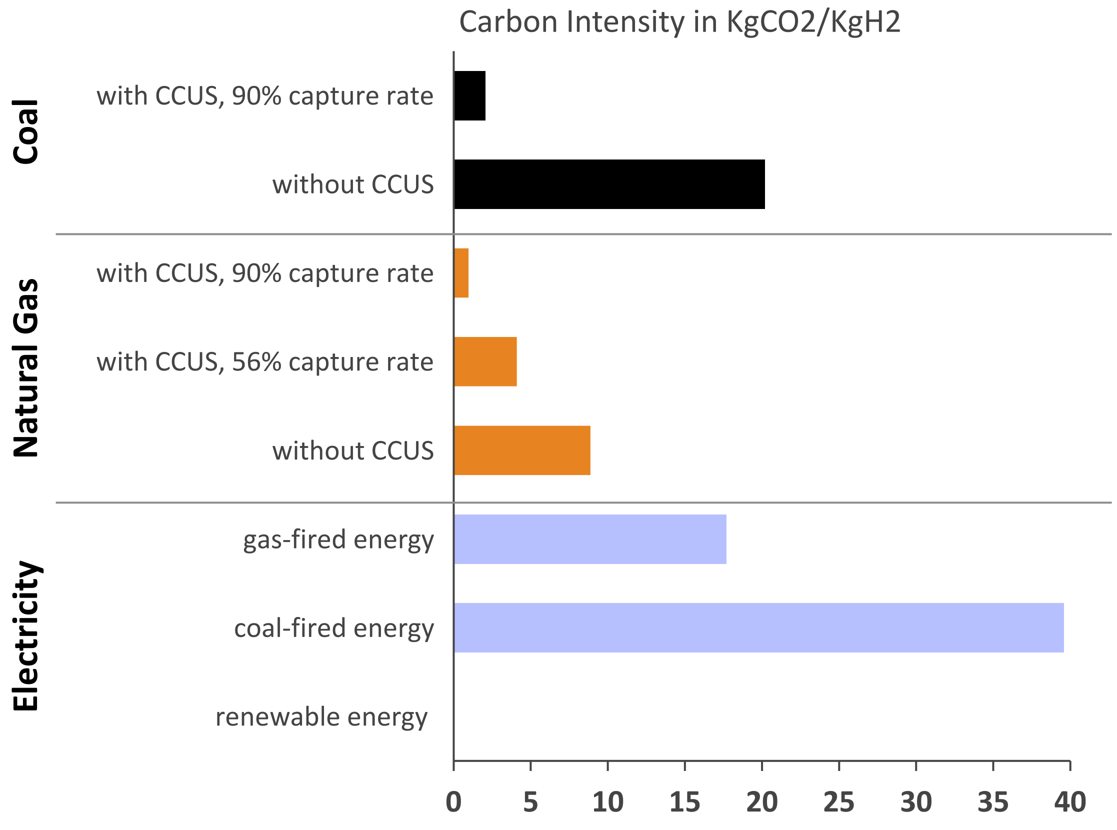


- The announced electrolyser manufacturing capacity is projected to grow significantly, **reaching over 100 GW per year by 2030**. However, even with this substantial increase, it will **not be sufficient** to meet **the forecasted capacity of 200 GW** per year by 2030 in the NZE Scenario
- Moreover, **only approximately 8%** of the announced electrolyser manufacturing capacity expansion has **reached the final investment decision**
- The electrolyzer manufacturing market is witnessing significant growth, which is leading to increased **fragmentation**. Key players in 2021, including ThyssenKrupp, NEL, and ITM Power, are projected to see their market share decline from 71% in 2021 to 24% in 2023
- Some companies are **expanding electrolyzer manufacturing capacity** and introducing new entrants **through joint ventures,** such as John Cockerill partnering with Jingli to establish the first manufacturing site in China
- It is estimated that **total expenditure** on electrolyzers will reach **$130 billion from 2022-2030**

Sources: *IEA "Energy Technology Perspective" (2023), Bloomberg NEF "Hydrogen Market Outlook" (2021), "Hydrogen Market Outlook Press Release" (2022)*

CCUS technology offers a way to reduce emissions from natural gas, while renewable energy is the path to eliminating CO2 emissions

Hydrogen carbon intensity using different production methods in KgCO2/KgH2



- Carbon emissions from fossil-fuel based hydrogen production can be **significantly reduced using carbon capture technology** (~54% reduction in carbon emissions using a 56% capture rate and ~89% reduction in the case of a 90% capture rate)
- **Renewable energy sources,** such as wind, solar, or hydroelectric power, offer a **carbon-neutral solution for hydrogen production** with a carbon intensity of zero. **This makes them the cleanest and most sustainable option in terms of carbon emissions**

- Transportation can add to the hydrogen carbon intensity for hydrogen obtained from methane reforming from natural gas (both with CCS and without), with **truck transportation** having the **highest carbon intensity contribution**
- Hydrogen production from **biomass with CCS** shows great potential for **achieving negative emissions** at reasonable costs, **but limited biomass feedstock availability and competition from other efficient routes** may hinder its widespread adoption for hydrogen production

Sources: *CICE "Hydrogen Carbon Intensity" (2023), IEA "Future of Hydrogen" (2019)*

Green and blue hydrogen are expected to be significantly cheaper than grey hydrogen by 2050, further highlighting their forecasted production growth

Blue and green hydrogen costs breakdown

Blue and green hydrogen costs depend primarily on production costs. In fact, **renewable power and electrolyzer CAPEX drive green hydrogen costs, whereas for blue hydrogen costs, the price of natural gas and the cost of CCS play crucial roles**. Both technologies have a significant potential for cost reduction through technological innovation and economies of scale.

Other factors impacting hydrogen costs include transportation and storage costs, O&M costs, carbon pricing, market maturity, and investments.

Costs overview and forecasts

- Currently, grey hydrogen is the most affordable, followed by blue and then green. However, in 2022, **green hydrogen reached cost parity with grey hydrogen in Europe** due to **higher carbon prices and elevated commodity prices.**
- By 2050, **green hydrogen is expected to be cheaper than grey hydrogen** in regions with low-cost renewable energy, while **the cost of blue hydrogen is projected to decrease** only slightly (5-10%) if methane leaks are reduced **in regions with very low natural gas prices**

Major contributors to production costs

Green Hydrogen

The cost of renewable electricity

Renewable energy costs have been decreasing, enabling reductions in green hydrogen costs.
Since 2010, **solar PV LCOEs* dropped by ~80%,** while **wind LCOEs have fallen by ~60%.**

The capital cost of the electrolyzers

The cost of electrolyzers is expected to decrease as the technology becomes more scalable.
Since 2010, **electrolyzer prices have decreased by 60%** and are expected to further **decrease by 40% in 2025.**

Blue Hydrogen

The price of natural gas

Natural gas prices are fluctuating and volatile. In 2022, due to the Russia-Ukraine war, fossil fuel prices rose, and so **the costs of blue and grey H_2 increased by over 70%**

The costs of CCS

The scale-up of carbon capture technology will make it reach economies of scale, which will decrease its **costs by around 20% by 2050**

Notes: *Levelized cost of electricity/energy*
Sources: *Goldman Sachs "Carbonomics, the clean hydrogen revolution" (2022), ETC "Making the Hydrogen Economy Possible" (2021), Press search*

Infrastructure for hydrogen supply chain

Infrastructure for hydrogen supply chain

1 Hydrogen Transportation

- Hydrogen transportation requires **conditioning such as compression, liquification, or the use of carriers** to enhance efficiency during transport.
- Presently, around 85% of hydrogen is produced and used on-site, while the remaining **15% is transported by trucks or pipelines.**
- So, as the demand for hydrogen grows in the future, transportation will depend on **other factors such as volume, distance, and end use**

2 Hydrogen Storage

- **Current optimal storage mean**: **Pressurized containers** are well-established and efficient for small-scale hydrogen storage
- Future Optimal storage mean: **Geological storage** will be crucial for large-scale applications, providing a cheaper option for longer storage periods
- However, geological storage still needs **further R&D and testing**

3 National strategies and roadmaps

- The recent wave of interest in decarbonization has led to a **rapid increase in national hydrogen strategies and roadmaps**
- Since 2017, **more than 42 governments** have established national hydrogen strategies and roadmaps

4 Interregional Trade

- **Europe** is expected to **import** hydrogen, while the **Middle East, the Americas**, and **Australia** are expected to become hydrogen exporters
- Numerous governments have announced around **60 international agreements**/hydrogen trade projects

Infrastructure for hydrogen supply chain

Transportation and Storage

Conditioning is required to safely transport and store hydrogen

Around 85% of hydrogen is produced and used on-site, while the remaining **15% is transported by trucks or pipelines.** As hydrogen demand grows in the future and larger volumes are required, ensuring that hydrogen is transported, stored, and distributed in a safe and cost-effective manner is critical to its widespread deployment. While hydrogen has a very high energy density per unit mass, it has a very low density per unit volume, which presents significant infrastructural challenges. To safely and economically transport and store hydrogen, its energy density needs to be increased through conditioning **(compressed, liquefied, or converted into other carriers like ammonia and liquid organic hydrogen carriers (LOHC))**

	Compressed hydrogen	Liquid hydrogen	Ammonia	LOHC
Compatible Transportation Means	Pipelines and trucks	Trucks and ships	Pipelines, Trucks, and ships	Trucks and ships
Pros	▪ No conversion is required (only compression) ▪ Transport and storage are proven at a commercial scale	▪ No reconversion required ▪ High purity hydrogen ▪ Limited energy consumption for Regasification	▪ Carbon-free carrier ▪ Produced on a large scale ▪ Already globally traded.	▪ Use of existing infrastructure ▪ Convenient for storage and transportation
Cons	▪ Not all regions have an existing gas network	▪ Cryogenic temperatures lead to high ▪ equipment cost ▪ Boil-off losses along value chain ▪ High energy losses for liquefaction	▪ High energy consumption ▪ Further purification needed ▪ Toxic and corrosive	▪ High energy consumption ▪ Further purification needed ▪ The carrier production process adds to the CO2 footprint

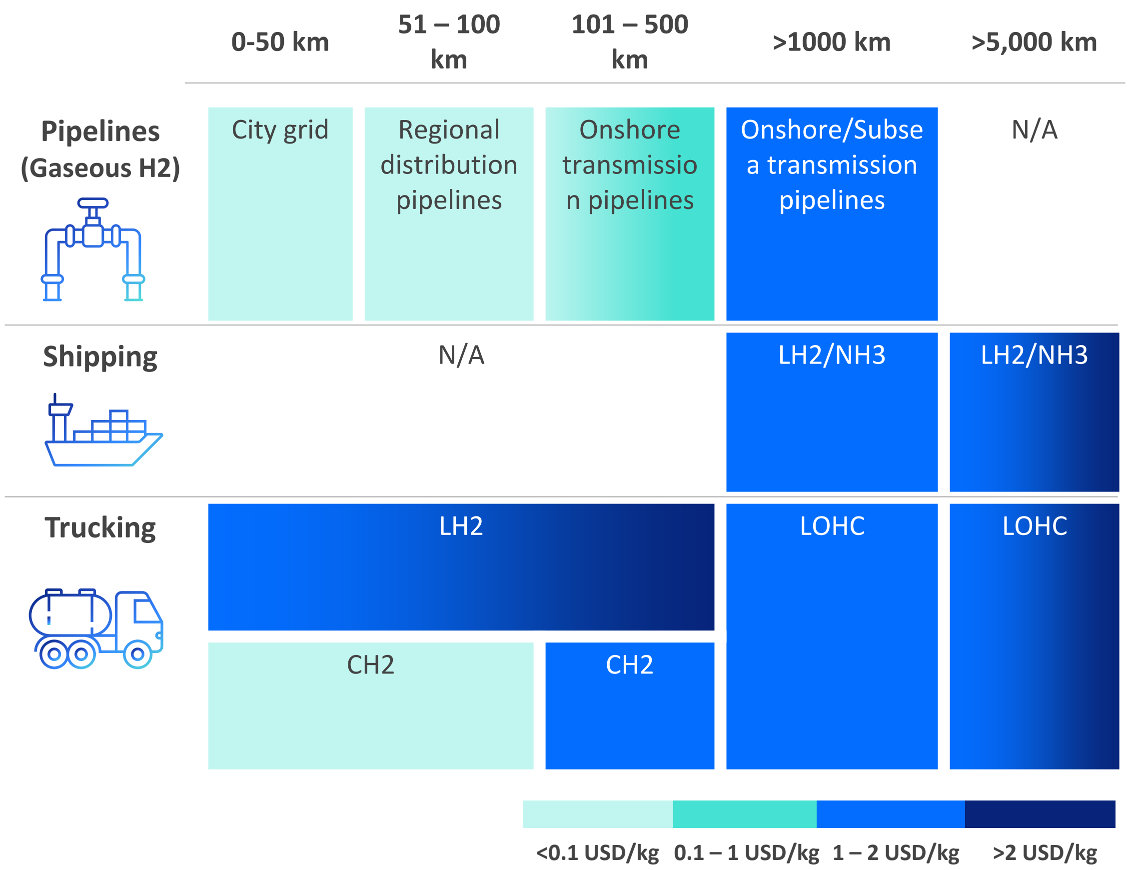
Sources: *Hydrogen Council "Hydrogen Insights" (2021), IRENA "Global Trade Hydrogen" (2022)*

The optimal transportation method for hydrogen depends on distance, volume, terrain, and end use

- **For short and medium range distances,** retrofitting **pipelines can provide a low-cost option to transport high volumes of H_2,** but only if existing pipeline networks are available and suitable for retrofits. **For lower or fluctuating demand, trucking** is more **suitable and cost-attractive**
- **For longer distances,** new or retrofitted **subsea transmission pipelines** become more cost-efficient as the hydrogen volume transported increases. However, they are not relevant for all the regions
- **For distances greater than 3,000 km** or for routes across bodies of water, **ships** are the best option as they allow for the transportation of large volumes of hydrogen (unlike trucks, which can be disregarded as they are better suited for smaller volumes)
- Choosing the optimal hydrogen carrier and transportation method can also depend on **terrain and end use.** For certain applications, like steel production, it is also **more practical to transport alternative forms** like reduced iron or steel rather than hydrogen and iron ore separately

Transporting hydrogen can be achieved by utilizing **existing natural gas pipelines**; however, they must undergo **retrofitting** while considering material compatibility, compression requirements, and pipeline capacity
Retrofitting NG pipelines can offer an investment cost that is **65-94% lower** than building **new hydrogen pipelines**. Nonetheless, this option is viable only in **regions where the necessary infrastructure is already in place.**

Distribution options of hydrogen by projected costs and distance



[1] Liquified hydrogen, [2] Ammonia , [3] Liquid Organic Hydrogen Carriers, [4] Compressed hydrogen

***Sources:** Hydrogen Council "Hydrogen Insights" (2021), Roland Berger "Hydrogen transportation | The key to unlocking the clean hydrogen economy" (2021)*

Underground storage is considered the most suitable and cost-effective hydrogen storage option, especially for large volumes

Hydrogen storage options

	Cost of storage (USD/kg)	Geographical availability	Volume of storage	Cycling (storage period)
Underground storage				
Salt caverns	0,23 / 0,11	Limited	Large	months-weeks
Rock caverns	0,71 / 0,23	Limited but abundant	Large	seasonal
Depleted gas fields	1,90 / 1,07	Limited	Medium	months-weeks
Above ground storage				
Pressurized containers	0,19 / 0,17	Not limited	Small	daily
Liquid hydrogen	4,57 / 0,95	Not limited	Small -medium	days-weeks
Ammonia	2,83 / 0,87	Not limited	Large	months-weeks
LOHCs	4,50 / 2,86	Not limited	Large	months-weeks
Metal hydrides	N/A	Not limited	Small	days-weeks

Benchmark 2019 | Future c.2050

- Pressurized containers are considered a well-established and efficient way to store hydrogen for short periods on a small scale. The cost is low and has a negligible impact on the overall delivery cost
- For upcoming **large-scale applications (such as energy storage medium and fuel for transportation and industry)**, geological storage is deemed crucial as it is expected to be cheaper, more suitable for larger volumes, and offer longer storage periods
- However, due to hydrogen's physical properties and porous nature, **further R&D and testing** are needed to use underground storage for hydrogen. Currently, only **6 salt caverns** are used for hydrogen storage in the world, with the remaining underground storage used for natural gas. Some companies are now considering underground storage options (such as **Humber Hydrogen Storage** and **Rehden**), announcing several planned projects by 2030

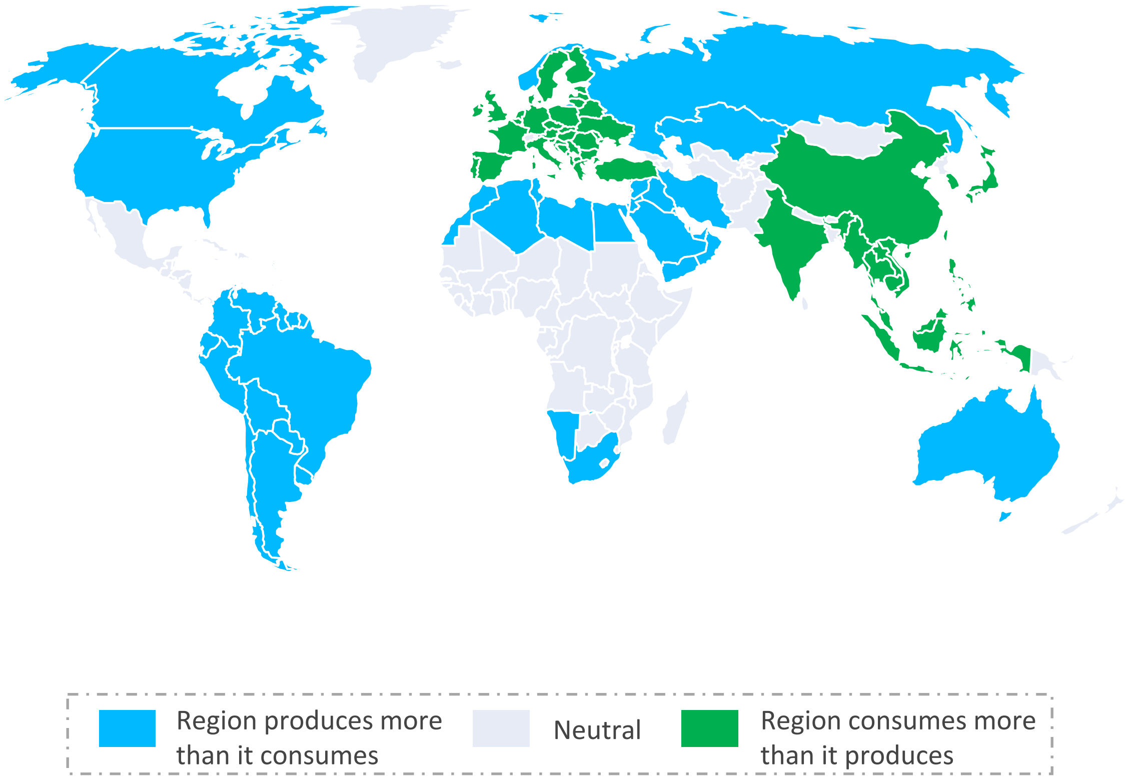
Sources: *IEA "Energy Technology Perspective" (2023), IEA "Global Hydrogen Review" (2022), Bloomberg NEF "Hydrogen Market Outlook" (2019)*

Infrastructure for hydrogen supply chain
Hydrogen interregional trade

Europe is expected to import hydrogen, while the Middle East, the Americas, and some countries in Asia are set to become hydrogen export hubs

- In 2050, around 50% of the hydrogen trade will use pipelines, including repurposed natural gas pipelines. The other half will be transported as ammonia via long-haul ships. Europe is primarily expected to be supplied by pipelines, whereas Asia will rely on ships
- Europe will need to increase its imports of hydrogen, which will result in the opening of significant opportunities for piped imports, specifically of renewable hydrogen **from North Africa**
- **The Middle East is expected to play a major role** in the exportation of hydrogen, especially through extensive **trade flows to Asia** that will mainly involve shipping hydrogen
- Japan, South Korea, and Singapore are among the markets that will face **supply constraints** and will need to begin importing hydrogen via carriers to keep up with the rising demand
- To reduce the risk of export concentration, it is important to unlock the potential of regions such as **Africa, the Americas, the Middle East, and Oceania**. However, achieving this goal would necessitate significant investments in technology transfers and infrastructure on a large scale in many countries within these regions

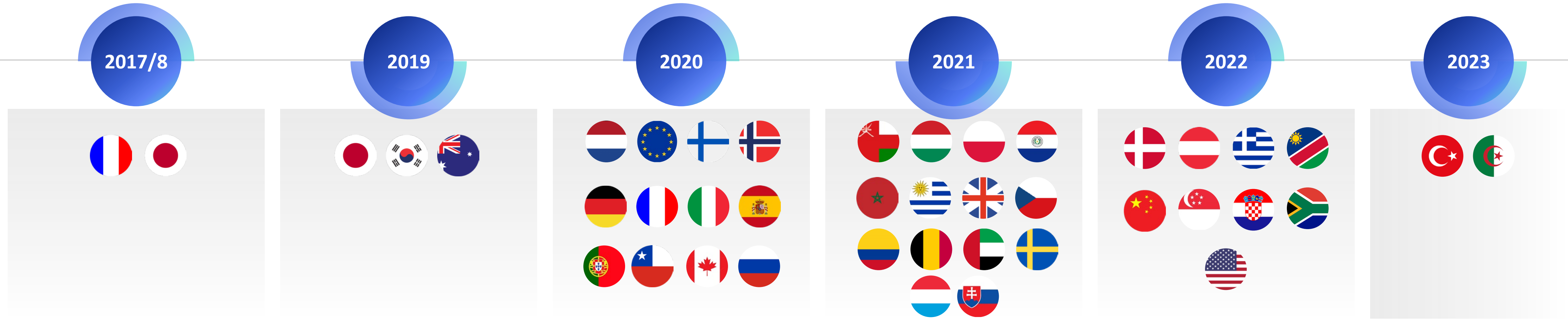
Hydrogen Trade potential by 2050



Sources: *Hydrogen Council "Global Hydrogen flows" (2022)*

Global policy interest and support for clean hydrogen have surged, resulting in a rapid increase in national hydrogen strategies and roadmaps

Timeline of national hydrogen strategies and roadmaps deployment



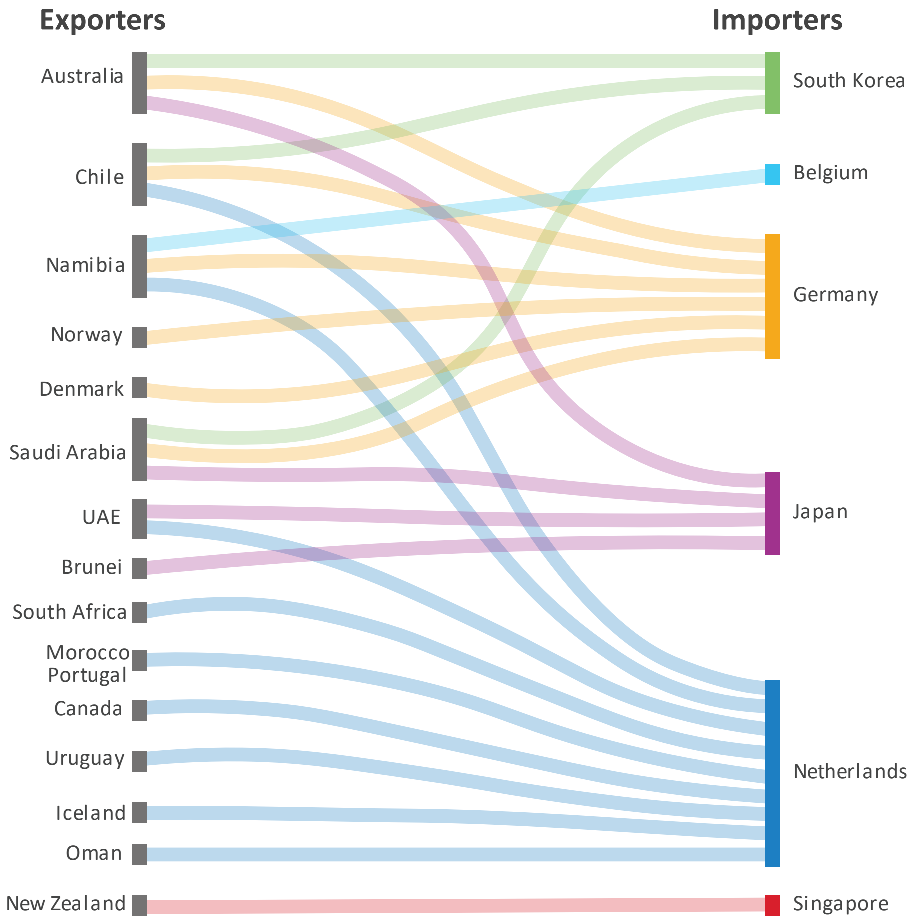
Recent focus on decarbonization has sparked a new wave of interest in hydrogen, especially in the last three years, with more than 42 governments releasing national hydrogen strategies and roadmaps:

- The **EU Hydrogen Strategy**, with a **2x40 GW electrolyzer capacity target by 2030**, is the **largest regional green hydrogen capacity target globally** and is backed by country-specific hydrogen strategies, roadmaps, and targets from most European countries
- **Japan and South Korea** have strategies that focus on **wider domestic adoption of hydrogen and the creation of a hydrogen economy**, with an **emphasis on transport**
- Australia's hydrogen strategy focuses on becoming a **major hydrogen export hub**
- **North and South America** have started to show signs of acceleration in policy initiatives on hydrogen. **Chile and Canada emerged as the first to publish national hydrogen strategies, with Chile having the largest single-country target** (25 GW of capacity in hydrogen projects with committed funding by 2030) and **Canada** aiming to have **about 30% of total final energy consumption by 2050** attributed to hydrogen

Sources: *Goldman Sachs "Carbonomics, the clean hydrogen revolution" (2022), ETC "Making the Hydrogen Economy Possible" (2021), CSIRO HyResource "International hydrogen strategies" (2023), Press Search*

In parallel with the rise of national hydrogen roadmaps, a significant upswing in bilateral hydrogen trade agreements has been recorded since 2020

Bilateral trade agreements (2021/2022)[1]



- Multiple governments have declared various international collaborations and projects for hydrogen trade. Out of the roughly **60 announced trade projects (including agreements, MOCs, and MOUs) as of 2021**, feasibility studies are currently underway for half of them
- Australia has established trade initiatives like "The Clean Hydrogen Trade Program," which concentrates on exporting clean hydrogen to Japan, making **Australia the supplier of choice for Japan**
- European governments are exploring ways **to accelerate the accessibility of hydrogen technologies and international trade**
- Oman's energy ministry had already signed many declarations of intent with **potential importers** like Germany, Belgium, and the Netherlands
- The collaboration between METI (Ministry of Economy, Trade and Industry in Japan) and the UAE ministry aims to explore the production of hydrogen for export to Japan, along with the use of hydrogen in Abu Dhabi
- By 2026, exports are expected to be at 2.4 MT per year and are set to **double to 6 MT by 2030**. The exports are targeted for import in Europe or Asia, notably in Germany, the Netherlands, and Japan

[1]A non-exhaustive list of trade agreements with prospective importers and exporters of hydrogen

Sources: *IEA "Global Hydrogen Review" (2021,2022), IRENA "Geopolitics of the Energy Transformation: The Hydrogen Factor" (2022)*

Conclusion

Clean hydrogen has a major role in decarbonization, in line with net zero emissions by 2050. To allow the hydrogen market to achieve its expected potential, infrastructure development is crucial. In fact, the largest gap in achieving net zero is found in hydrogen infrastructure, with only 10% of announced investments currently dedicated to this area. To address this, the industry should focus on proposing and developing hydrogen infrastructure, including terminals, storage, carriers, and transportation. R&D efforts also play a significant role in enhancing technology performance and reducing energy consumption in various transportation and storage modes.

The development of the hydrogen market requires policy frameworks, regulations, and interregional agreements to support this expected growth. Governments should develop national hydrogen strategies that serve as a reference for private actors in the hydrogen industry, stimulating higher levels of financing. An effective national strategy should provide a clear roadmap for expanding hydrogen adoption.

Several countries have already developed strategies detailing their roadmaps and development plans for the hydrogen sector. In addition to focusing on their local hydrogen markets, countries are prioritizing international cooperation to facilitate cross-border trade and efficiently balance supply and demand.

Abbreviations and acronyms

H_2	Hydrogen	**O&M**	Operation and maintenance
SMR	Steam methane reformation	**CH_2**	Compressed hydrogen
CCUS	Carbon capture, utilization and storage	**NH_3**	Ammonia
CCS	Carbon capture and storage	**LH_2**	Liquid hydrogen
LDV	Light duty vehicle	**LOHC**	Liquid organic hydrogen carriers
HDV	Heavy duty vehicle	**GHG**	Greenhouse Gas Emissions
NZE	Net Zero Emissions	**NG**	Natural gas
LCOE	Levelized cost of electricity/energy	**PV**	Photovoltaics

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