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Carbonomics

The Rise of Clean Hydrogen

Clean hydrogen has a major role to play in the path towards net zero carbon, providing de-carbonization solutions in the most challenging parts of the **Carbonomics** cost curve - including long-haul transport, steel, chemicals, heating and long-term power storage. Clean hydrogen cost competitiveness is also closely linked to cost deflation and large scale developments in renewable power and carbon capture (two key technologies to produce it), creating three symbiotic pillars of de-carbonization.

Clean hydrogen is gaining strong political and business momentum, emerging as a major component in governments' net zero plans such as the European Green Deal. This is why we believe that the hydrogen value chain deserves serious focus after three false starts in the past 50 years. Hydrogen is very versatile, both in its production and consumption: it is light, storable, has high energy content per unit mass and can be readily produced at an industrial scale. The key challenge comes from the fact that hydrogen (in its ambient form as a gas) is the lightest element and so has a low energy density per unit of volume, making long-distance transportation and storage complex and costly. In this report we analyze the clean hydrogen company ecosystem, the cost competitiveness of green and blue hydrogen in key applications and its key role in **Carbonomics: the green engine of economic recovery.**

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Hydrogen In numbers

Clean hydrogen has the potential to aid the de-carbonization of c. 45% of global anthropogenic emissions, we estimate...

...addressing key 'hard to de-carbonize' sectors, including long-haul transport, steel, chemicals, heating and long-term power storage.

Hydrogen fuel cells generate zero CO2 (just water vapour), but 'grey' hydrogen production (from natural gas or coal) generates c. 9 and c. 20 kg CO2/kg hydrogen...

...hence the need to switch to 'blue' and 'green' hydrogen, with c.90-100% lower carbon intensity compared to traditional 'grey' hydrogen

Clean hydrogen is currently costly to produce, c. 1.3-2x higher for 'blue' and c. 2-7x for 'green', compared to 'grey'..

...and its cost improvement is closely linked to large scale developments in renewable power and carbon capture, creating three pillars of de-carbonization driving up to an estimated $16 trn of infrastructure investments by 2030E

..benefiting from global renewables costs falling >70% over the last decade and a return to carbon capture investments after a 'lost decade"

Hydrogen screens attractively as fuel, with >2.5x the energy content per unit mass of gasoline and >2x that of natural gas…

..making it attractive for long haul transport, with compressed hydrogen fuel cell systems having c. 70% lower weight per unit of output energy compared to batteries…

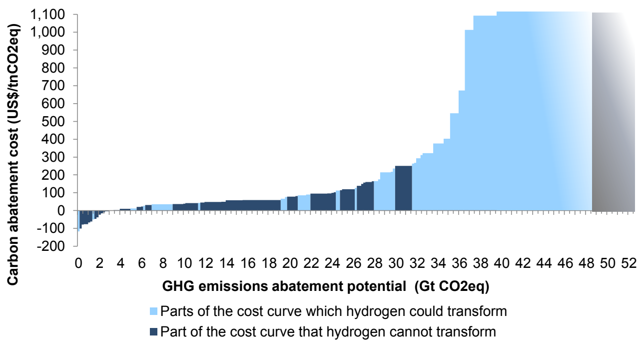
..and >30% lower volume per unit of output energy

The main weakness for hydrogen applications remains its low overall life-cycle energy efficiency (well-to-wheel), c. 25-40% compared to c. 70-90% for batteries

Source: US Department of Energy, Company data, Goldman Sachs Global Investment Research

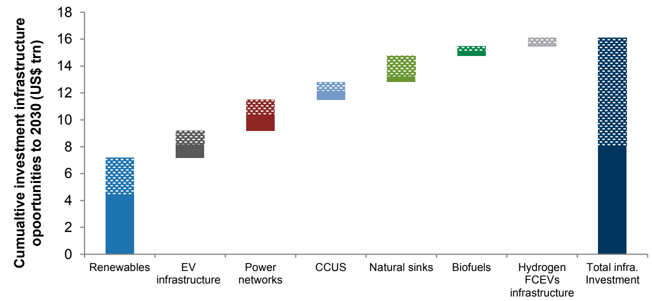
The rise of clean hydrogen in 12 charts

Exhibit 1: Clean hydrogen has the potential to aid the de-carbonization of 45% of global GHG emissions, we estimate...
Carbon abatement cost ($/tnCO2eq) vs GHG emissions abatement potential (GtCO2eq)



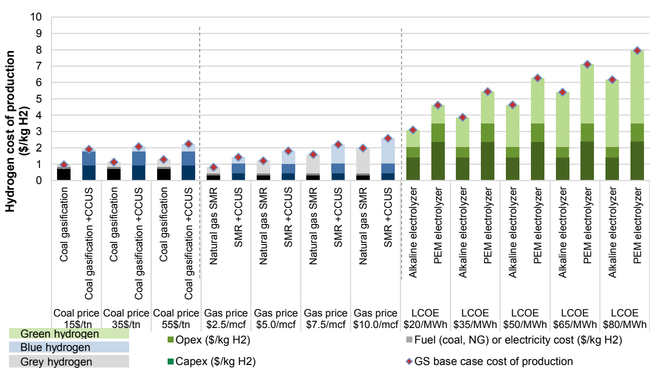
Source: Goldman Sachs Global Investment Research

Exhibit 2: ...fostering clean tech investments in renewables, carbon capture and FCEVs fueling infrastructure
Estimated cumulative investment in clean energy transition to 2030E (US$tn)



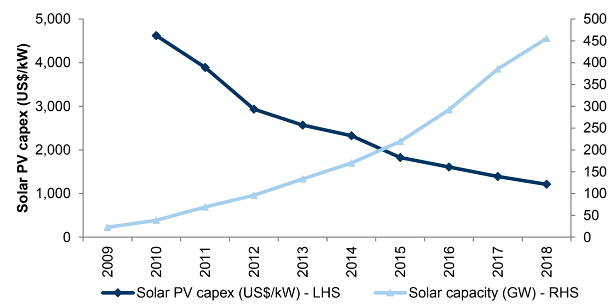
Source: IEA, Goldman Sachs Global Investment Research

Exhibit 3: Clean hydrogen is currently expensive due to the cost of electricity and carbon capture...
Hydrogen cost of production under different technologies & fuel prices



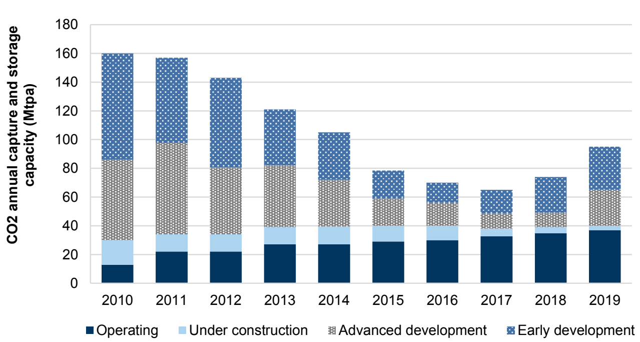
Source: Company data, Goldman Sachs Global Investment Research

Exhibit 4: ...but as solar PV shows, costs can improve dramatically with scale...
Solar PV capex ($/kW) vs global cumulative solar PV capacity (GW)



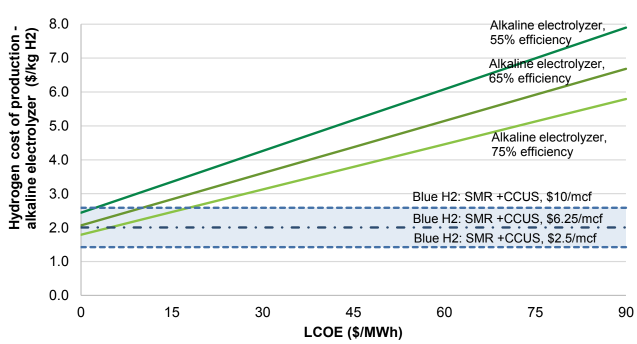
Source: IRENA, Company data, Goldman Sachs Global Investment Research

Exhibit 5: ...and carbon capture is coming back from a 'lost decade'
Annual CO2 capture & storage capacity from large-scale CCS facilities



Source: Global CCS Institute, Goldman Sachs Global Investment Research

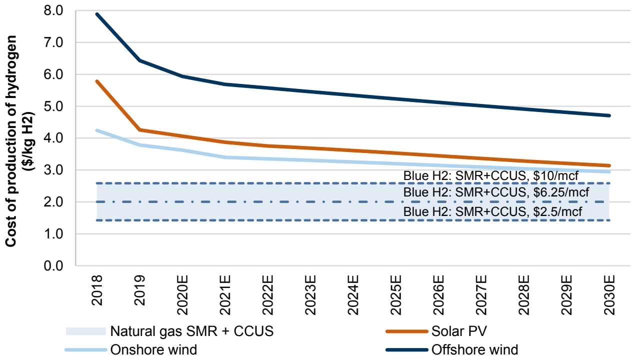
Exhibit 6: Blue hydrogen has a strong cost advantage in the near and medium term...
Hydrogen cost of production ($/kg H2) vs LCOE ($/MWh)



Source: Goldman Sachs Global Investment Research

Exhibit 7: ...but we expect green hydrogen to become cost competitive by the end of the decade in low-cost renewable locations...

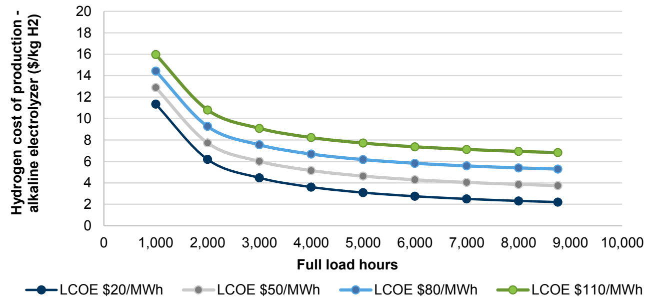
LCOH ($/kg H2) implied in the cost of production for hydrogen



Source: IRENA, Goldman Sachs Global Investment Research

Exhibit 8: ...thanks to higher electrolyzer utilization and lower cost of electricity

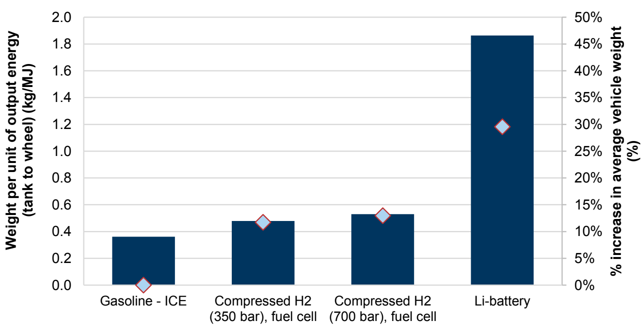
Hydrogen cost of production for typical alkaline electrolyzer variation with full load hours and LCOE



Source: Goldman Sachs Global Investment Research

Exhibit 9: Hydrogen is a better energy storage option than batteries from a weight perspective...

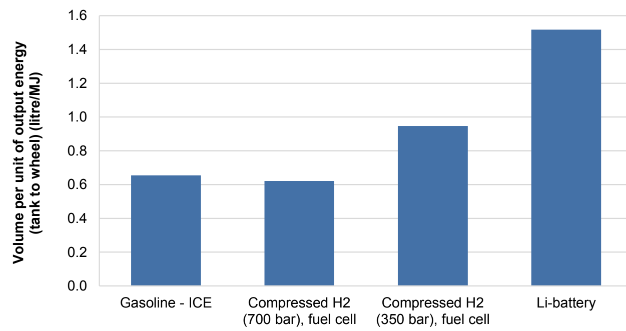
Weight per unit of output energy (tank-to-wheel) and % increase in average vehicle weight



Source: DOE, EIA, Goldman Sachs Global Investment Research

Exhibit 10: ...and can also take less space if stored in compressed form

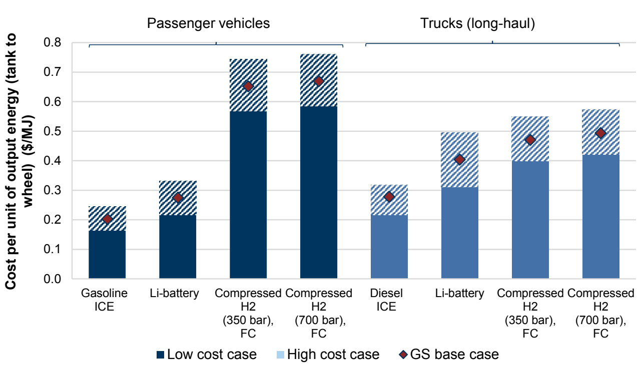
Volume per unit of output energy (tank-to-wheel, litre/MJ)



Source: DOE, EIA, Goldman Sachs Global Investment Research

Exhibit 11: Compressed hydrogen becomes more cost competitive for long-haul transport given its high energy content per unit mass (and need for less frequent refuelling)...

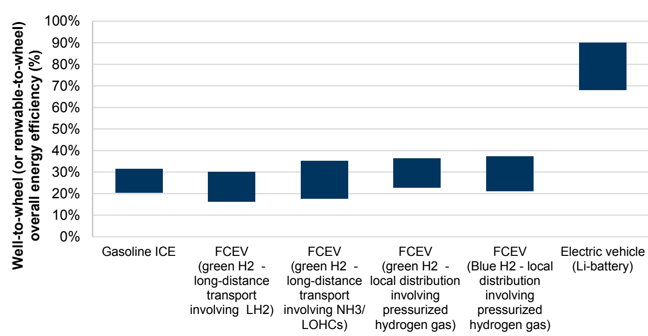
Cost per unit of output energy (tank-to-wheel, $/MJ)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 12: ...but one of its primary weaknesses remains its low overall well-to-wheel efficiency

Well-to-wheel (or renewable-to-wheel) overall efficiency (%)



Source: Company data, Goldman Sachs Global Investment Research

Clean hydrogen company ecosystem

Hydrogen Production

Blue H_2

Carbon capture technologies

OGCI members
Aker Solutions
Svante Inc. (Inventys)
C-Capture
CO2 Solutions
Blue Planet
Climeworks
Carbon Engineering
Global Thermostat

Integrated clean hydrogen supply chain players

Air Liquide
Linde Group
Taiyo Nippon Sanso
Air Products Chemical Inc.

Green H_2

Renewable power generation

RWE
Orsted
EDP/EDPR
Enel
Iberdrola
SSE
Acciona
ERG
Falck
Neoen
Encavis
Canadian Solar
First Solar
Renova
Verbund
Solaria

Electrolyzer manufacturers

Hydrogenics (Cummins)
Nel Hydrogen
ITM Power
McPhy Hydrogen
Asahi KASEI
Thyssenkrupp
Siemens
SunHydrogen
H-TEC Systems
Green Hydrogen Systems
H2B2

Storage, distribution, transport

Storage

Hexagon Composites
Plastic Omnium
Worthington Industries
Faurecia
Vopak
ILJIN Composites
MAHYTEC
NPROXX
Calvera
Faber Cylinders

Distribution, transport & other infrastructure

Kawasaki
Iwatani Corporation
Korea Gas (KOGAS)
ENEOS
Snam
Enagas
Nel Hydrogen
Nikola Motors

Applications

Fuel cell manufacturers

Ballard Power
FuelCell Energy
AFC Energy
Ceres Power
Doosan Fuel Cell
PLUG Power
Powercell Sweden
Bloom Energy
Mitsubishi Hitachi Power systems (MHPS)
SFC Energy
Cell Impact
Proton Power Systems
Hydrogenic (Cummins)
PowerHouse Energy
3M
Bosch
Michelin
ErlingKlinker
Schaeffler Group
SinoHytec
Intelligent Energy
GenCell Energy
Arcola Energy
Horizon Fuel Cell
Nedstack
Liebherr
GORE

Mobility

Toyota
Hyundai
Daimler
Alstom
Stadler
Audi
BMW Group
Nikola Motor
Volvo
Honda
Safran
GM
Faurecia
Airbus
GWM
ABB
Yanmar
AVL

Energy suppliers

Engie
EON
Enel
EDF

Industrial

SSAB AB
ArcelorMittal
Anglo American
Aperam
Fortescue Metals
Siemens
Bosch
Mitsubishi
Johnson Matthey
Voestalpine
CNH Industrial
ThyssenKrupp
Umicore
Baker Hughes

Buildings

Worcester Bosch (Bosch)
Giacomini Group
Viessmann Group
Solid Power

Other global partners in clean H_2 projects

Equinor
RDShell
TOTAL
BP
Sinopec
Saudi Aramco
Chevron
Galp
OMV
ITOCHU Corporation
McDermott
Mitsubishi Industries
Woodside
Marubeni
Covestro

- **Bold** *denotes publicly listed companies*
- Non-bold *for private companies*

**** We note that the list of companies across the clean hydrogen value chain we present above is not exhaustive, and the universe of companies involved in the global chain is likely to be larger***

Source: Company data, Goldman Sachs Global Investment Research

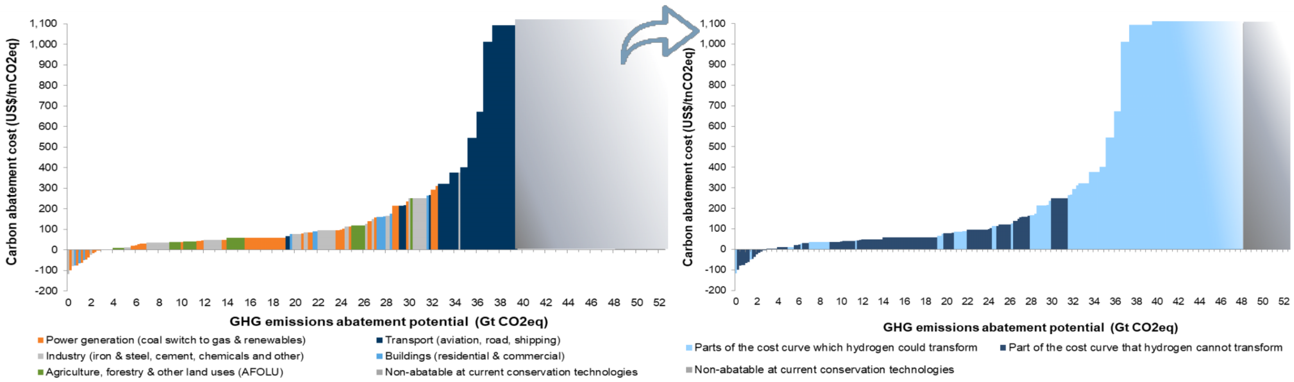
Hydrogen has the potential to transform the carbon abatement cost curve

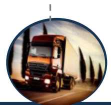
We highlighted in our deep-dive report Carbonomics that the route to net zero carbon is likely to follow two complementary paths: conservation and sequestration. The former refers to all technologies enabling the reduction of gross greenhouse gases emitted and the latter refers to natural sinks and carbon capture, usage and storage technologies (CCUS) that reduce net emissions by subtracting carbon from the atmosphere. As part of our Carbonomics analysis, we constructed a **carbon abatement cost curve for de-carbonization** presented in Exhibit 13 which shows the conservation cost curve of GHG emissions relative to the current global anthropogenic (i.e. related to human activities) GHG emissions. In this analysis, we included de-carbonization technologies that reduce GHG emissions and are currently available at commercial large scale, and present the findings of this analysis at the current costs associated with each technology's adoption. We include almost 100 different applications of GHG conservation technologies across all key sectors globally: power generation, industry, transport, buildings and agriculture.

Despite the wealth of relatively low-cost de-carbonization opportunities, the **abatement cost curve is very steep as we move beyond 50% de-carbonization**. Moreover, we estimate that c.25% of current global anthropogenic GHG emissions are not abatable under current commercially available large-scale technologies at prices <US$1,000/tn$CO_2$eq, calling for technological innovation and breakthroughs to unlock the net zero carbon potential. Examining the emerging technologies that could meaningfully transform the de-carbonization cost curve, it becomes evident to us that **hydrogen** is currently at the forefront of this technological challenge: based on our analysis, it has the potential to **transform 45% of the cost curve** (including the non-abatable emissions <$1,000/tn$CO_2$) and can be attractively positioned in a number of transportation, building, power generation and industrial applications.

Exhibit 13: Hydrogen has the potential to transform c. 45% of the cost curve of de-carbonization (45% of global anthropogenic GHG emissions) across four key and highly emitting sectors, we estimate

Addressing the non-abatable GHG emissions under current large-scale, commercially available technologies

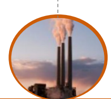




TRANSPORTATION

The role of H_2

- **Road transport:** Fuel cell electric vehicles (FCEVs) can be an alternative de-carbonization solution for transport, with short refueling time and lower weight making them particularly useful in long-haul and heavy transportation.
- **Rail:** Hydrogen trains could be useful de-carbonization tools particularly for rail freight.
- **Aviation:** Hydorgen-based synthetic fuels ('power-to-liquids') can be a de-carbonization solution with minimal changes required to existing infrastructure.
- **Shipping/marine:** Hydrogen and ammonia could both be used for domestic shipping aiding the de-carbonization of marine.



POWER GENERATION

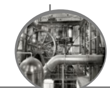
The role of H_2

- The ablity to reach full de-carbonization of power generation networks and enable full uptake of renewable variable energy sources is highly reliant on the ability to achieve intraday and seasonal storage. Hydrogen could be a key solution to the **energy storage challenge** whilst also **adding flexibility to the power network** through further integration.
- Hydrogen could be used for co-firing in existing hydrocarbon-based power plants (such as coal) reducing the carbon impact of existing plants in the near-term.

BUILDINGS

The role of H_2

- Hydrogen can be the key to de-carbonizing **space heating in buildings**. This can done by using 100% clean hydrogen although gas network upgrades may be required. Alternatively, blending of hydrogen in current pipeline infrastructure could be a lower-cost alternative. Clean methane produced from clean hydrogen (synthetic fuel) could be another possible solution.



INDUSTRY & WASTE

The role of H_2

- **Oil refining**: Oil refining is the largest source of hydrogen demand and the use of clean ('green' or 'blue') hydrogen could be used to replace higher carbon intensity merchant purchases.
- **Iron & Steel:** Substituting natural gas with clean hydrogen in current DRI production routes is a process currently demonstrated in pilot scale.
- **Chemicals:** Hydrogen is central to a large number of primary chemical industrial processes including the production of ammonia and methanol. Using clean hydrogen can help reduce emissions across these large-scale processes.
- **High temperature heat:** Hydrogen can be used to replace fossil fuels in a wide range of processes that require high temperature heat.

Source: Goldman Sachs Global Investment Research

The revival of hydrogen in the Age of Climate Change

An introduction to hydrogen, the element that could help unlock full de-carbonization potential and transform the de-carbonization cost curve

Hydrogen as a fuel screens attractively amongst other conventionally used fuels for its low weight (hydrogen is the lightest element) and high energy content per unit mass, >2.5x the energy content per unit mass of both natural gas and gasoline as shown in Exhibit 14, and is already readily produced (as 'grey' hydrogen) at a large industrial scale through a wide range of sources and routes. Hydrogen's role in the energy ecosystems is not new and has a long history in transport/industrial applications, used as a fuel since the 18th century to lift blimps and in the production of a number of key industrial chemicals relevant today such as ammonia. The IEA estimates that the demand for hydrogen in its pure form is around 70 Mtpa with the majority of this demand stemming from the oil refining industry (over 50% of H_2 pure form demand) and ammonia production for the fertilizers manufacturing industry (>40%). If combining demand for hydrogen in non-pure form, total demand exceeds 100 Mtpa (source: IRENA). Despite characteristics that make hydrogen uniquely attractive for energy applications (storage, fuel and feedstock), hydrogen in its ambient form is a highly reactive (i.e. combustible) gas with very low energy density (energy content per unit volume), meaning that it requires careful handling, transport and distribution as well as typically high pressure systems for its use in final applications.

Exhibit 14: Hydrogen has >2.5x the energy content per unit mass compared to natural gas and gasoline yet its very low weight implies a much lower energy density per unit volume in its gaseous form at ambient conditions

Fuel properties	Energy per unit mass (MJ/kg)	Density (kg/m3)	Energy density (MJ/L)	Specific energy - per unit mass (kWh/kg)	Energy density - per unit volume (kWh/L)	Physical conditions
Gasoline	46.4	737.1	34.20	12.89	9.5000	Ambient, 1 bar, 25 ”c
Natural gas (ambient)	53.6	0.7	0.04	14.89	0.0101	Ambient, 1 bar, 25 ”C
LNG	53.6	414.2	22.20	14.89	6.1667	Liquefaction temperature: -160 ”C
Hydrogen (ambient)	120.1	0.09	0.01	33.36	0.0028	Ambient, 1 bar, 25 ”C
Liquid hydrogen	120.1	70.8	8.49	33.36	2.3586	Liquefaction temperature: -253 ”C, 1 bar

Abbreviations: MJ = megajoules, m3 = cubic meters, L = litre, kWh= kiloWatt hour, kg= kilograms

Source: Company data, EIA, IEA, Goldman Sachs Global Investment Research

The revival of hydrogen: a new wave of support and policy action

While hydrogen has gone through several waves of interest in the past 50 years, none of these translated into sustainably rising investment and broader adoption in energy systems. Nonetheless, the recent focus on de-carbonization and the scale up and accelerated growth of low carbon technologies such as renewables have sparked a new wave of interest in the properties and the supply chain scale-up of hydrogen. Over the past few years, the intensified focus on de-carbonization and climate change solutions has begun to translate into renewed policy action aimed at the wider adoption of clean hydrogen (as outlined in Exhibit 15, initially in the transport sector through fuel cell electric vehicles (FCEVs) and more broadly in power generation energy storage systems). Policy support and economic considerations, with the acceleration of low cost renewables and electrification infrastructure, seem to be converging to create unprecedented momentum in the use of hydrogen and paving the way for potentially more rapid deployment and investment in hydrogen technologies and the required infrastructure.

Exhibit 15: A new wave of enthusiasm for hydrogen with numerous examples of new announcements, incentives and developments over the past two years

Region/country	Recent hydrogen initiatives
Europe	
EU	**European Comissions's** long-term published de-carbonization strategy which forms part of the **EU Green deal** includes the latest push of the region for wider adoption of low carbon technologies including hydrogen. The Comissions has also set up a **'Hydrogen Energy Network'**, an informal group of experts composed of representatives from the ministries in charge of energy policy in EU Member States, aiming to support national authorities to develop hydrogen technology opportunities. 28 countries have signed the delcaration on the '**Hydrogen Initiative**' which promotes cooperation on sustainable hydrogen technologies. **'Hydrogen Europe'** is a leading European association promoting the development of hydrogen as the enabler of net zero society. Currently, it has over 160 industrial members across Europe. Initiatives include the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), a public- private partnership with the Europen Comission that drives a funding stream of €1.33bn under the EU Horizon 2020 Program, with the aim of accelerating the market adoption of H2 technologies in energy and transport.
France	**French Government Hydrogen Deployment Plan:** The plan sets out the national strategy towards the integration of hydrogen into the country's energy mix, including specific short-term and long-term targets. Amongst those are the achievement of 10% de-carbonization through hydrogen by 2023, as well as, development of zero emissions solutions for road, rail etc., with the deployment on the horizon for 2023 of 5,000 light utility vehicles, 200 heavy vehicles (bus, trucks, trains (TER), boats) and 100 hydrogen stations to refuel vehicles with locally produced hydrogen. As part of the broader National Hydrogen Strategy announced in 2018, the French Government has committed €100 mn to research initiatives/projects targetted at decarbonizing the industrial sector, incorporating hydrogen into various transportation sectors and those focused on using hydrogen as a means of storage capacity for renewable energy.
Germany	**German Government National Innovation Programme for Hydrogen and Fuel Cell Technology (NIP2):** Federal funding program specifically allocated to projects that are involved in the research and development of hydrogen technologies at scale. The initial phase of the program (NIP) resulted in a combined investment from the Federal government and industry toalling c. €1.4 bn for ten years (2006-16). Under NIP 2 (2016-26), funds totalling €250mn were made available from the BMVI (the Federal Ministry of Transport and Digital Infrastructure) from 2017-19, with a further €481 mn budgeted for 2019-22. The program continues to support hydrogen technologies including subsidies for publicly accessible hydrogen refuelling stations, FCEVs, hydrogen-powered trains and the H2 mobility programme. Germany was the first country in Europe with the development of an integrated vision on the development of hydrogen refuelling infrastructure and the implementation of FCEV's: 'H2-Mobility Germany'.
Austria	In March 2019, the Austrian Federal Ministry for Sustainability and Tourism (BMNT), with the participation of the Federal Ministry of Transport, Infrastructure and Technology (BMVIT), had begun drafting a **nationwide hydrogen strategy**. The hydrogen strategy is now part of the 'Hydrogen Initiative' with the elaborated targets and measures to be included in the national climate and energy plan.
Netherlands	Hydrogen forms a key pillar of the **Dutch Climate Agreement** with a hydrogen development programme to be implemented to accommodate large-scale production and storage of renewable electricity with hydrogen technology. The ambition is to install an electrolysis capacity of 500 MW by 2025 and of 3-4 GW in 2030 and to develop a solid hydrogen infrastructure. The ambition also extends to mobility with 15,000 FCEVs and 3,000 heavy-duty trucks and 50 HRSs by 2025, and 300,000 FCEVs by 2030. The Dutch provinces of Groningen and Drenthe published the "Investment agenda hydrogen Noord-Nederland", in which €2.8 bn of planned investments in hydrogen projects will be undertaken by both government and the private sector, with the goal of achieving clean hydrogen production at scale by 2030 from what will be known as the Hydrogen Valley region in the North of the Netherlands. The plan aims to develop production installations of 100MW for green hydrogen and 1.2GW for blue hydrogen.
UK	The **UK Government has launched a £90 million package** announced to tackle emissions from homes and heavy industry – including funding for Europe's first large scale, low-carbon hydrogen plants which could generate enough clean energy to heat over 200,000 homes. £70 million will include funding for 2 of Europe's first large scale, low carbon hydrogen production plants (on the banks of the Mersey and near Aberdeen). Overall, the £70 million funding amount includes £28 mn for 5 demonstration phase projects from the 'Hydrogen Supply programme', £18.5 mn for the industrial fuel switching programme, £21 mn for UK Research and Innovation (UKRI) Local Smart Energy Projects, £3 mn for UKRI Key Technology Components for Local Energy Systems and £22 mn for UKRI Research funding. Amongst the 5 hydrogen projects that have been awarded funding to date are HyNet, HyPER, Acorn, Gigastack and the Dolphyn project.

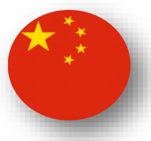
Asia-Pacific

Japan

Japan adopted a **"Basic Hydrogen Strategy"** in 2017 and in 2019 updated its Strategic Map for Hydrogen and Fuel Cells. This strategy primarily aims to achieve cost parity with competing fuels. To this end, the government began investing in R&D and the facilitation, including support for low-cost, zero-emission hydrogen production, an expansion of the hydrogen infrastructure for import and transport within Japan, and an increase of hydrogen use in various areas such as mobility, cogeneration of power and heat, as well as power generation. The Development Bank of Japan, has joined a consortium of companies, to launch the **Japan H2 Mobility** initative which guided by the Japanese Central Government's Ministerial Council on Renewable Energy, Hydrogen and Related Issues, plans the deployment of 400 hydrogen fuel stations over the next ten years with 80 to be operational by 2022.

Japan hosted the **Annual Hydrogen Ministerial Congress Meetings** bringing together representatives from around the world to promote the adoption of hydrogen technologies. At the end of the 2019 meeting, the Japanese Government announced it had recieved support from 30 countries for a plan to set up 10,000 hydrogen refuelling stations worldwide within 10 years.

China



Made in China 2025': The State Council in 2015 issued a 10-year plan aiming to improve the Chinese manufacturing industry. New Energy Vehicles and Equipment are one of the 10 priority sectors mentioned. Following this plan, in 2016 the Energy Saving and New Energy Vehicle Technology Roadmap was published, which includes a Technology Roadmap for Hydrogen Fuel Cell Vehicles. China's target for FCEVs deployment is to deploy one million by 2030 and >1000 stations, and 50,000 FCVs with >300 stations by 2025. China has also introduced state **subsidies on the purchase of New Energy Vehicles (NEVs).** The government had announced plans in 2015 to end the subsidies this year (2020), but said in March it would extend them to 2022. China has set a target for NEVs, which also include plug-in hybrids and hydrogen fuel cell vehicles, to account for more than a fifth of auto sales by 2025.

Regional initiatives:
- **Wuhan** Hydrogen Industry Development Plan, with Wuhan announcing plans to become the first Chinese Hydrogen City by 2025, with 3 to 5 world leading hydrogen enterprises and 30 to 100 hydrogen fueling stations. According to the plan, until 2020 (phase I) 20 HRS will be constructed in the city to support the 2,000 - 3,000 FC buses and commercial vehicles operating. By 2025 (Phase II) this will be increased to 30-100 HRS and the number of vehicles (buses, commercial and passenger cars) is expected to reach 10,000-30,000.
- **Shanghai** Fuell Cell Vehicle Development Plan was published in September 2017 and describes 3 development stages. The overall objective of the plan is to build an entire FCEVs value chain and promote FCEVs commercialization. The key targets of the develpment plan include: (1) Short term (2017-20): 3,000 FCEVs & 5-10 Hydrogen Fuel Stations (HRS), (2) Medium term (2021-25): 30,000 FCVs & 50 HRS and (3) Long-term (2026-30): FCEV value chain output of c. $45bn.

Australia

National Hydrogen Strategy was published in November 2019 outlining the vision for the development and scale up of the country's hydrogen ecosystem. The strategy aims to position Australia's hydrogen industry as a major global player by 2030 and identifies 57 joint actions in areas such as regulation, infrastructure, mobility and R&D.

Major funding announcements include:
(a) Australian Renewable Energy Agency (ARENA) funding round of AU$70mn for fast tracking of hydrogen developments in Australia, focusing primarily on the funding of projects that involve commercial scale deployments of electrolysers, aiming to be over 10 MW in scale.
(b) The Clean Energy Finance Corporation (CEFC) has welcomed the launch of the AU$300 million Advancing Hydrogen Fund, reflected in the Australian Government Clean Energy Finance Corporation Investment Mandate Direction 2020. The Mandate directs the CEFC to make available up to AU$300 million in CEFC finance to support the growth of a clean, innovative, safe and competitive Australian hydrogen industry.

South Korea

Published a **Hydrogen Economy Roadmap** in 2019 with 2022 and 2040 targets for buses, FCEVs and refuelling stations (targeting FCEV production capacity of 6.2 mn and deployment of 40,000 FC buses, 30,000 FC trucks and 1,200 HRSs by 2040). The country has also provided financial support for refuelling stations and reduced permitting restrictions.

North America

USA

H2@Scale initaitive: An initiaive from the Department of Energy (DOE), funding projects that do R&D into wide-scale H2 production and utilization in the US. Allocated $64mn to accelerate hydrogen projects. Focus areas for funding include:
(a) Electrolyzer Manufacturing R&D (up to $15mn)
(b) Advanced Carbon Fiber for Compressed Gas Storage Tanks (up to $15mn)
(c) Fuel Cell R&D and Domestic Manufacturing for Medium and Heavy Duty Transportation (up to $10mn)
(d) H2@Scale New Markets R&D – HySteel (up to $8mn)
(e) H2@Scale New Markets Demonstrations in Maritime and Data Centers (up to $14mn)
(f) Training and Workforce Development (up to $2mn)

California ameneded the Low Carbon Fuel Standard with more strict reduction in carbon intensity expected by 2030, incentivizing the development of refuelling stations and enabling CCUS operators to participating in generating credits from low-carbon hydrogen. California Fuel Cell Partnership outlined targets for 1,000 hydrogen refuelling stations and 1,000,000 FCEVs by 2030.

**** We highlight that the above list of hydrogen targetted initiatives is not exhaustive, and acknowledge that there are other national initatives around the globe currently underway***

Source: European Commission, French government, German government, Austrian Federal Ministry for Sustainability and Tourism (BMNT), Government of the Netherlands, UK Department for Business Energy & Industrial Strategy, Japan's Ministry of Economy Trade and Industry (METI), Japan's Ministerial Council on Renewable Energy Hydrogen and Related Issues, The State Council The People's Republic of China, Australian Government Department of Industry Science Energy and Resources, Australian Renewable Energy Agency (ARENA), Korea Ministry of Trade Industry and Energy, US Department of Energy (DOE), California Air Resources Board (CARB), California Fuel Cell Partnership, German Federal Ministry of Transport and Digital Infrastructure, Goldman Sachs Global Investment Research

‘Blue’ and ‘green’ hydrogen set the stage for de-carbonization

Clean hydrogen could be the key missing piece of the puzzle to reach net zero, connecting two critical components of the de-carbonization technological ecosystem: carbon sequestration and clean power generation

Hydrogen has a number of valuable attributes, two of which make it unique in the Age of Climate Change: (1) its ability to be stored and used as a clean fuel without direct emissions of GHG gases and/or air pollutants and (2) the wide variety of clean production pathways that could be adopted in its production, offering flexibility along supply chains.

There are three types of hydrogen, depending on route of production: grey, blue and green. ‘Grey’ hydrogen, the most carbon-intensive form, is based on hydrocarbon-feedstock & fuel processes, typically natural gas for steam-methane-reforming (SMR) or autothermal reforming (ATR), but also coal gasification.

The low-carbon intensity pathways for hydrogen production and what makes the fuel **uniquely positioned to benefit from two key technologies in the clean tech ecosystem - carbon capture and renewable power generation -** are ‘**blue**‘ and ‘**green**‘ hydrogen. ‘Blue’ hydrogen refers to the conventional natural gas-based hydrogen production process (SMR or ATR) coupled with carbon capture whilst ‘green’ hydrogen refers to the production of hydrogen from water electrolysis where electricity is sourced from zero carbon (renewable) energies.

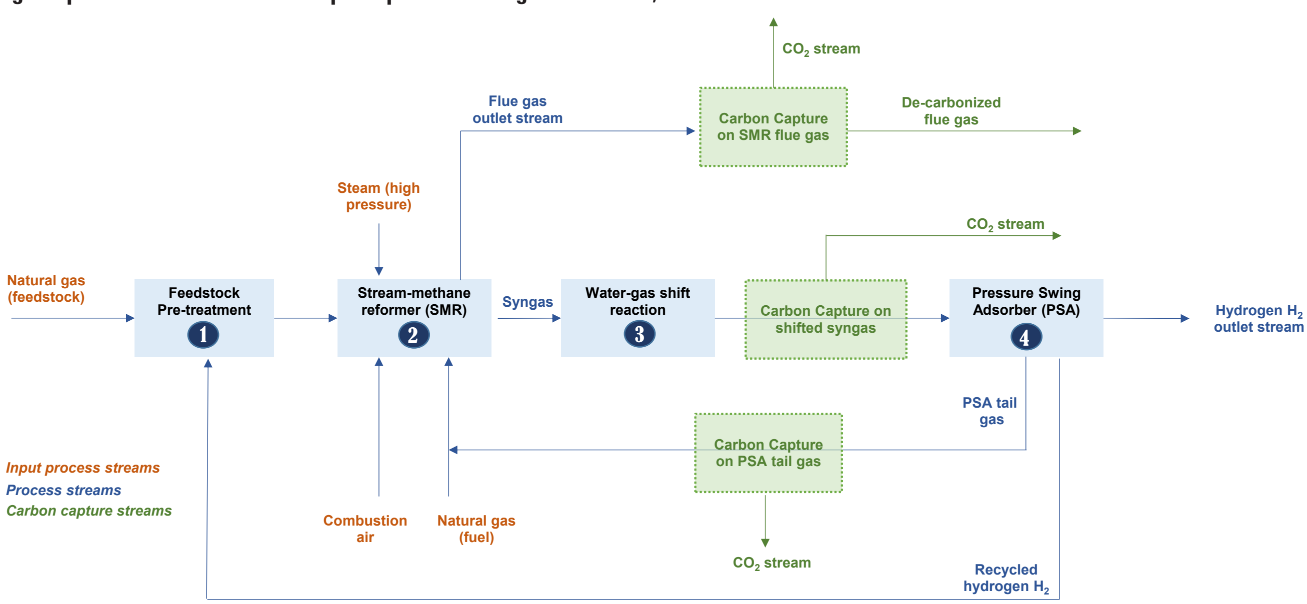
Today, over c.75% of hydrogen is produced from natural gas, with the rest mostly from coal. Less than c.2% of hydrogen production is currently produced via electrolysis, the least carbon intense hydrogen production pathway (according to the IEA). Production of hydrogen through low carbon electricity is not currently carried out on a large commercial scale and still shows a wide range of variability, including the capital expenditure requirements associated with electrolyzers, operating time, conversion efficiency and, most critically, the cost of electricity. In our view, this is a key area in the de-carbonization debate that calls for innovation and technological progress and that could potentially unlock the ‘green’ hydrogen scale-up opportunity. Similarly, carbon capture, utilization and storage technologies (CCUS), whilst developed at scale, have been largely under-invested over the past decade compared to other clean technologies and have not enjoyed the economies of scale that other technologies have, yet are critical in the low-carbon, low-cost transition to clean hydrogen.

(1) 'Blue' hydrogen and the critical role of sequestration in supporting the low carbon hydrogen transition in the medium term

'Blue' hydrogen refers to the production of hydrogen from **natural gas** through either steam-methane reforming (SMR) or through autothermal reforming (ATR) whereby emissions are captured through **carbon capture technologies (CCUS).** The production of 'blue' hydrogen for de-carbonization offers several advantages in the near to medium term as it utilizes the currently conventional, large-scale commercial hydrogen production pathways and infrastructure, with c. 75% of global hydrogen production globally relying on natural gas.

The most widespread method for hydrogen production is natural gas-based steam-methane reforming, which is a process that uses water (steam) as an oxidant and a source of hydrogen. Natural gas in SMR acts as both a fuel (c.30-45% of it is combusted to fuel the process giving rise to a diluted CO_2 stream) and a feedstock. The typical steps of the process involve: (1) feedstock pre-treatment unit (desulfurization) where sulphur and chlorine is removed from the natural gas feedstock; (2) the stream subsequently enters the steam-methane reformer unit where natural gas is combined with pressurized steam to produce syngas (blend of carbon monoxide and hydrogen); (3) the syngas outlet stream, mostly consisting of carbon monoxide and hydrogen, undergoes a 'water-gas shift' reaction where carbon monoxide and water are reacted using a catalyst to produce carbon dioxide and more hydrogen; and (4) the final process step removes carbon dioxide and other impurities from the hydrogen stream, increasing its purity in what is referred to as a 'pressure-swing adsorption' (PSA).

Exhibit 16: Schematic diagram presenting the steps of a typical 'blue' hydrogen production process combining SMR with carbon capture (diagram presents several carbon capture potential integration routes)

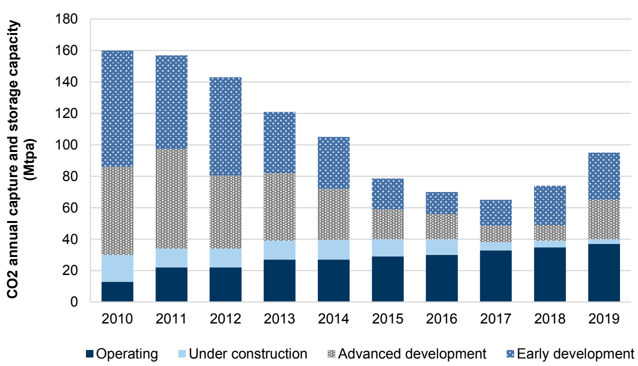


Source: Company data, IEA GHG, Goldman Sachs Global Investment Research

An alternative process to SMR is a partial oxidation process (using oxygen as the oxidant), yet more typically a combination of both process is used - known as autothermal reforming (ATR). Adopting CCUS technologies to SMR and ATR plants for hydrogen production **can result in c.90% reduction in carbon emissions** on aggregate according to industry studies. The schematic of a typical SMR process with CCUS is shown in Exhibit 16, which indicates the three potential carbon capture locations (SMR flue gas, shifted syngas and PSA tail gas) with the SMR flue gas being the stream with the highest CO_2 concentration and highest carbon capture potential.

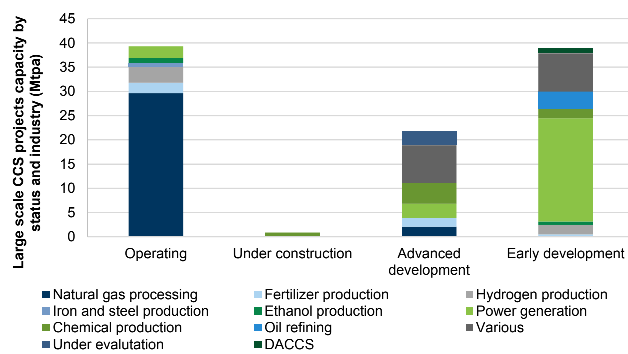
The scale-up of 'blue' hydrogen is solely reliant on the wider adoption and integration of carbon capture, utilization and storage technologies, which resembles the incremental cost for the production of 'blue' hydrogen vs 'grey'. As we have highlighted in our deep-dive de-carbonization report Carbonomics, sequestration is likely to play a vital role in aiding de-carbonization efforts, particularly in harder-to-abate sectors and in achieving net zero anthropogenic (i.e. related to human activities) emissions. Currently, there are 20 large-scale CCS facilities operating globally (mostly in the US, Canada and Norway) with a total capacity exceeding 35 Mtpa. Notably, over recent years, more projects in the development stage are focusing on industries with lower CO_2 stream concentrations such as industrial plants and coal & gas power generation plants.

Exhibit 17: The pipeline of large-scale CCS facilities is regaining momentum after a 'lost decade' of underinvestment...
Annual CO2 capture & storage capacity from large-scale CCS facilities



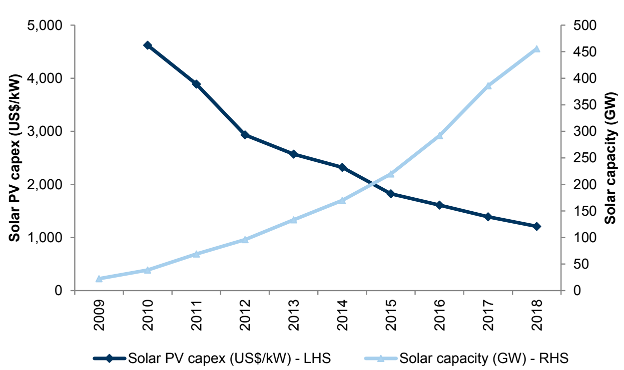
Source: Global CCS Institute Status Report 2019

Exhibit 18: ...as more projects in the development stage start to focus on industries with lower CO2 stream concentrations (such as industrial & power generation)
Large-scale CCS projects by status and industry of capture (Mtpa, 2019)



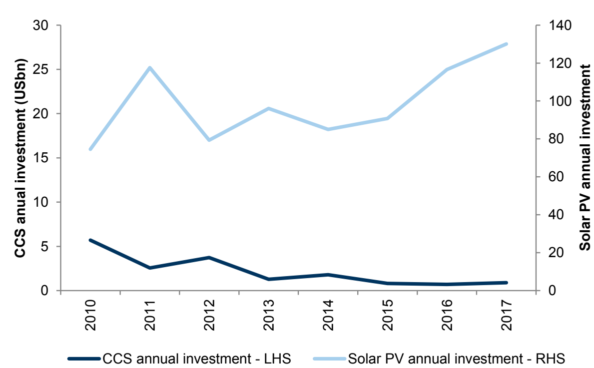
Source: Global CCS Institute, Goldman Sachs Global Investment Research

Exhibit 19: Solar PV cost has fallen 70%+ over the last decade as cumulative solar capacity has increased exponentially...
Solar PV capex ($/kW) vs global cumulative solar PV capacity (GW)



Source: Company data, IRENA, Goldman Sachs Global Investment Research

Exhibit 20: ...while languishing investment in CCS sequestration technologies has possibly prevented a similar cost improvement
Annual investment in solar PV (LHS) and large-scale CCS

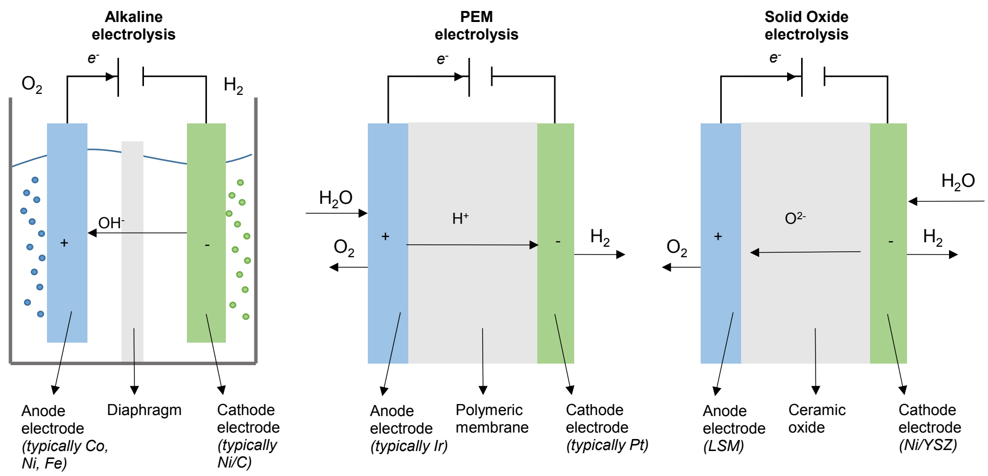


Source: Company data, IRENA, Goldman Sachs Global Investment Research

2) 'Green' hydrogen: the ultimate de-carbonization tool with a large longer-term potential

'Green' hydrogen is typically produced via water electrolysis, an electrochemical process in which water is split into hydrogen and oxygen. Dedicated 'green' hydrogen production electrolysis remains a very niche part of the global hydrogen production, yet with renewable energy sourced electricity costs on a persisting downwards trajectory (solar PV, onshore and offshore wind), focus and interest are growing. The key underlying technology for green hydrogen production is the electrolyzer, and there are three distinct types: **alkaline** electrolysis, **proton exchange membrane** electrolysis (PEM) and **solid oxide electrolysis cells** (SOECs).

Exhibit 21: Simplified schematic of the three electrolysis technologies for the production of 'green' hydrogen



	Alkaline	PEM	Solid Oxide
Anode	$4OH^- \leftrightarrow 2H_2O + 4e^- + O_2$	$2H_2O \leftrightarrow 4H^+ + O_2 + 4e^-$	$O^{2-} \leftrightarrow 1/2O_2 + 2e^-$
Cathode	$4H_2O + 4e^- \leftrightarrow 4OH^- + 2H_2$	$4H^+ + 4e^- \leftrightarrow 2H_2$	$H_2O + 2e^- \leftrightarrow H_2 + O^{2-}$

	Alkaline electrolyzer	PEM electrolyzer	SOEC electrolyzer
Capex (US$/kWe)	500-1350	900-1750	>2300
Electrical efficiency	55-70%	50-65%	>70%
Operating temperature (”C)	60-80	50-80	500-1000
Opearing pressure (bar)	<30	30 to 80	c. 1

Source: The Fuel Cells and Hydrogen Joint Undertaking (FCH JU), Company data, IEA, Goldman Sachs Global Investment Research

The most widely adopted and mature technology is **alkaline electrolysis,** characterized by relatively low electrolyzer capital cost (less expensive/fewer precious metals typically used compared to other electrolysis technologies) and relatively high efficiencies - typically varying from 55% to 70%. The reaction occurs in a solution comprised of water and the liquid electrolyte (typically potassium hydroxide) between two electrodes. When sufficient voltage is applied between the electrodes, the oppositely charged ions (OH^- and H+) are attracted to the oppositely charged electrodes. The anode accumulates water (through the combination of OH^- ions) whilst the cathode gives hydrogen.

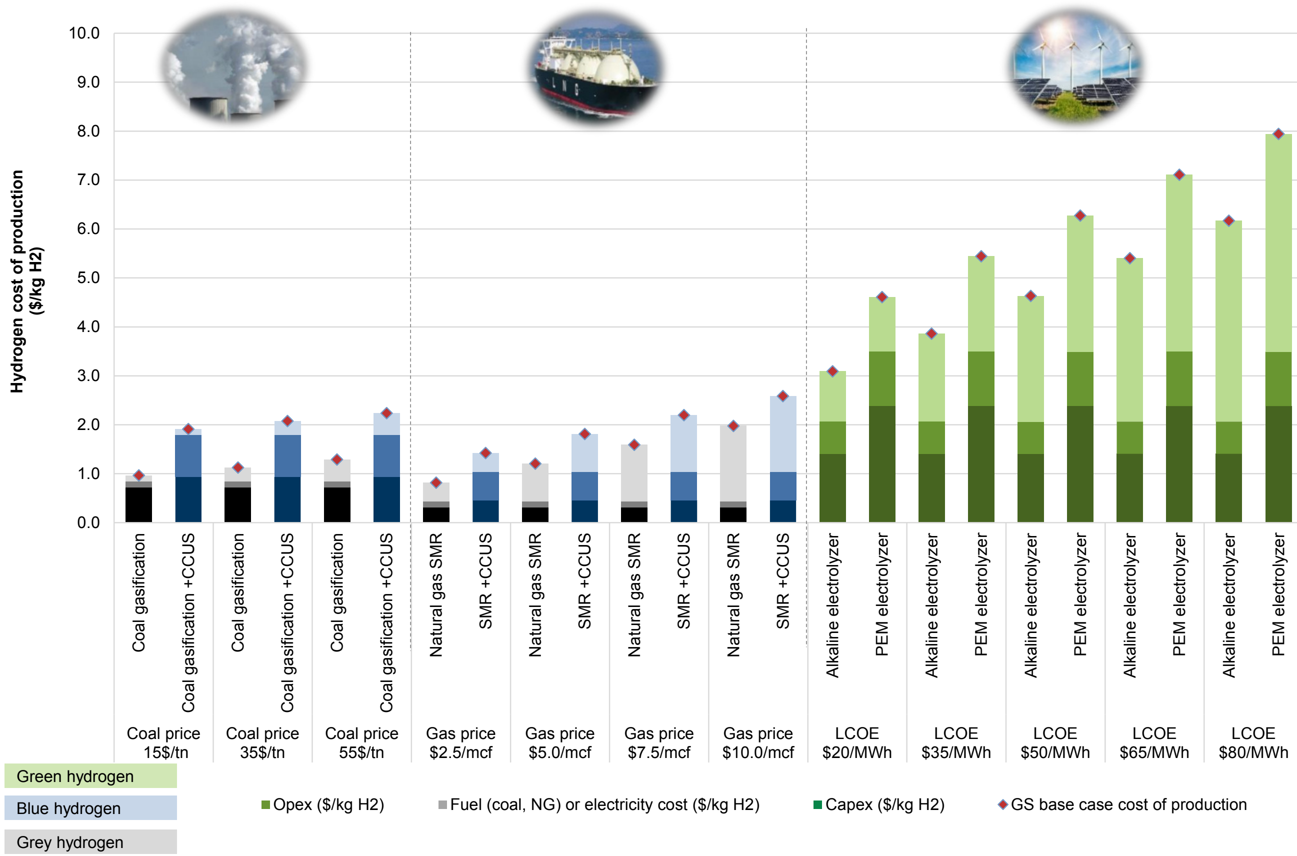
PEM electrolysis is based on the principle of using pure water as the electrolyte solution and therefore overcomes some of the issues associated with hydroxide solutions (used for alkaline electrolysis) while also being more compact in size, operating at higher pressures and therefore having the ability to provide highly pressurized hydrogen. The process involves the use of a conductive solid polymer membrane. When voltage is applied between the two electrodes, oxygen in the water molecules creates protons, electrons and O_2 at the anode while the positively charged hydrogen ions travel through the proton conducting polymer towards the cathode where they combine to form hydrogen (H_2). The electrolyte and two electrodes are sandwiched between two bipolar plates whose role is to transport water to the plates, transport product gases away from the cell, conduct electricity and circulate a coolant fluid to cool down the process. Despite the production benefits over traditional alkaline electrolysis (outlined above), they typically require the use of expensive electrode catalyst materials (such as platinum and iridium) and membrane materials, resulting in overall higher costs and as such have seen less widespread adoption compared to alkaline electrolyzers.

The third type of electrolysis technology is **SOECs**, a technology that to date is much less widely adopted and has not reached large scale commercialization. Principally, this uses ceramics as the electrolyte and operates at very high temperatures (>500°C) under which it can potentially reach efficiencies >70%. Our cost of production analysis that follows focuses on the two primary types of electrolysis (alkaline and PEM) that are most widely adopted and developed at commercial scale.

Our cost of production analysis leads us to believe that 'blue' will likely be the primary pathway in the near to medium term until 'green' reaches cost parity

Whilst 'blue' and 'green' hydrogen are the lowest carbon intensity hydrogen production pathways, both of these technologies are more costly when compared to the traditional hydrocarbon-based 'grey' hydrogen production based on our hydrogen cost of production analysis, as shown in Exhibit 22. For 'blue' hydrogen, the cost of production is dependent on a number of technological and economics factors, the price of natural gas being the most critical one followed by the additional cost for carbon capture technology integration with the SMR plant. On our estimates, the cost of production of 'blue' hydrogen from natural gas SMR is c. \$0.6/kg H_2, higher than traditional SMR without carbon capture. For 'green' hydrogen, the cost of production is primarily related to the capex of the electrolyzer, the electrolyzer's conversion efficiency, load hours and, most importantly, the cost of electricity, which makes up c. 30-65% of the total cost of production depending on the levelized cost of electricity (LCOE).

Exhibit 22: 'Blue' and 'green' hydrogen set the stage for de-carbonization with 'blue' currently having a lower cost of production compared to 'green' hydrogen, yet both more costly than traditional 'grey' hydrogen - thus there is a need for technological innovation and investment for both carbon capture and electrolyzer technologies

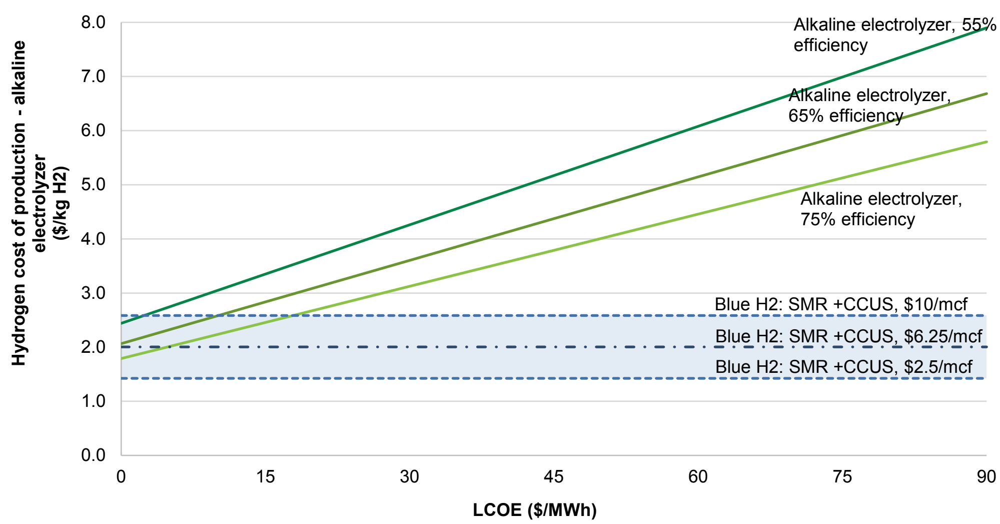


Source: Company data, Goldman Sachs Global Investment Research

Overall, we estimate the **cost of production** of **green hydrogen can be 1.3-5.5x that of blue hydrogen** depending on the price of natural gas and the LCOE. This leads us to conclude that **both 'blue' and 'green' hydrogen will form key pillars of the low carbon transition**, but with **'blue' facilitating the near- and medium-term transition** until **'green' reaches cost parity longer term**. In Exhibit 23 we show our estimates of the hydrogen cost of production (using the simplest, lower cost and most widely adopted alkaline electrolysis route) for different costs of electricity (LCOE) and for different electrolyzer efficiencies. Overall, this implies that the cost of electricity required for 'green' hydrogen to come into cost parity with high-cost 'blue' hydrogen needs to be on the order of 5-25$/MWh LCOE assuming that the electrolyzer and carbon capture technologies capital costs remain at the current level (only electricity cost varies along the 'green' hydrogen lines and natural gas cost varies along 'blue' hydrogen lines).

Exhibit 23: A LCOE of 5-25$/MWh is required for 'green' hydrogen to be in cost parity with the high-cost 'blue' hydrogen scenario for an alkaline electrolyzer efficiency of 55-75% (assuming electrolyzer capex and cost of carbon capture remain at current levels)

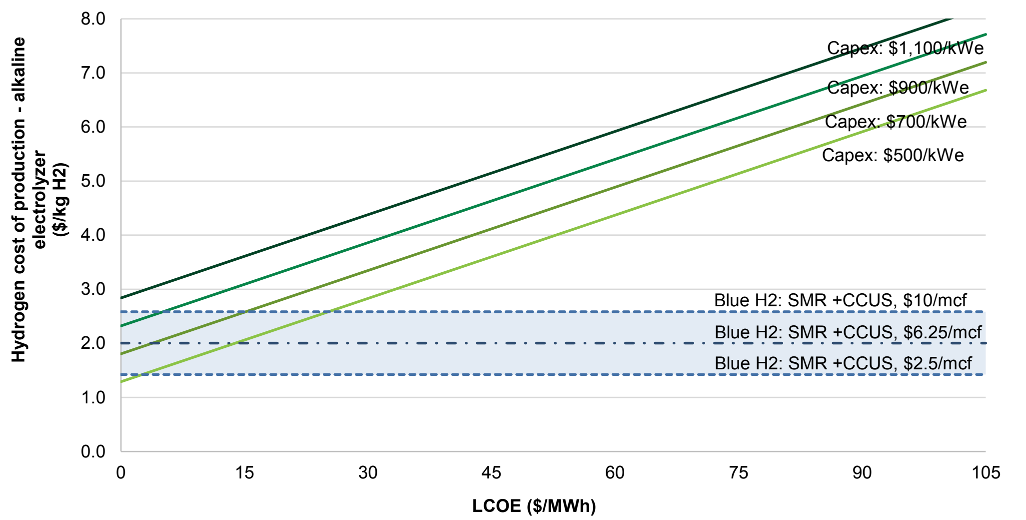
Hydrogen cost of production ($/kg H2) vs LCOE ($/MWh)



Source: Goldman Sachs Global Investment Research

Exhibit 24: The cost of the electrolyer also impacts the overall cost of producing 'green' hydrogen, with a LCOE of <$30/MWh required for electrolyzers with a capex exceeding $500/kWe to reach cost parity with high cost 'blue' hydrogen

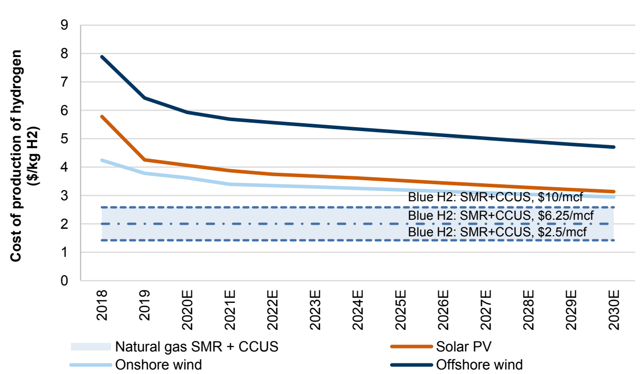
Hydrogen cost of production ($/kg H2) vs LCOE ($/MWh)



Source: Goldman Sachs Global Investment Research

Exhibit 25: The global average LCOE for renewables implies that onshore wind and low cost solar PV could reach cost parity with high cost 'blue' hydrogen ($10/mcf gas price) by 2030E, accompanied by a reduction in electrolyzer costs...

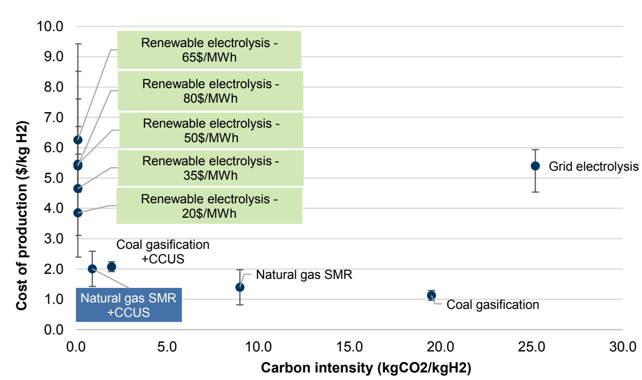
LCOH ($/kg H2) implied in the cost of production for hydrogen through time



Source: IRENA, Goldman Sachs Global Investment Research

Exhibit 26: ...with both 'green' and 'blue' hydrogen setting the stage for the de-carbonization debate, having a carbon intensity that is c.90-100% lower than traditional 'grey' hydrogen

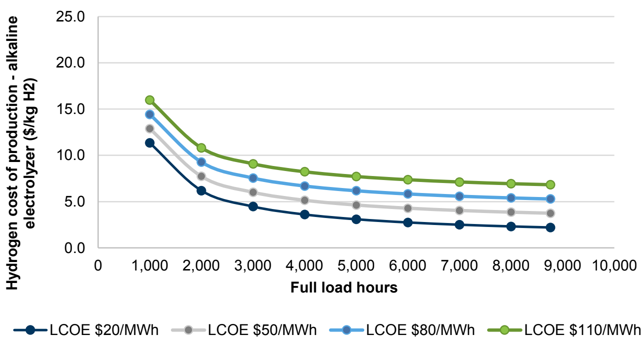
Cost of production of hydrogen ($/kg H2) vs carbon intensity for different technologies (kg CO2/kg H2)



Source: Goldman Sachs Global Investment Research

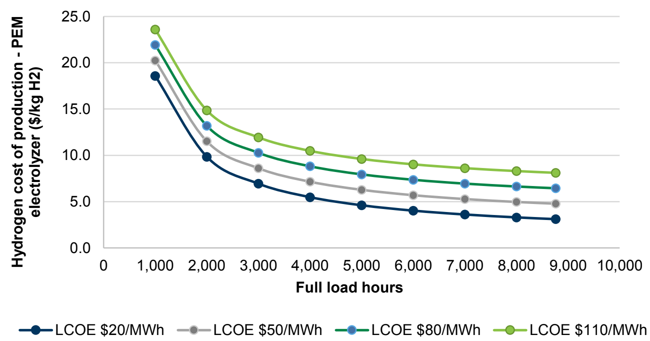
Apart from the electrolyzer efficiency and the cost of electricity (LCOE), the full load hours of operation of the electrolyzer can also have a notable impact on the overall cost of producing hydrogen. Exhibit 27 and Exhibit 28 show estimated variation in the cost of production of hydrogen with the full load hours for an alkaline and a PEM electrolyzer, respectively. The charts indicate that for full load hours >5,000 (representing 57% of total annual hours working at full capacity), the cost of production curve flattens and the cost of production is no longer materially impacted by the full load hours. On the other hand, the cost of production shows a linear correlation with electrolyzer capex for both alkaline and PEM electrolyzers, as shown in Exhibit 29 and Exhibit 30. It is worth noting that the implied cost per electroyzer has the potential to reduce when using larger multi-stack systems which involve combining several electrolyzer stacks together, therefore increasing the system's overall capacity and reducing the capex portion of the cost. This, along with technological innovation and economies of scale, is one of the key potential areas of cost reduction.

Exhibit 27: The full load hours of the electrolyzer can have a notable impact on the cost of production if <5,000, but cost of production becomes flatter after that for alkaline electrolyzers...
Hydrogen cost of production vs alkaline electrolyzer full load hours



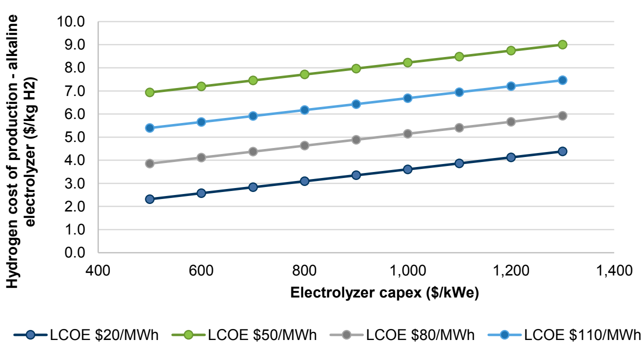
Source: Goldman Sachs Global Investment Research

Exhibit 28: ...with a similar trend observed for the PEM electrolyzers
Hydrogen cost of production vs PEM electrolyzer full load hours



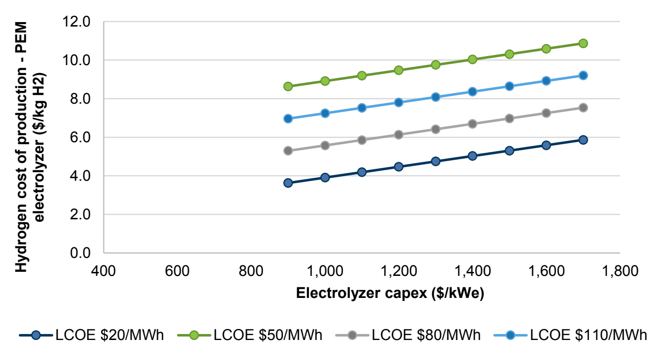
Source: Goldman Sachs Global Investment Research

Exhibit 29: The cost of production of 'green' hydrogen shows a linear correlation with electrolyzer capex for alkaline systems...
Hydrogen cost of production vs alkaline electrolyzer capex ($/kg H2)



Source: Goldman Sachs Global Investment Research

Exhibit 30: ...and a similar trend is observed in more costly PEM electrolyzers
Hydrogen cost of production vs PEM electrolyzer capex ($/kg H2)



Source: Goldman Sachs Global Investment Research

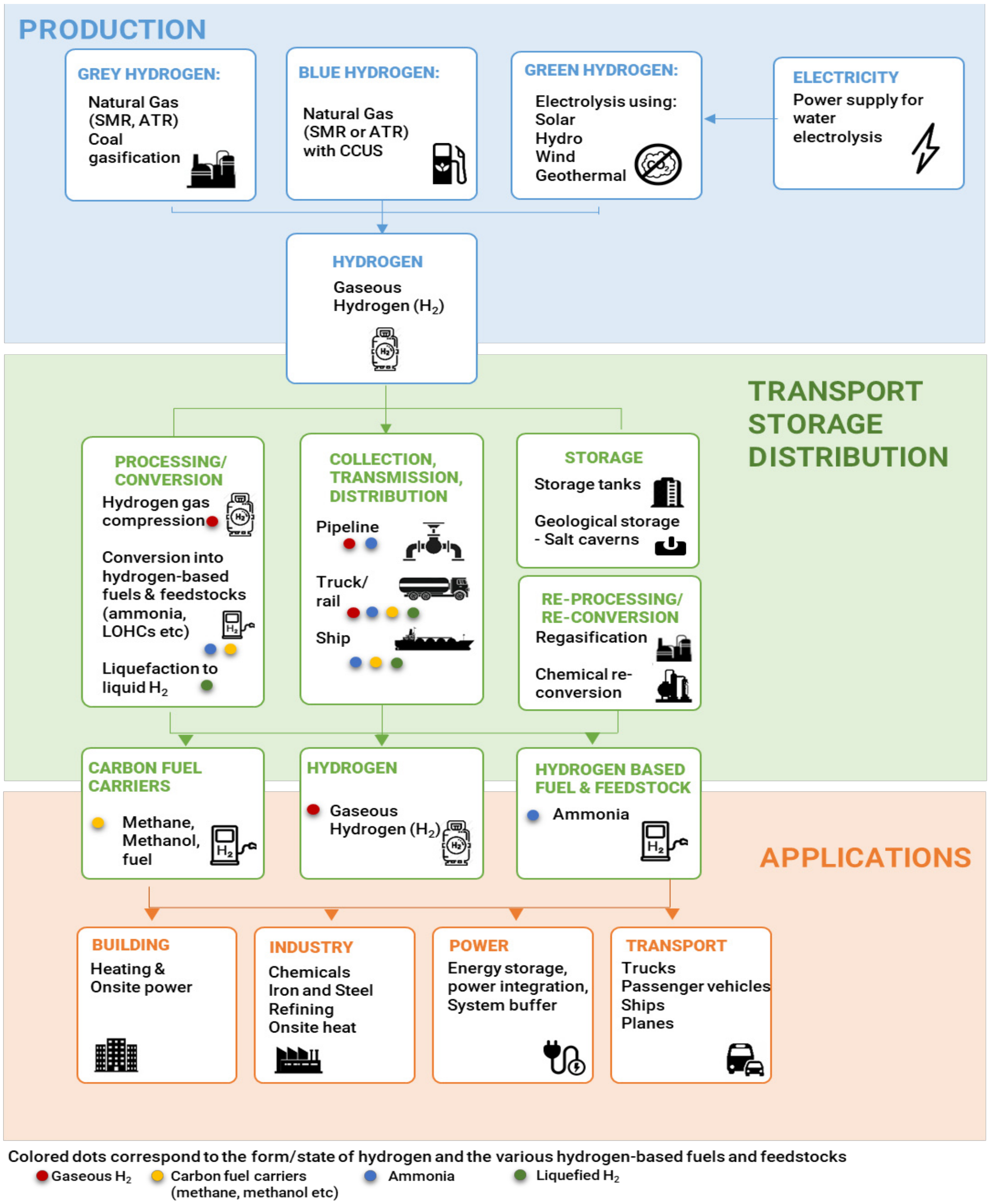
The hydrogen supply chain: Transport, storage and distribution the key technological and infrastructure challenges

Safe and cost-efficient transport, storage and distribution of hydrogen will be critical in setting the pace of its large-scale deployment. The low energy density of the fuel under ambient conditions, its high diffusivity in some materials including types of steel and iron pipes, and its highly flammable nature present important technological and infrastructure challenges to its large-scale adoption in transport and heating. We therefore view that its **initial acceleration and use is likely to be more locally concentrated (hydrogen hubs)** whilst the large-scale globally integrated value chain is likely to be more challenging to develop and take longer to materialize.

- **Storage**: Hydrogen is at present primarily stored in a gaseous or liquid form in storage tanks. Compressed hydrogen has less than one-fifth of the energy density of gasoline and therefore storing the equivalent energy amount requires multiple times the space (presenting a challenge for storage in refueling stations). Ammonia offers a liquid alternative for hydrogen storage (ammonia is formed from hydrogen combined with nitrogen through a reversible reaction), yet energy losses during conversion and re-conversion add to costs and reduce overall energy efficiency. The need for large-scale storage solutions that enable longer-term storage is increasingly important for hydrogen to become more widely employed, including storage in refueling stations, export terminals and energy storage in power generation. Geological storage such as salt caverns, depleted oil & gas fields and aquifers could be potential longer-term hydrogen storage options.
- **Long-distance transmission:** Transporting hydrogen fuel over longer distances typically occurs in four distinct forms: hydrogen, ammonia, liquid organic hydrogen carriers (LOHCs such as toluene) and liquefied hydrogen. The existing natural gas pipeline system infrastructure could be used to transport hydrogen locally or domestically, particularly when the pipe material is polyethylene. Alternatively, hydrogen blending at small portions (typically <10% of volume for most regions) is in use today, albeit the upper limit is constrained by the equipment connected to the grid and needs to be assessed on a case-by-case basis. Shipping could form a potential solution longer term, yet given the very low liquefaction point of hydrogen (-250°C), technological innovation is necessary to enhance the feasibility and economics. Ammonia and LOHCs (such as toluene) for hydrogen transport by ship are preferred options to be considered in that aspect, as per industry players, as they do not require cryogenic conditions for liquedaction or handling and are some of the commonly used methods for long-distance transport today.
- **Local distribution:** Pipelines are commonly used for local distribution of hydrogen. The distinct properties of hydrogen however require low-pressure distribution pipes made from polyethylene or fibre-reinforced polymers. Hydrogen blending in the existing gas infrastructure is currently being tested in several countries globally, even beyond the current upper threshold of 5-6%. New dedicated distribution pipelines are likely to be a material infrastructure challenge. Trucks carrying compressed hydrogen are also currently used as a local distribution solution for shorter distances

(both in compressed gaseous form and liquefied form in cryogenic tankers).

Exhibit 31: Schematic summary of hydrogen supply chain

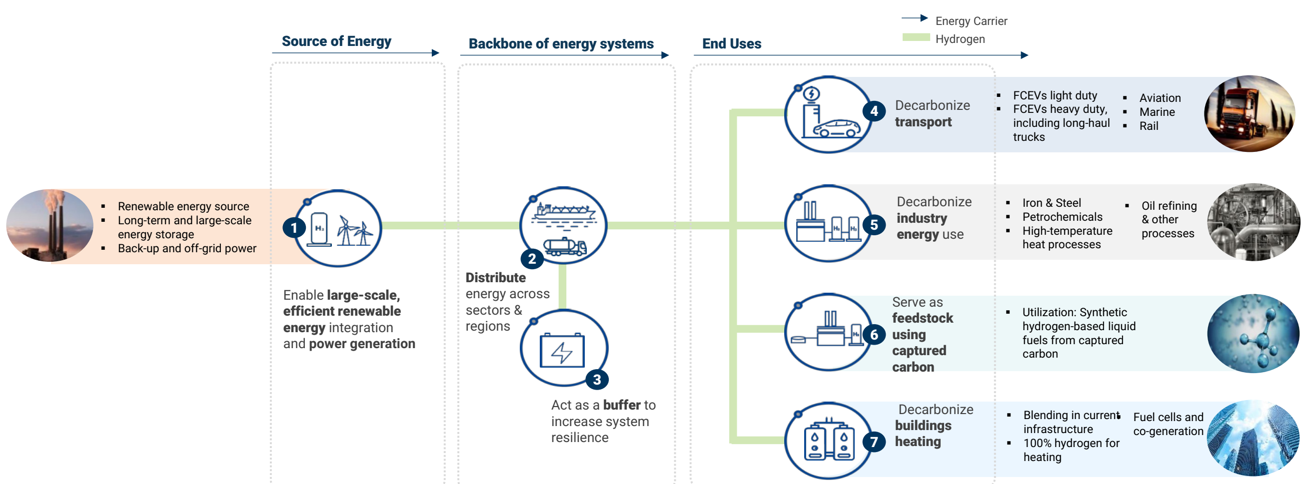


Source: Goldman Sachs Global Investment Research

A major opportunity for hydrogen in applications spanning most of the 'harder-to-abate' sector-related emissions

Hydrogen has a complex value chain, with several challenges related to transport and storage that need to be overcomed for its wide scale adoption. That said, the **upside towards achieving net zero could be material, on our estimates unlocking more than half of the c.25% non-abatable emissions <US$1,000/ton carbon pricing given its versatility to** serve as a clean energy fuel alternative for industrial applications, an energy storage solution for long-haul transport (fuel cell electric vehicles, aviation, shipping) and for heating and seasonal variations in power demand, allowing higher penetration of renewables. Potential de-carbonization opportunities that could be unlocked through development of hydrogen technologies and the supply chain are outlined in Exhibit 32.

Exhibit 32: Hydrogen could have a critical role in aiding de-carbonization longer term across a wide variety of sectors, including long-haul transport, industry, energy storage in power generation and heating in buildings

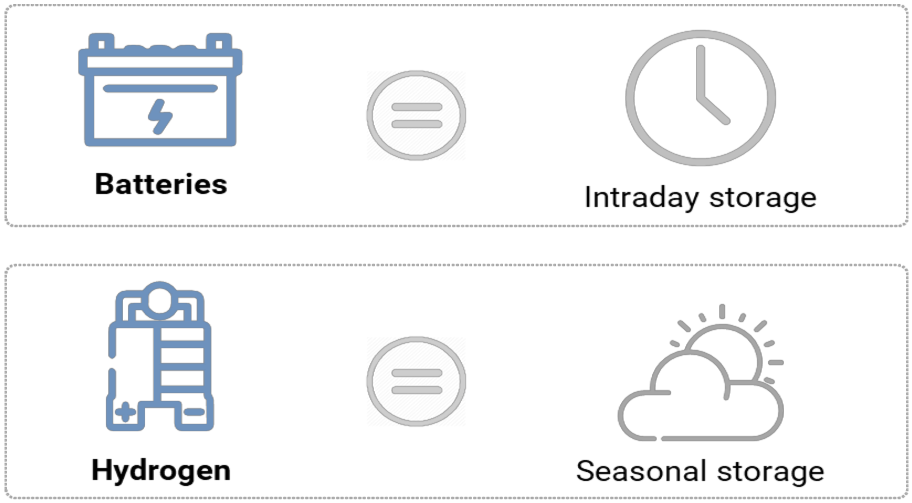


Source: Hydrogen Council, Goldman Sachs Global Investment Research

1) Power generation: The key to solving the energy seasonal storage challenge

To reach full de-carbonization of power markets, we believe both batteries and hydrogen will play a larger and complementary role to address different challenges. While batteries are currently the most developed technology for intraday power generation storage, we consider it mostly irrelevant for seasonal storage and see hydrogen as a potential candidate to address this challenge.

Exhibit 33: We expect batteries to be used for intraday power generation storage and hydrogen for seasonal storage

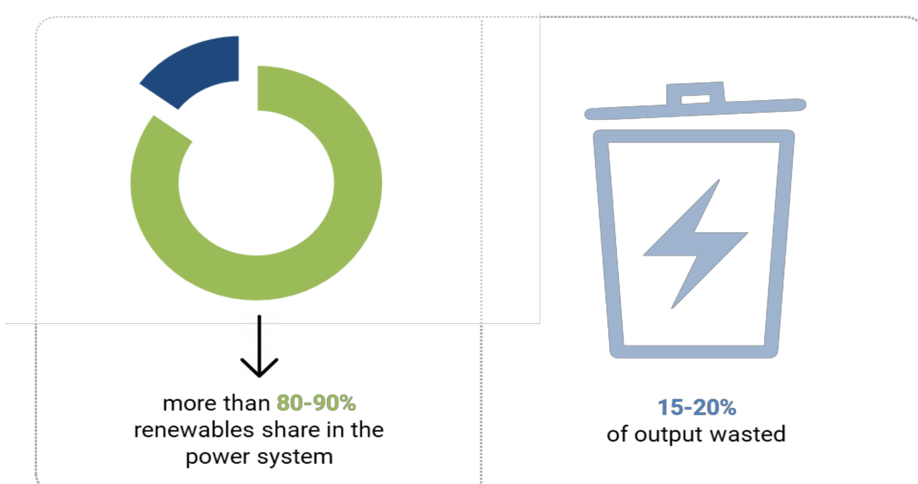


Source: Goldman Sachs Global Investment Research

RES could potentially satisfy up to 90% of power demand

According to our analysis, power systems can rely on renewable supplies up until about 90%. We believe power systems are unlikely to increase the share of renewables further given: (1) although the correlation between parks significantly drops as the distance exceeds 200km, and despite the complementarity between offshore wind and solar PV production hours, the intermittency/unpredictability would still imply hours without reliable security of supply; and (2) beyond a 90% share, curtailment – the output from RES sources which is wasted as it is produced during hours with insufficient demand – could reach 15%-20%; this would begin to become very costly for the system.

Exhibit 34: Beyond 90% renewables share in the power system, curtailment (wasted output) could reach 15%-20%, we estimate



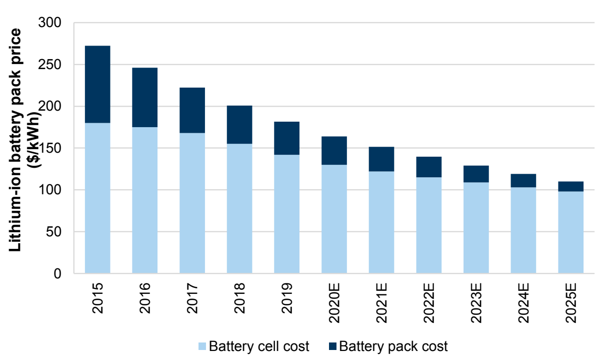
Source: Goldman Sachs Global Investment Research

In order to achieve 100% carbon-free power generation, there is need for energy storage technological breakthroughs. We view that both batteries and hydrogen can have a role to play when it comes to energy storage and we expect the deployment of batteries to primarily focus on intraday storage, while hydrogen could potentially satisfy the need for seasonal storage.

1) Solving the energy storage challenge: The growing role of battery technology

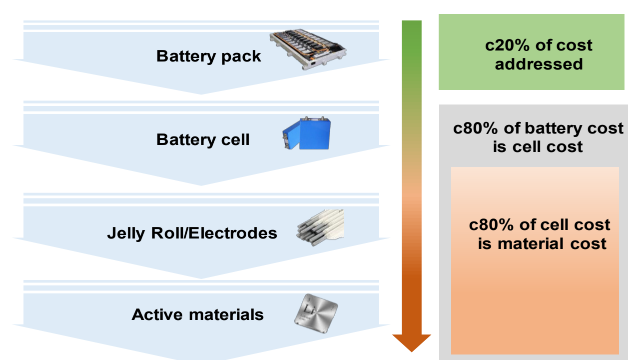
Battery technology and its evolution plays a key role in aiding de-carbonization of both transport and power generation. The high focus on electric batteries over the past decade has helped to reduce battery costs by over c.50% the past five years alone owing to the rapid scale-up of battery manufacturing for passenger electric vehicles (EVs), and with lithium-ion batteries continuing to be the most widely used type. Nonetheless, the technology is currently not readily available at large, commercial scale for long-haul transport trucks, shipping and aviation or for long-term battery storage for renewable energy. Notably, the majority of the reduction in battery cost emissions has come from the battery pack, yet c.80% of the remaining cost is dominated by the battery cell where cost reduction requires further technological innovation.

Exhibit 35: Lithium-ion battery pack costs have fallen materially over the past few years, primarily from battery pack cost reductions...
Lithium-ion battery pack and cell price (US$/kWh, LHS)



Source: Goldman Sachs Global Investment Research

Exhibit 36: ...with the remaining cost reductions required to come from the cell
Battery pack and cell cost breakdown

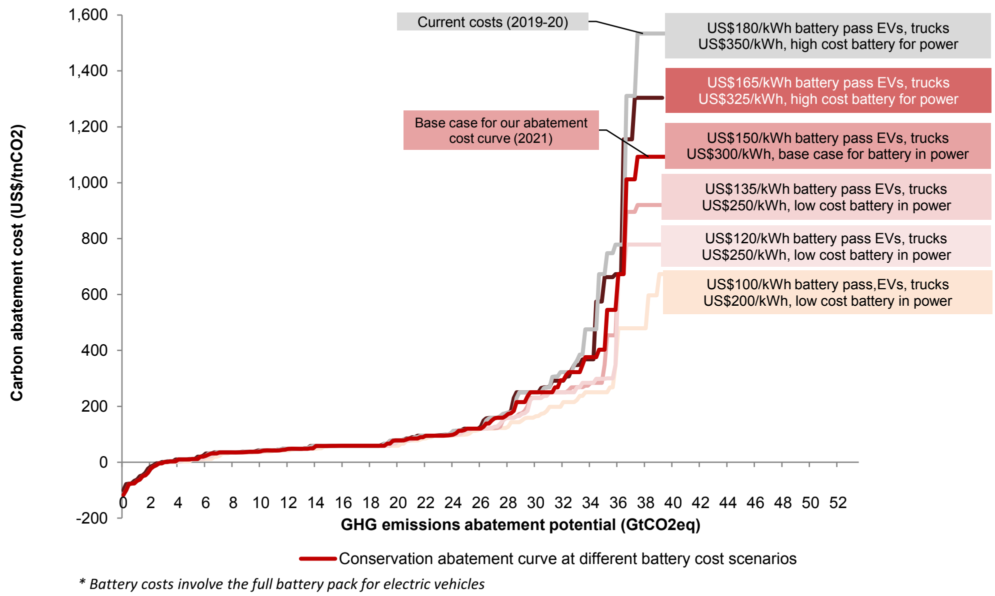


Source: BMW Company data, Goldman Sachs Global Investment Research

Batteries are particularly suited in sunny climates (e.g. Southern Spain/Italy, California, Middle East) where solar PV production is largely stable throughout the year and can be stored for evening usage of up to 4-6 hours. In contrast to strong projections by many industry consultants, we do not see batteries fully bridging the gap to net zero in power generation. Our analysis assumes c.80GW of storage by 2050 (well below BNEF estimates), or c.5% of the RES installed base by then, in Europe.

In Exhibit 37, we analyze the case for different battery cost scenarios (full battery pack cost) for electric vehicles, including trucks, and for energy storage in power generation. This shows a high sensitivity of the shape of the cost curve to battery costs, which suggests the battery technology has the potential to transform the higher end of the de-carbonization cost spectrum, which is dominated by transport. Lower battery costs for passenger EVs, both rural and urban, as well as trucks can have a notable impact in reducing the overall cost of de-carbonization. However, in our view battery technology in its current construct remains unlikely to offer a solution to the de-carbonization of aviation, shipping and seasonal variations of power demand, providing hydrogen with a key role to play in these areas.

Exhibit 37: A potential breakthrough in battery technology and associated costs could help transform the current de-carbonization cost curve through lower costs in transport and power generation
Conservation carbon abatement cost curve for anthropogenic GHG emissions for different battery cost scenarios in passenger transport and power generation

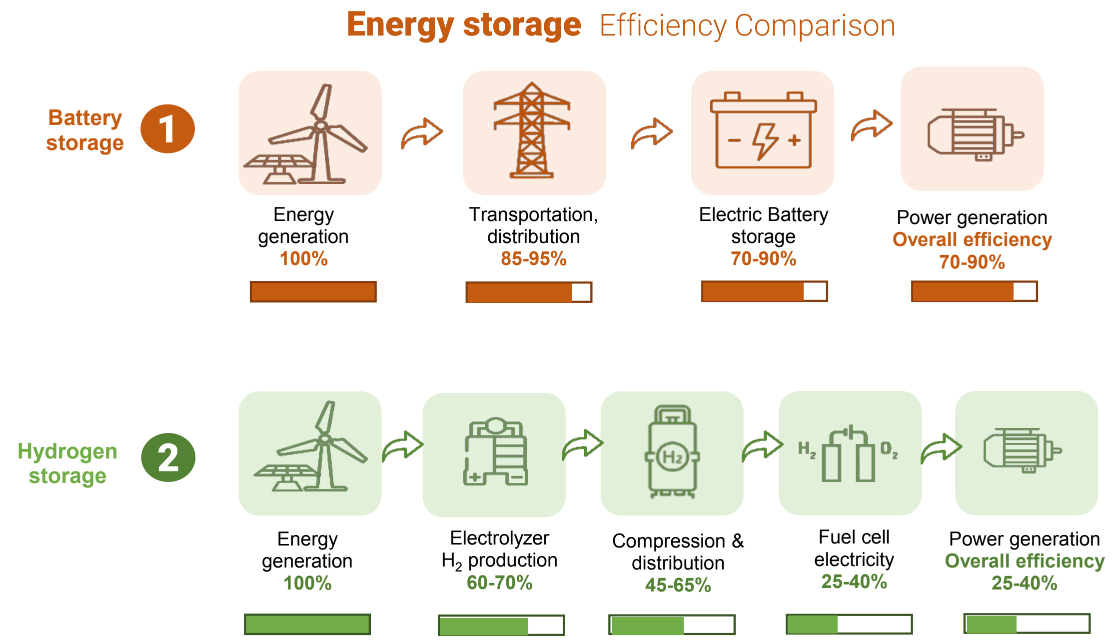


Source: Goldman Sachs Global Investment Research

2) Solving the energy storage challenge: The potential opportunity for hydrogen in seasonal storage

Hydrogen could potentially be used for energy storage and flexible power generation. The process involves storing 'green' hydrogen and reconverting it back to power through the use of fuel cells to offset the seasonal mismatch between power demand and renewable output. Fuel cells have efficiencies that typically vary in the range of 50-60%. This is in general a weak point for hydrogen-based storage options as they suffer from a low life-cycle energy efficiency. The overall energy efficiency for hydrogen used for local distribution and onsite use lies in the range of 25-40% based on our analysis when compared to battery electrical storage of c.70-90%.

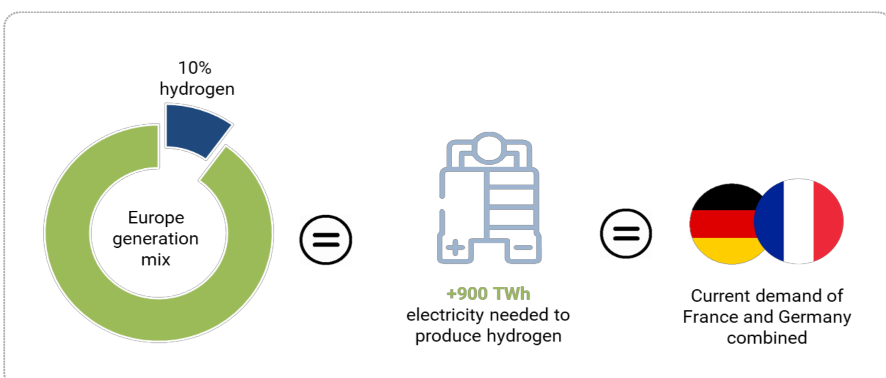
Exhibit 38: While hydrogen could be the key to solving the seasonal storage challenge in power generation, the overall energy efficiency remains the weak spot of hydrogen, c.25-40% compared to c. 70-90% for batteries



Source: Company data, Goldman Sachs Global Investment Research

If Europe were to meet 10% of its power needs from hydrogen/fuel cells in the long term, global hydrogen demand could rise by 25%-30% we estimate, while fully de-carbonizing the production of this hydrogen would imply about 900TWh of incremental electricity demand, equivalent to the current demand of France and Germany combined.

Exhibit 39: If 10% of Europe power needs were met with hydrogen, we estimate this could require about 900TWh of additional electricity, equivalent to the current demand of France and Germany combined.



Source: Goldman Sachs Global Investment Research

2) Transport: A unique opportunity for de-carbonization of long-haul transport

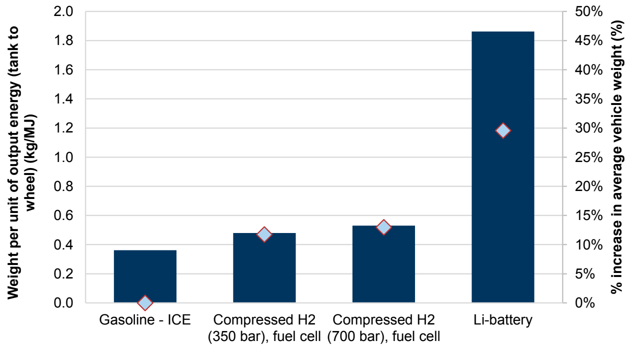
Hydrogen's key attributes (low weight and high energy per unit mass, short refueling time, zero direct emissions when sourced from renewable energy sources) make it an attractive candidate as a transportation fuel. Hydrogen can be used in its pure form in fuel cell electric vehicles (FCEVs), but also, as shown in Exhibit 31 and Exhibit 47, can be converted into hydrogen-based fuels including synthetic methane, methanol and ammonia in a process commonly known as 'power-to-liquid', potentially applicable for aviation and shipping where the use of direct hydrogen or electricity is particularly challenging.

For all hydrogen applications, the **volume requirement** for on-board storage remains, along with the comparatively low **overall well-to-wheel (or power generation to wheel) efficiency**, the **two key challenges for use of hydrogen**. As we highlighted in the first section of this report, hydrogen has some unique properties that make it screen attractively as a fuel, for example having >2.5x the energy density per unit mass compared to conventional fossil fuels. Nonetheless, hydrogen in ambient conditions (1 bar atmospheric pressure) has eight times lower energy density than conventional fuels such as natural gas under equivalent conditions, which requires the need of compression for use in on-board storage such as in FCEVs. To date, compressed hydrogen is being used for road transport (including light-duty but also buses, trucks and trains), with passenger vehicles accounting for the vast majority of fuel cell electric vehicles deployed. Japan, the US, the EU and South Korea are leading the current FCEV fleet, yet many other countries have recently set hydrogen adoption targets in mobility (Exhibit 45). In the company universe, Toyota, Hyundai, Honda and Daimler have all released or announced pipelines of FCEVs.

The exhibits that follow present our **comparative analysis for hydrogen** fuel cell electric vehicles (FCEVs) and how these screen on a weight per unit of output energy and volume per unit of output energy compared to other large-scale employed commercial vehicles - electric vehicles (EVs) and gasoline internal combustion engine vehicles (ICE). Exhibit 40 shows that for a fully loaded (or fully charged) average passenger vehicle, compressed hydrogen FCEVs screen attractively compared to Li-battery EVs on a weight per unit of output energy basis (tank-to-wheel). Similarly, hydrogen in its compressed form leads to FCEVs screening attractively on a volume per unit of energy output compared to EVs. However, FCEVs screen less attractively in terms of the cost (US$) per unit of output energy, which is >2x the cost for equivalent EVs and ICE gasoline passenger vehicles. The cost per unit of energy output for FCEVs becomes more competitive when considering long-haul heavy transport, as their long range implies less frequent refueling required and as large capacity (>300kWh) batteries in EVs remain costly. This makes **FCEVs attractive for long-haul transport applications such as buses and trucks**. For the purpose of this analysis we consider the weight and the volume of the system that stores and converts input energy to output energy across all three types of vehicles. This includes the internal combustion engine and gasoline tank components for ICE passenger vehicles, the Li-battery for EVs, the fuel cell and compressed hydrogen storage tank for FCEVs.

Exhibit 40: FCEVs (average passenger vehicle) using compressed hydrogen screen attractively on a weight per unit of output energy basis when compared to Li-battery EVs...

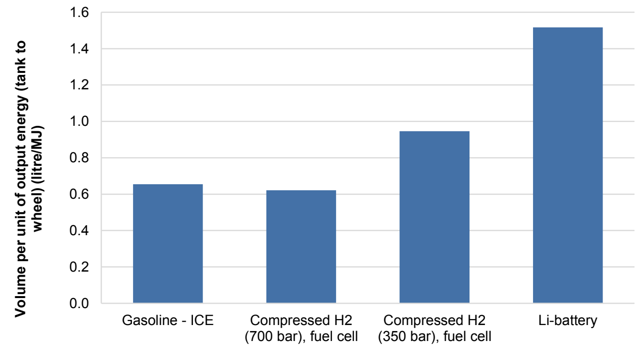
Weight per unit of output energy (tank-to-wheel basis, kg/MJ) for different average passenger vehicles and % increase in average vehicle weight



Source: US Department of Energy, EIA, Goldman Sachs Global Investment Research

Exhibit 41: ...and considering the compressed form of hydrogen used in FCEVs, they also screen attractively on a volume per unit of output basis

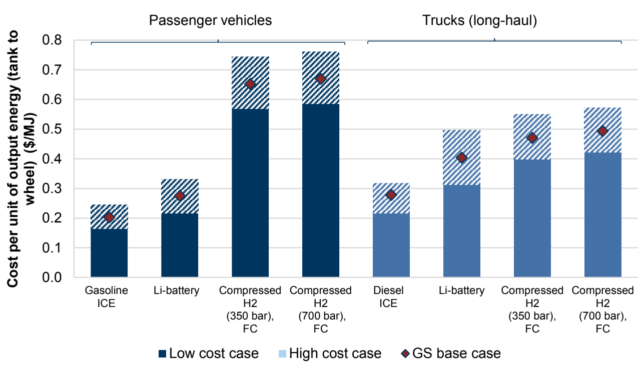
Volume per unit of output energy (tank-to-wheel basis) (litre/MJ)



Source: US Department of Energy, Company data, Goldman Sachs Global Investment Research

Exhibit 42: FCEVs screen less attractively compared to EVs and gasoline ICE for short-haul passenger vehicles, yet they become more competitive in long-haul transport applications (such as trucks)

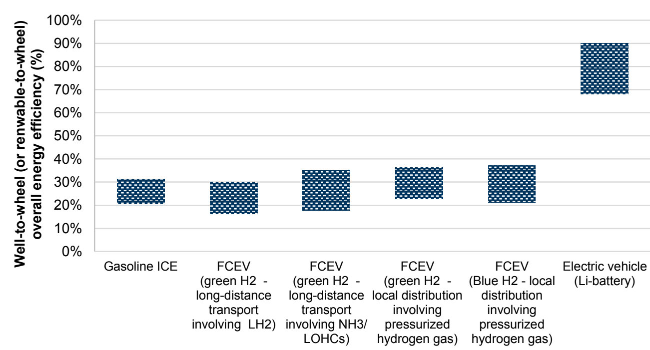
Cost per unit of output energy (tank-to-wheel basis, $/MJ)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 43: ...yet the low overall efficiency of FCEVs remain their key weakness when compared to electric vehicles

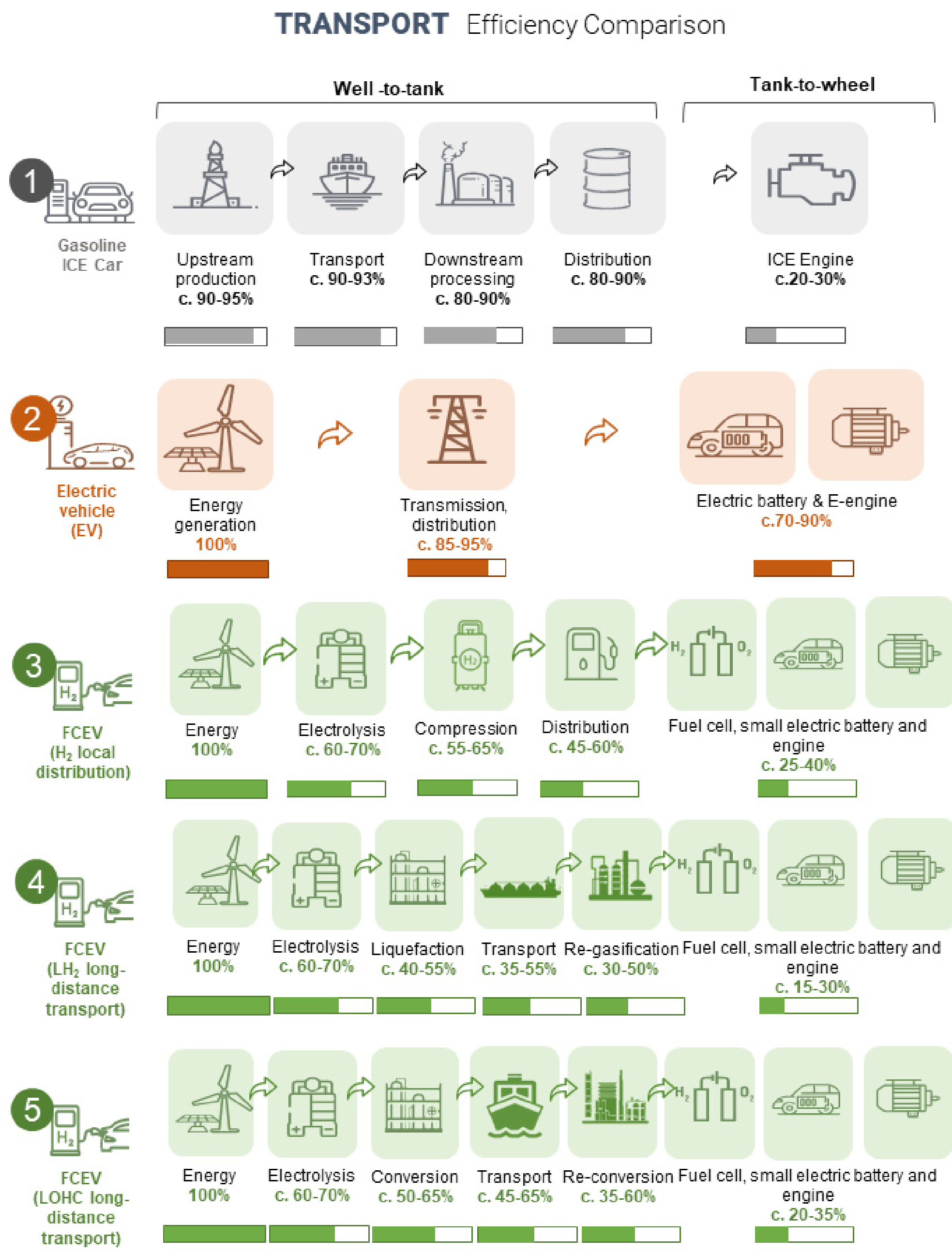
Well-to-wheel (or renewable-to-wheel) energy efficiency (%)



Source: Company data, Goldman Sachs Global Investment Research

On a well-to-wheel basis, the **key challenge for hydrogen** remains its low **overall energy efficiency**, as show in Exhibit 44, with the local distribution pressurized hydrogen having an overall well-to-wheel efficiency of 25-40%, reducing down to 15-30% for liquefied hydrogen or 25-35% for liquid organic hydrogen carriers and ammonia due to the additional liquefaction/gasification and conversion/re-conversion steps required. This compares to c. 70-90% efficiency for electric vehicles.

Exhibit 44: Hydrogen has a low efficiency, on a comparative basis, with electric vehicles being twice as efficient on a well-to-wheel basis



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 45: A number of countries have already set fuel cell electric vehicle (FCEV) and hydrogen refueling stations (HRS) infrastructure targets

Country	Targets set for hydrogen in mobility	Timeline	Source and details of strategic plan
Japan	200,000 FCEVs 800,000 FCEVs 1,200 FC buses 10,000 forklifts 320 HRS 900 HRS	by 2025 by 2030 by 2030 by 2030 by 2025 by 2030	The Strategic Road Map for Hydrogen and Fuel Cells, by METI Japan, 2019.
South Korea	40,000 FC buses 30,000 FC trucks 80,000 FCEVs taxis 2.9 mn FCEVs (domestic) 310 HRS 1,200 HRS	by 2040 by 2040 by 2040 by 2040 by 2022 by 2040	Hydrogen Economy Roadmap, Ministry of Trade, Industry and Energy, Korea, 2019.
US	1,000 HRS - California 1 mn FCEVs - California	by 2030 by 2030	California Air Resources Board (CARB), California Energy Commission (CEC) 2018.
China	50,000 FCEVs 1 mn FCEVs 300 HRS 1,000 HRS	by 2025 by 2030 by 2025 by 2030	Made in China 2025' plan by the Chinese Government, 2015. Energy Saving and New Energy Vehicle Technology Roadmap, 2016.
Netherlands	15,000 FCEVs 300,000 FCEVs 3,000 FC heavy-duty vehicles 50 HRS	by 2025 by 2030 by 2025 by 2025	Government of the Netherlands, National Climate Agreement, The Netherlands, 2019.
Germany	100 HRS 400 HRS	by 2020 by 2025	National Innovation Programme for Hydrogen and Fuel Cell Technology, Germany, 2019.
France	5,000 FCEVs 20,000-50,000 FCEVs 200 FC heavy vehicles (bus, trucks etc) 800-2,000 FC heavy vehicles (bus, trucks etc) 100 HRS 400-1,000 HRS	by 2023 by 2028 by 2023 by 2028 by 2023 by 2028	MinistŁre de la Transition Øcologique et solidaire, Plan de déploiement de l'hydrogène pour la transition ØnergØtique, France, 2018.
UK	65 HRS	by 2020	Summary on national plans for alternative fuel infrastructure, European Commission, 2014.
Spain	500 FCEVs and 20 HRS	by 2020	Summary on national plans for alternative fuel infrastructure, European Commission, 2014.
Belgium	22 HRS	by 2020	Summary on national plans for alternative fuel infrastructure, European Commission, 2014.
Finland	21 HRS	by 2030	Summary on national plans for alternative fuel infrastructure, European Commission, 2014.

FCEVs = Fuel cell electric vehicles
HRS = Hydrogen refuelling stations
FC = Fuel cell

Source: Stated sources, Goldman Sachs Global Investment Research

The Rail Industry and the hydrogen opportunity

Despite the fact that the rail industry is already a frontrunner in the European energy transition (causing only 0.1% of total GHG emissions), c20% of rail traffic and 40% of network are still under the diesel regime[1]). Within this context, we believe that hydrogen trains will help to reduce further the emissions and noise levels caused by the industry. Fuel Cells and Hydrogen (FCH) trains have become a focus for rail OEMs in recent years. While FCH technology tests started in 2005, the first commercial trains were presented in 2016 by Alstom, entering operation in Germany in 2018. While still in early development and according to Alstom >25% higher in terms of upfront costs (see here for the takeaways from our Rail Series webcast), its environmental, technical and economic profile makes hydrogen trains attractive to replace the diesel-powered fleet. According to the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) and the Shift2Rail Joint Undertaking (S2R JU), the technology could make up to 20% of new European trains by 2030, replacing c30% of diesel trains.

What are the main advantages of Hydrogen Trains?

1. **Environmental profile**, as the hydrogen trains are able to provide a zero-emission performance and lower noise as well as air contaminants. Notably, the green attractiveness seems to not come at the expense of the technical performance, and instead it is coupled with the flexibility of the diesel-powered trains. For instance, hydrogen trains can be fueled in less than 20 minutes, operate for up to 18 hours without refueling, and cover up to 1000km at a maximum speed of c180km/h.
2. **Life-cycle cost effectiveness.** The cost profile varies across the main applications (Multiple Units, Shunter, Locomotive), with the Multiple Units currently being considered the most viable and actionable option by Alstom. Its total cost of ownership is estimated[2] to be 3% lower than Catenary Electrification and 6% higher than diesel trains in 2022, equating to a cost premium of c.0.5€/km. In order to reduce the total cost of ownership, there are opportunities both on the opex (electricity price) and capex (economies of scale) sides.

What are the main examples of hydrogen Passenger Trains?

Alstom has been the first railway manufacturer worldwide to develop a passenger train based on hydrogen technology, the Coradia iLint. The hydrogen train was firstly presented in 2016 and entered service in Germany in 2018, with 2 trains running since then. Europe has been the most buoyant market for hydrogen trains: In Germany, Alstom secured two orders for a total of 41 trains last year, which will be fully operational in 2022, and in the Netherlands it has successfully completed preliminary tests. This couples with France, where there is an ongoing tender for regionals trains in the Northern regions, and Italy, where Alstom has announced a JV with Snam for the joint development of hydrogen trains. As a part of the 5-year agreement, Alstom will manufacture and maintain newly built or converted hydrogen trains, while Snam will develop the infrastructures for production, transport and refuelling. Outside Europe, in 2019 Stadler won in 2019 its first contract to supply a hydrogen-powered train to San Bernardino County Transportation Authority in the US, which will be delivered in 2024, with an option to order four more vehicles in the future.

[1] Source: "Study on the Use of Fuel Cells and Hydrogen in the Railway Environment" commissioned by Fuel Cells and Hydrogen Joint Undertaking (FCH JU) and the Shift2Rail Joint Undertaking (S2R JU), 2019.

[2] Source: "Study on the Use of Fuel Cells and Hydrogen in the Railway Environment" commissioned by

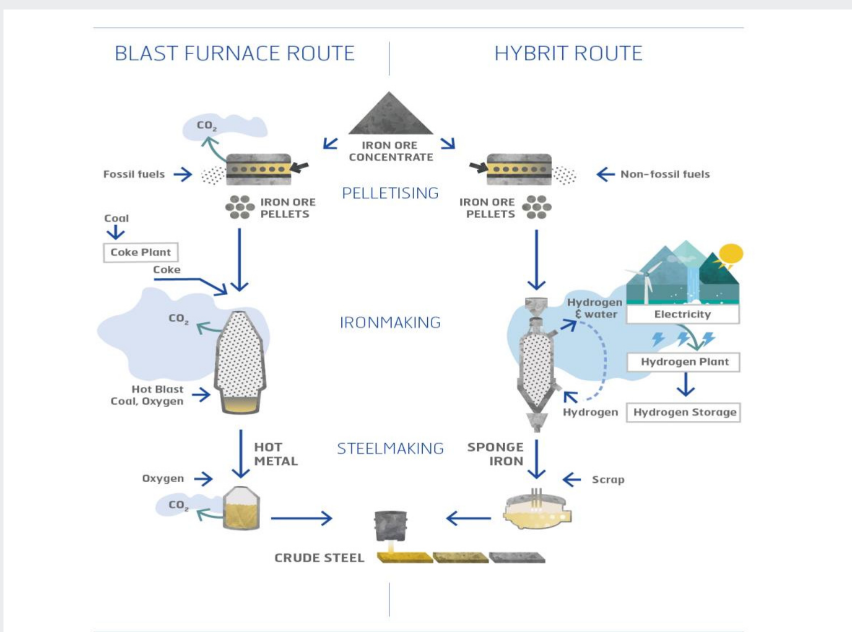
3) Industrial applications: Case study of iron & steel de-carbonization

Demand for hydrogen is currently dominated by industrial applications, with oil refining, ammonia production, methanol production and steel production via the direct reduction of iron ore (DIR) the major sources. In the context of de-carbonization, clean hydrogen (either 'green' or 'blue' through the retrofit of CCUS across industrial plants) could be used as a fuel (providing high-temperature heat required in industrial plants) or feedstock aiding the clean production of its end products and the de-carbonization processes involved. One key industrial applications of clean hydrogen that has recently attracted industry interest is the production of net-zero carbon steel to help meet the growing global steel demands with lower emissions. A number of projects are currently underway to develop these processes and move towards commercialization, as outlined in the box that follows.

Examples of projects targeting de-carbonization of steel

- **HYBRIT**: In 2016, SSAB, LKAB and Vattenfall formed a partnership for the de-carbonization of steel through a modified DRI-EAF process aiming at producing the first fossil-free steel making technology with net zero carbon footprint. During 2018, a pilot plant for fossil-free steel production in Luleå, Sweden started construction. The total cost for the pilot phase is estimated at SEK 1.4 billion. The Swedish Energy Agency will contribute more than SEK 500 million towards the pilot phase and the three owners, SSAB, LKAB and Vattenfall, will each contribute one third of the remaining costs. The Swedish Energy Agency earlier contributed SEK 60 million to the pre-feasibility study and a four-year research project.

Exhibit 46: HYBRITT process route schematic diagram



Source: HYBRITT, Company data

Fuel Cells and Hydrogen Joint Undertaking (FCH JU) and the Shift2Rail Joint Undertaking (S2R JU), 2019.

- **SALCOS:** An initiative undertaken by Salzgitter AG and Fraunhofer Institute to develop a process for hydrogen-based reduction of iron ore using the DRI-EAF route. The process initially involves the reduction of the iron ore to iron with the aid of natural gas and a higher volume of hydrogen in a direct reduction reactor. Based on this method, a reduction of iron of up to 85% can be achieved according to the operators, with CO_2 savings of initially up to 50% theoretically possible. If, in the future, switching the entire production to a direct reduction plant is possible, they project that this figure could be raised to up to 85%.
- **ΣIDERWIN:** A research project by ArcelorMittal which is in pilot phase. It utilizes an electrochemical process supplied by renewable sources to transform iron oxides into steel plate with a significant reduction of energy use.
- **COURSE 50:** An initiative from the Japanese Iron and Steel Federation which aims to reduce of the carbon footprint of steel production through the use of higher proportion of hydrogen for the iron ore reduction as well as capture the CO_2 content of the process streams.
- **HIsarna:** In 2004, a group of European steel companies (including Tata Steel) and research institutes formed ULCOS, which stands for Ultra-Low Carbon Dioxide Steel making. Its mission is to identify technologies that might help reduce carbon emissions of steel making by 50% per tonne by 2050. HIsarna is one of these technologies and is a process involving an upgraded smelt reduction that processes iron in a single step. The process does not require the manufacturing of iron ore agglomerates such as pellets and sinter, nor the production of coke, which are necessary for the blast furnace process. Without these steps, the HIsarna process is more energy efficient and has a lower carbon intensity than traditional iron making processes, especially when combined with CCUS, according to the operators.

4) Synthetic hydrogen-based fuels and feedstocks

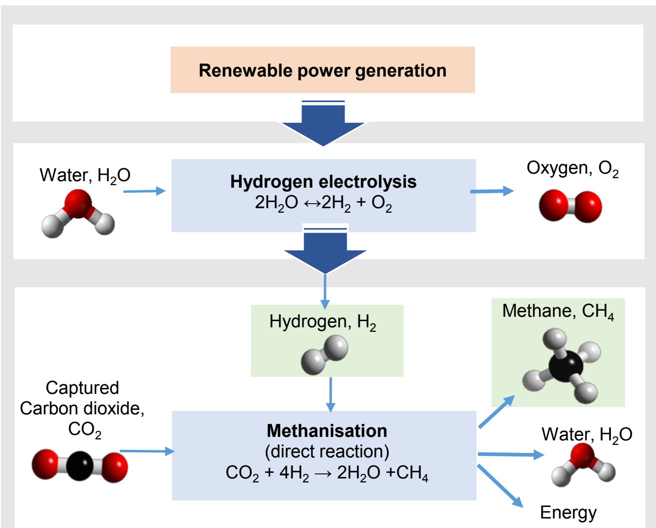
An acceleration of hydrogen large-scale adoption could materialize on the back of its ability to form ammonia and other liquid organic hydrogen carriers (LOHCs), but also its ability to combine with CO_2/CO to produce synthetic hydrocarbons /liquid fuels such as synthetic methanol, diesel and jet fuel. In our view, the former (ability to form ammonia & LOHCs) has the potential to enhance the pace of hydrogen adoption by aiding storage and transportation (liquid ammonia has a higher volumetric density than liquid hydrogen and can be liquefied at a higher temperature of -33°C vs hydrogen at -253°C and methane at -160°C), while the latter (ability to combine with CO_2/CO) acts as a CO_2 utilization route with a wide range of applications. Some hydrogen-based synthetic feedbacks and fuels developed to date include:

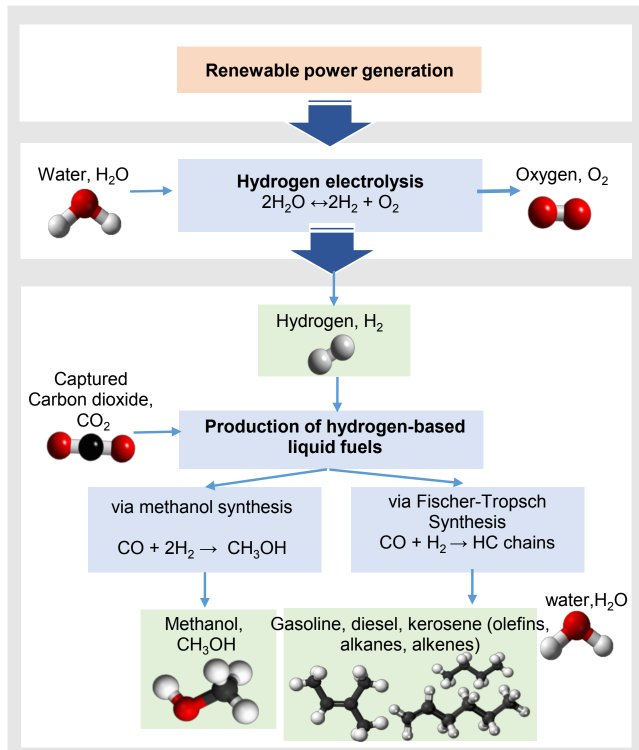
- **Synthetic methane:** This is the most commonly produced synthetic hydrogen-based fuel and the production pathway involves a methanation process (mostly catalytic but biological routes are also possible) that utilizes the direct reaction between hydrogen and CO_2 to produce methane, with water the main reaction by-product.
- **Synthetic methanol**: Methanol has c.80% higher energy density than hydrogen and its production route from syngas (through hydrogen) is well developed

commercially. The first CO_2-to-methanol facility, known as George Olah Renewable Methane Plant, is located in Iceland and was commissioned in 2012 with a capacity of 1000 tpa of methanol before its expansion to 4,000 tpa in 2015. The CO_2 feedstock is captured from a nearby power plant while hydrogen is produced via electrolysis and used to directly hydronate the captured CO_2. The 'Vulcanol' product is then sold for use as a gasoline additive and feedstock for biodiesel production.

- **Synthetic diesel, kerosene and other fuels:** Synthetic diesel or kerosene is the result of a reaction occurring between carbon monoxide (CO) and hydrogen. Carbon monoxide could be obtained from captured CO_2, with the resulting syngas, CO_2 and hydrogen converted into synthetic fuels via the Fischer Tropsch synthesis route.

Exhibit 47: Hydrogen produced from net zero electricity can be used in CO2 utilization processes for the production of synthetic hydrogen-based fuels such as methane, methanol, diesel and gasoline





Source: The Royal Society, Goldman Sachs Global Investment Research

Appendix: Companies with clean hydrogen exposure

As part of our analysis, we have identified a broad universe of companies involved across different parts of the clean hydrogen supply chain, both publicly listed and private companies. We present these in the table that follows in this Appendix and we note that the universe is not exhaustive.

We have also screened the broad universe of companies exposed to the clean hydrogen supply chain for materiality and show 'Clean hydrogen exposure materiality' list (shown with green circles) consisting of publicly listed companies that meet one of two criteria:

1) Material revenue (>10%) exposure to the clean hydrogen supply chain. This captures companies with direct operational focus on hydrogen technologies such as manufacturing of fuel cells or electrolyzers ('technology-enablers').

2) Companies that despite a relatively small current revenue exposure have leading ambitions and targets amongst their sector peers with regard to clean hydrogen, particularly in applications. We note that whilst we aim to capture a broad clean hydrogen universe of companies, the list presented below is not exhaustive.

Company	Activities across the hydrogen value chain	Stock Exchange	Ticker	Market Cap ($bn)	GS clean hydrogen exposure materiality
Integrated players along the clean hydrogen supply chain					
Integrated players along the clean hydrogen supply chain					
Air Liquide	Air Liquide produces hydrogen at a large scale for chemical and industrial applications, with a major focus on clean hydrogen over recent years, both 'green' and 'blue'. Air Liquide has developed a cold capture system (Cryocap™) that captures the CO_2 released during this hydrogen production through a cryogenic process. The first Cryocap™ unit is installed in Port Jérôme, and has an annual capture capacity of 100,000 tonnes of CO_2. Air Liquide is also demonstrating the advantages of electrolysis-produced hydrogen by leading a major project in Europe, HyBalance. The company has committed to produce at least 50% of its hydrogen through carbon-free processes (combining biogas reforming, water electrolysis technologies and carbon capture technologies). The company is involved across the whole spectrum of the hydrogen supply chain (e.g. production, transportation, storage, distribution).	Euronext Paris	AIRP.PA	70.6	●
Linde Group	Linde is one of the leading suppliers of steam reformer plants that produce hydrogen from natural gas feedstocks, with more than 200 constructed units to date with capacities ranging from 300 to over 200,000 Nm3/h. The company is also involved in every part of the supply chain, from production to storage (cryogenic tanks), transportation (liquefiers) and transmission. Linde produces hydrogen using both conventional and, increasingly, green routes and it is a project partner of "Energiepark Mainz", one of the largest green hydrogen production plants in the world where wind-generated electricity is used for the electrolysis of water.	NYSE, Frankfurt Stock Exchange	LIN, LINI.DE	117.9	●
Air Products Chemical Inc.	Air Products is one of the global leaders in hydrogen, with activities and technologies that span the whole spectrum of the hydrogen supply chain, providing storage, transport, production and separation systems. In 2019, Air Products unveiled a pilot project to generate some of Europe's first Guarantees of Origin (GO) for sustainable, renewable hydrogen produced in The Netherlands, under the CertifHy scheme. The GOs are being sought for hydrogen produced at the Rotterdam chloralkaline electrolyser plants of Nouryon. Additionally, Air Products has experience with the capture of CO2 from natural gas reforming and has been selected under the Industrial Carbon Capture and Sequestration Program (ICCS) to design, construct and operate a system to capture CO2 from two steam methane reformers in Port Arthur. Recently, the company announced that it has signed an agreement with ACWA Power and NEOM for a $5 billion large-scale green hydrogen-based ammonia production facility powered by renewable energy. The project, which will be equally owned by the three partners, will be sited in NEOM, a new model for sustainable living located in the north west corner of the Kingdom of Saudi Arabia, and will produce green ammonia for export to global markets.	NYSE	APD	58.6	●
Taiyo Nippon Sanso	Taiyo Nippon Sanso is involved in a wide range of hydrogen production activities. The company designed the 'Hydro Shuttle', a package-type hydrogen refueling station to supply hydrogen gas to FCEVs.	Tokyo Stock Exchange	4091.T	7.1	●

Note: Pricing for market cap in these exhibits is as of July 7, 2020 market close.

Source: Company data, Thomson Reuters Datastream, Goldman Sachs Global Investment Research

Company	Activities across the hydrogen value chain	Stock Exchange	Ticker	Market Cap ($bn)	GS clean hydrogen exposure materiality
Hydrogen Production					
Blue Hydrogen					
Carbon Capture technologies					
OGCI Members	The Oil and Gas Climate Initiative (OGCI), is an international industry-led consortium which includes 12 member companies from the oil and gas industry: BP, Chevron, CNPC, Eni, Equinor, ExxonMobil, Occidental, Petrobras, Repsol, Saudi Aramco, Shell and Total. It was established in 2014 and has a mandate to work together to "accelerate the reduction of greenhouse gas emissions" in full support of the Paris Agreement and its aims.	N/A			
Aker Solutions	Aker Solutions offers services, products and solutions throughout the whole CCUS chain, from capture via transport to safe storage. The company has been involved in a range of projects, from the Sleipner CO2 platform delivery up to recent design, delivery and operation of the amine plant at Technology Centre Mongstad, Norway. Aker Solutions has developed a post combustion technology that can efficiently reduce the CO2 emissions from industrial flue gases.	Olso Stock Exchange (OSE)	AKSOL.OL	0.3	
Svante Inc.(Inventys)	Svante Inc. designs and manufacturers technology that captures CO_2 from flue gas from industrial processes, concentrates the captured CO_2 and releases it for storage or industrial re-use. Applications include Steel & Aluminium production, Cement Production & Fertilizer production.	N/A			
C-Capture	C-Capture provides solvent-based technologies for the removal of CO_2 from emissions using a post-combustion capture approach. The technologies provided are applicable for carbon capture from a wide range of industrial processes, including hydrogen in SMR.	N/A			
CO2 Solutions	CO2 Solutions focuses on the research and development of enzyme technology used in the carbon-capture process, with applications for the capture of carbon from GHG-intensive installations.	N/A			
Blue Planet	Blue Planet developed the Liquid Condensed Phase (LCP) technology to capture and convert CO_2 into carbonate rocks, which is then used as input for concrete and other building materials.	N/A			
Climeworks	Climeworks focuses on delivering direct air carbon capture solutions. It currently has several pilot plans in operation, notably in Switzerland, Iceland and Italy, which capture c. 900/50/150 tCO_2pa, respectively.	N/A			
Carbon Engineering	Carbon Engineering, a Canadian-based company founded in 2009, is adopting a solvent-based cycle process for direct air carbon capture. The company is developing a plant in partnership with Occidental Petroleum that it expects could capture 1 Mt CO_2 pa when it begins operations.	N/A			
Global Thermostat	Founded in 2010, Global Thermostat's direct air carbon capture approach involves amine-based chemical sorbents that are bounded to a porous ceramic 'monolith' structure to capture carbon dioxide directly from the atmosphere.	N/A			
Green Hydrogen					
Electrolyzer Manufacturers					
Hydrogenics (Cummins)	Hydrogenics, a Cummins Inc. company, designs, manufactures and installs industrial and commercial hydrogen generation, fuel cells and MW-scale energy storage solutions. Amongst these are PEM and alkaline hydrogen generators for industrial processes and fueling stations, hydrogen fuel cells for electric vehicles and fuel cell installations for freestanding electrical power plants. Hydrogenics was acquired by Cummins in 2019.	NYSE	CMI	25.9	
Nel Hydrogen	Nel Hydrogen provides solutions to produce, store and distribute hydrogen from renewable energy. The company□designs and manufactures alkaline and proton exchange membrane (PEM) water electrolyzers, with over 3,500 electrolyzers installed globally to date.	Oslo Stock Exchange	NEL.OL	3.2	
ITM Power	ITM Power Plc designs and manufactures integrated hydrogen energy solutions.The company's electrolyzers are primarily based on Proton Exchange Membrane (PEM) technology. The company recently announced the construction of its global manufacturing headquarters in Sheffield, UK, with an electrolyzer manufacturing capacity of up to 1GW per annum.	London Stock Exchange	ITM.L	1.8	
McPhy Hydrogen	McPhy designs and manufactures electrolyzers for a wide range of applications (mobility, power-to-gas, industrial and energy storage) whilst also focusing on the provision of technologies for hydrogen refueling stations.	Euronext Paris	MCPHY.PA	0.4	
Asahi KASEI	Asahi Kasei Corporation is a multinational Japanese chemical company, and one of the leading suppliers of chlor-alkali electrolysis systems, used in >125 production sites and >25 countries worldwide. In 2018, the company started a demonstration project for green hydrogen production at the Hydrogen Competence Centre h2herten in Germany.	Tokyo Stock Exchange	3407.T	11.0	
Thyssenkrupp	As it relates to hydrogen applications, ThyssenKrupp AG develops and manufactures water electrolysis technological solutions, with primary focus on chlor-alkali routes. The company has produced over 200,000 electrolysis cells to date, with over 600 plants erected globally making use of their electrolysis technology.	Frankfurt Stock Exchange	TKA.DE	4.6	
Siemens	Siemens designs and manufactures the Silyzer portfolio of PEM water electrolyzers which allow for the large-scale production of hydrogen from renewable power sources. The company will develop and deploy a large-scale version of their Silyzer electrolyzer in Western Australia as part of a project that will produce green hydrogen from up to 5GW of renewable energy capacity.	Frankfurt Stock Exchange	SIEGn.DE	103.6	
SunHydrogen	The company is developing and intends to bring to market a new solar hydrogen generator technology that eliminates the need for a separate electrolyzer, by integrating the electrolysis process directly into the solar cell, allowing for the cost-effective production of hydrogen from renewable solar energy.	OTC Market	HYSR	N/A	
Green Hydrogen Systems	Green Hydrogen Systems developed a commercially viable platform for producing green hydrogen, with both alkaline and PEM electorlyzers (including Hyprovide™ P-Series and HyProvide™ A-Series).	N/A			
H-TEC Systems	H-Tec Systems is a manufacturer of high performance PEM electrolyzers and stacks focused on serving a variety of sectors including the mobility, power-to-gas and freight transport segments.	N/A			
H2B2	H2B2 offers proprietary technology for the development of PEM electrolyzers, aiming to be a leader in holding MW stacks, whilst also providing solutions, undertaking production and maintenance of large-scale green hydrogen production facilities. The company offers a wide range of electrolyzer products.	N/A			

Source: Company data, Thomson Reuters Datastream, Goldman Sachs Global Investment Research

Company	Activities across the hydrogen value chain	Stock Exchange	Ticker	Market Cap ($bn)	GS clean hydrogen exposure materiality
Hydrogen storage, distribution and transport					
Transportation, distribution infrastructure & other (Compression, gasification & liquefaction)					
Kawaski Heavy Industries Ltd.	Kawasaki Heavy Industries (KHI) is focused on the large-scale liquefaction and transport of hydrogen. The company is currently developing its first liquefied hydrogen carrier, the 8000 tonne "SUISO Frontier" vessel. This vessel was developed to provide a means of transporting liquefied hydrogen, cooled to –253°C, safely and in large quantities over long distances by sea. Kawasaki plans to complete the vessel's construction by late 2020.	Tokyo Stock Exchange	7012.T	2.4	
Iwatani Corporation	Iwatani Corporation, through their participation in the Hydrogen Council (one of the steering members), is engaged in a wide variety of global hydrogen initiatives including the development of a network of Hydrogen Refuelling Stations (HRS), with a significant market share of the HRS market in Japan, as well as having recently acquired a number of HRS in California (US). Additionally, the company has formed a number of global partnerships, including with ITM Power for the development of electrolyzers for clean hydrogen production.	Tokyo Stock Exchange	8088.T	1.8	
Korea Gas (KOGAS)	KOGAS is involved in the large-scale production, storage and distribution of hydrogen. KOGAS is a key partner in the development and operation of special purpose corporation called HyNet, which plans to install 100 hydrogen refuelling stations in South Korea by 2022. Korea Gas plans to invest W4.7 trillion (US$4.01 billion) to build 25 hydrogen-producing facilities by 2030. Under the plan, KOGAS will construct hydrogen-producing facilities and pipelines totaling 700 kilometers to transport the gas.	Korean Stock Exchange	036460.KS	2.0	
ENEOS (JX Nippon Oil & Energy Corp)	ENEOS focuses on the development of a network of hydrogen refuelling stations with a geographic focus on the Japanese market. The company operates a large network of fuel stations in Japan, including more than 40 hydrogen refuelling stations in four major metropolitan areas.	Tokyo Stock Exchange	5020.T	11.6	
Enagas	Enagas is an infrastructure operator and manager of natural gas and renewable gas transmission networks. The company develops national and international projects to contribute to the de-carbonization process such as the development of renewable gases which include hydrogen, which can be transported by the company's pipelines network.	Madrid Stock Exchange	ENAG.MC	6.2	
Snam	In 2019, Snam was the first company in Europe to introduce a mix of 5% hydrogen and natural gas in its transmission network. The trial involved supplying H2NG (hydrogen-natural gas mixture) for a month to two industrial companies. Through this project, 3.5 billion cubic meters of hydrogen could be added to its utility network each year. At present, Snam is in the process of verifying the full compatibility of its infrastructure with increasing amounts of hydrogen mixed with natural gas as well as studying hydrogen production from renewable electricity.	Milan Stock Exchange	SRG.MI	17.1	
Storage					
Hexagon Composites	Hexagon Composites manufactures High Pressure Hydrogen Cylinders (HPHC) for fuel cell electric vehicles as well as ground storage solutions for Hydrogen Refuelling Stations (HRS). The company offers a wide range of hydrogen storage & distribution solutions.	Oslo Stock Exchange	HEX.OL	0.9	
Plastic Omnium	Plastic Omnium designs and manufactures high pressure gas vessel storage solutions. The company created in early 2018 a dedicated entity to develop a complete offer from high pressure gas vessels storage to fuel cell systems including management.	Euronext Paris	POM.PA	3.2	
Faurecia	Faurecia's focus in the hydrogen space is the manufacturing of high-pressure hydrogen storage tanks for mobility applications. The company was recently awarded a significant contract for fuel cell electric vehicle storage systems from Hyundai Motor Company.The company is a JV partner in SYMBIO (alongside Michelin), a large-scale manufacturer of components for fuel cell electric vehicles.	Euronext Paris	EO.PA	5.5	
Vopak	Through its Vopak Ventures portfolio companies HyET and Hydrogenious, Vopak is involved with the development of hydrogen storage and electromechanical compression solutions for both household applications and hydrogen refuelling stations. Vopak is also a partner in H-vision project in Rotterdam.	Euronext Amsterdam	VPK.AS	7.0	
Worthington Industries	Worthington Industries manufacturers compressed hydrogen fuel tanks for fuel cell electric vehicles, supplying several OEMs with hydrogen storage solutions globally. Applications include passenger FCEVs, buses, trucking and stationary storage.	NYSE	WOR	1.9	
ILJIN Composites	ILJIN Composites develops and produces composite fuel tanks for compressed gases used in mobility applications, such as hydrogen fuel cell vehicles. The company is a member of the Hydrogen Council and has in the past been involved in a number of partnerships, including the supplying of hydrogen fuel tanks to Hyundai for hydorgen-fueled buses.	Korean Stock Exchange	081000.KS	0.6	
MAHYTEC	MAHYTEC designs and manufactures hydrogen storage solutions, including composite-based hydrogen storage tanks, allowing for the storage of hydrogen in either liquid, solid or gaseous form.	N/A			
NPROXX	NPROXX manufactures high-pressure hydrogen storage tanks (Type 4 pressure vessels) for the storage of hydrogen under high pressure, suitable for a range of mobility applications	N/A			
Faber Cylinders	Faber cylinders is focused on the production of hydrogen storage cylinders (Type 1,2,3 and 4) used for a range of gases including hydrogen.	N/A			
Calvera	Calvera integrates all processes for the manufacture of transport and storage equipment of high-pressure compressed gas including hydrogen (one of the company's three business lines).	N/A			

Source: Company data, Thomson Reuters Datastream, Goldman Sachs Global Investment Research

Company	Activities across the hydrogen value chain	Stock Exchange	Ticker	Market Cap ($bn)	GS clean hydrogen exposure materiality
Applications					
Fuel cell manufacturers					
Ballard Power Systems	Ballard Power designs and manufactures fuel cell technologies including heavy-duty modules, fuel cell stacks and power backup systems. Applications include mobility markets such as Rail, Marine and Automotive as well as stationery power backup applications.	NASDAQ	BLDP	4.8	
Fuel cell Energy	The company's fuel cell solutions include "SureSource" products, modular power plants designed and manufactured by the company. These are available in different sizes and configurations including natural gas letdown station energy recover, fuel cell carbon capture and distributed hydrogen.	NASDAQ	FCEL	0.6	
AFC Energy	AFC Energy produces alkaline-based fuel cells, and the company has developed as part of its H-Power a patented proprietary design. The technology is focused on further developing the hydroxyl group of chemicals that contribute to the operation and efficiency of existing fuel cells. As such, the company uses HydroX-Cell(L)TM and HydroX-Cell(S)TM terminology to define its fuel cell products.	London Stock Exchange	AFC.LN	0.1	
Ceres Power	Ceres Power develops fuel cell technology that is then licensed to OEMs and manufacturing partners in exchange for a license fee and future royalties on systems and stacks used in final products sold. The company's core technology is SteelCellfi, a solid oxide fuel cell on a steel backbone.	London Stock Exchange	CWR.LN	1.3	
Doosan Fuel Cell	Doosan Fuel Cell manufactures fuel cells, with primary focus stationary fuel cell applications.	Korean Stock Exchange	336260.KS	1.4	
PLUG Power	PLUG Power has a portfolio of fuel cell products, with a variety of products including GenDrive (lift trucks), GenSure (stationary applications), ProGen (OEMs), GenFuel (full suite of fueling solutions) and GenCare (aftermarket service).	NASDAQ	PLUG	3.0	
Bloom Energy	Bloom Energy, based on its proprietary solid oxide fuel cell technology, provides fuel cell solutions. These are designed for modularity, and according to the company any number of its systems can be clustered together in various configurations to form solutions from hundreds of kilowatts to many tens of megawatts.	NYSE	BE	1.4	
Powercell Sweden	PowerCell Sweden develops and produces fuel cell stacks and fuel cell systems, primarily based on PEM fuel cell technology. The products address a number of markets including transportation, marine and power generation.	Stockholm Stock Exchange	PCELL.ST	1.9	
SFC Energy AG	SFC Energy manufactures fuel cells based primarily on PEM technology, with a focus on mobility, defence & security, oil & gas and industrial energy applications.	Frankfurt Stock Exchange	F3C.DE	0.2	
Proton Power Systems	Through Proton Motor Fuel Cell GmbH, the company focuses on the production of fuel cell systems for applications primarily in the power generation segment and transport.	London Stock Exchange	PPS.LN	0.7	
Cell Impact	Cell Impact designs and produces bipolar flow plates for hydrogen fuel cell technologies.	Frankfurt Stock Exchange	ICL.PA	0.2	
PowerHouse Energy Group	PowerHouse has developed the integrated DMGfi System which allows for the conversion of carbonaceous organic materials into hydrogen, which is then used as feedstock for a series of fuel cells, to develop clean electricity for a variety of applications.	London Stock Exchange	PHE.LN	0.1	
Michelin	Michelin, through its JV with Faurecia, SYMBIO, focuses on the development and production of hydrogen fuel cell systems, primarily with mobility applications ranging from light passenger vehicles to buses and heavy-duty trucks.	Euronext Paris	MICP.PA	18.8	
Mitsubishi Heavy Industries	Through its subsidiary Mitsubishi Hitachi Power Systems (MHPS), the company specializes in developing large, industrial-scale hybrid systems of Solid Oxide Fuel Cells (SOFC) and Micro Gas Turbines (MGT).	Tokyo Stock Exchange	7011.T	8.1	
ErlingKlinker AG	ErlingKlinker AG supplies various automotive components to the fuel cell electric vehicles market, with a focus on supplying OEMs with an extensive range of components as well as PEM fuel cell stacks.	Frankfurt Stock Exchange	ZIL2.DE	0.4	
Schaeffler Group	Schaeffler develops and manufactures key components for fuel cells such as bipolar plates that form the core of the fuel cell and control units, low-friction bearings and thermal management modules that impact the fuel cells' efficiency.	Frankfurt Stock Exchange	SHA.DE	5.1	
3M Co.	3M manufactures advanced electrocatalysers, fluoropolymers, membranes and various other components for fuel cells.	NYSE	MMM	89.1	
Bosch	Bosch is active in the hydrogen ecosystem in the areas of manufacturing components such as hydrogen injection systems, control units for fuel cell systems and sensors that are essential to the manufacturing and operation of fuel cells in both mobility and stationery applications. The company is working with PowerCell Sweden to develop fuel cell stack systems.	National Stock Exchange of India	BOSH.BO	5.3	
Horizon Fuel Cell Technologies	Horizon Fuel Cell Technologies was founded in Singapore in 2003 and currently operates 5 international subsidiaries. The company is a global producer of a wide range of fuel cell products (with a particular focus on PEM fuel cell technology) and is focused on four sectors (automotive, telecom, defense/aerospace, and consumer products).	N/A			
SinoHytec	SinoHytec is involved in the research and development and industrialization of hydrogen fuel cell engine technologies. SinoHytec offers a product series covering various components, with hydrogen fuel cell engine as the core product, including bipolar plates, stacks, intelligent DC/DC, hydrogen systems and test platforms.	N/A			
GenCell energy	GenCell Energy manufactures and markets a range of ammonia and hydrogen-fuelled fuel cell energy solutions, with various market applications including power solutions for the telecoms industry and backup power solutions for utilities and large commercial power users.	N/A			
Intellegent Energy	Intelligent Energy is a fuel cell engineering company focused on the development, manufacturing and commercialization of PEM fuel cell products for customers in the automotive, stationary power and Unmanned Aerial Vehicle (UAV) sectors.	N/A			
Nedstack	Nedstack researches and develops PEM fuel cell stack technologies, with a focus on power solutions for critical infrastructure installations globally. Nedstack has been operating in the PEM fuel cell manufacturing space for over 20 years and have an installed base of over 500 systems globally.	N/A			
Arcola Energy	Arcola Energy is focused on the manufacturing, installation and service of fuel cell solutions primarily for transportation and critical systems power backup applications.	N/A			
Liebherr	Liebherr specializes in the development of fuel cell power systems for various applications ranging from the emergency power systems for the aviation sector to fuel cell stacks for the automotive sector.	N/A			
GORE	GORE Fuel Cell Technologies designs and manufactures membranes and membrane electrode assemblies (MEAs), a key input to the polymer electrode or proton exchange membrane (PEM) fuel cell industry manufacturing industry.	N/A			

Source: Company data, Thomson Reuters Datastream, Goldman Sachs Global Investment Research

Company	Activities across the hydrogen value chain	Stock Exchange	Ticker	Market Cap ($bn)	GS clean hydrogen exposure materiality
Mobility					
Toyota Motor	Toyota is actively investing in fuel-cell technologies and has been one of the leaders amongst the OEM manufacturers in Fuel Cell Electric Vehicle (FCEV) technologies. The company plans to mass manufacture key fuel cell components such as fuel stacks and hydrogen tanks, with the aim of rolling out more FCEVs in the future. The Toyota Mirai is the world's first full production hydrogen fuel cell saloon and winner of the World Green Car award in 2016. It can be driven for around 300 miles from a full 5kg tank of hydrogen. Toyota's plan, announced in December 2019, calls for a FCEV sales weighting of 5-10% by 2050.	Tokyo Stock Exchange	7203.T	205.4	
Hyundai Motor	Hyundai Motor Company is focused on the development of FCEVs, primarily the SUV segment. The company launched its "FCEV Vision 2030" strategy, committing to produce 700,000 fuel-cell systems annually by 2030, 500,000 of which will be made for FCEVs. Under 'FCEV Vision 2030', HMG along with suppliers, will invest KRW 7.6 trillion by 2030.	Korean Stock Exchange	005380.KS	17.7	
Daimler (Mercedes)	Daimler is focused on developing FCEVs for the passenger vehicle and commercial vehicle segment. Through a partnership with Volvo Group, the company expects to start series production of heavy-duty fuel cell commercial vehicles for heavy long-distance haulage purposes. In 2019, the company's Trucks & Buses unit announced the ambition to only be selling battery-electric or hydrogen-powered buses and trucks in European, Japanese and North American markets by 2039.	Frankfurt Stock Exchange	DAI.PA	45.7	
Alstom	Alstom is focused on integrating hydrogen technologies to allow for the commercial adoption of hydrogen-powered trains. The company developed the world's first hydrogen-powered train in 2016, the Coradia iLint, which was approved for commercial passenger service in Germany in 2018.	Euronext Paris	ALSO.PA	10.9	
Honda Motor	Honda is involved in the development of FCEVs and R&D relating to hydrogen production and refuelling stations. The company has developed and commercialized its Clarity line.	Tokyo Stock Exchange	7267.T	46.6	
BMW Group	The BMW group, through a hydrogen development partnership with Toyota started in 2013, has developed the iHydrogen NEXT FCEV in 2019 (unveiled at the 2019 Frankfurt Motor Show (IAA)), a concept vehicle of its first hydrogen-powered FCEV based on an existing product line.	Frankfurt Stock Exchange	BMWG.DE	42.3	
Stadler	Stadler is a Swiss rail manufacturer offering a wide range of products, including modular rail vehicles, tailor-made designs and rail services. In 2019, the company signed the first contract to supply a hydrogen-powered train to run in the United States. The train of the FLIRT H_2 type is planned for passenger service in 2024. San Bernardino County Transportation Authority (SBCTA) awarded the contract.	Swiss Stock Exhange	SRAIL.SW	4.1	
GM	GM formed a strategic alliance with Honda in 2013 to develop hydrogen powered FCEVs, with both companies committing $85mn in 2017 towards R&D focused on reducing the costs of fuel cell production at scale. The company is focused on the development of passenger FCEVs as well as FCEVs for military transport applications. The company recently announced the Silent Utility Rover Universal Superstructure (SURUS), a flexible fuel cell electric platform with autonomous capabilities.	NYSE	GM	36.0	
Audi (Volkswagen)	Audi's h-tron product line is focused on manufacturing FCEVs for the premium mobility space. At the 2016 unveiling of the h-tron fuel cell concept, Audi claimed a range of up to 600km (373 miles).	Frankfurt Stock Exchange	VOWG_p.DE	80.3	
Volvo	The Volvo Group announced plans for 50/50 joint venture with Daimler Truck AG to develop and produce fuel cells for heavy-duty applications and other use cases.	Stockholm Stock Exchange	VOLVb.ST	34.1	
GWM	GWM was the first Chinese automaker to join the Hydrogen council and has been investing in R&D into new energy technologies including hydrogen fuel cells since 2006. In 2018, GWM established China's first hydrogen technology centre which will focus on the testing and pilot manufacturing of core components for the FCEV manufacturing process.	Shanghai Stock Exchange/ The Stock Exchange of Hong Kong	2333.HK, 601633.SS	18.3	
Nikola Motor Company	Nikola Motor Company designs and manufactures electric components, drivetrains and vehicles including the Nikola One and Nikola Two electric semi-trucks. As part of the company's ambition to develop the hydrogen trucking industry, Nikola recently signed a purchase order with Nel ASA for 85-megawatt alkaline electrolyzers to support five of the world's first 8 ton per day hydrogen fueling stations.	Nasdaq	NKLA	14.5	
ABB	ABB has developed a modular fuel cell solution for a power supply system for use in marine applications. The fuel cell technology is applicable to high and low voltage as well as AC and DC power systems, and can be used in combination with batteries or engines.	Swiss Stock Exhange	ABBN.S	52.7	
Airbus	Airbus is increasing R&D efforts into different methods of electric propulsion for aviation, including the development of hydrogen fuel cell propulsion systems. Airbus has developed the E-Fan X aircraft, a hybrid-electric aircraft that will be powered by a hybrid propulsion system, with the potential to include a fuel-cell system to power an electric motor that will replace one of the traditional turbines.	Euronext Paris	AIR.PA	59.6	
Safran	Safran operates in the aircraft propulsion and equipment, space and defense markets. The company has been involved in a number of projects for the development and implementation of fuel cell systems for autonomous on-board electrical power generation for aircrafts.	Euronext Paris	SAF.PA	42.9	
Yanmar Holdings Co.	Yanmar Holdings Co. and its subsidiary Yanmar Power Technology Co. announced the development of a hydrogen fuel cell system for maritime applications based on fuel cell technology for automobiles. The company aims to install the maritime fuel cell system on its own boat and start a field demonstration test by the end of 2020.	N/A			
AVL	AVL is focused on the development, simulation and testing technology of powertrains (hybrid, combustion engines, transmission, electric drive, power electronics, batteries, fuel cells and software). In addition to the engineering, testing and simulation solutions, AVL has built up an extensive portfolio of fuel cell technologies (e.g. PEM, SOFC). Today AVL is involved in numerous fuel cell development projects together with various leading global players.	N/A			

Source: Company data, Thomson Reuters Datastream, Goldman Sachs Global Investment Research

Company	Activities across the hydrogen value chain	Stock Exchange	Ticker	Market Cap ($bn)	GS clean hydrogen exposure materiality
Industrial applications					
SSAB AB	SSABB is one of the lead partners of the HYBIT Joint Venture (along with LKAB, Vattenfall), an initiative focused on the development of low-carbon steel. During 2018, work started on the construction of a pilot plant for fossil-free steel production in Sweden.	Stockholm Stock Exchange	SSABa.ST	2.8	●
Johnson Matthey	Johnson Matthey supplies key catalysts for hydrogen production via steam reforming. The KATALCOTM product range allows for hydrogen production using a range of feedstocks from natural gas and refinery off-gas to LPG and naphtha.	London Stock Exchange	LON: JMAT	5.2	●
CNH Industrial	CNH Industrial, through its subsidiaries IVECO and FPT Industrial, develops hydrogen fuel cell commercial vehicles.The company has partnered with Nikola Corporation to accelerate the development and adoption of hydrogen fuel-cell and battery electric heavy-duty truck solutions.	NYSE	CNHI	9.5	●
Thyssenkrupp	In addition to its electrolyzer manufacturing activities, Thyssenkrupp has designed the 'hydrogen route' project, developing technologies to reconfigure the steel production process using hydrogen as a reducing agent in blast furnaces instead of the traditional fossil fuel routes.	Frankfurt Stock Exchange	TKA.DE	4.6	●
Voestalpine	As part of the H2FUTURE project, partners Voestalpine, Verbund, Siemens, Austrian Power Grid, K1-MET and TNO are researching the industrial production of green hydrogen as a means of replacing fossil fuels in steel production over the long term. Voestalpine is one of the leading companies looking into the de-carbonization of steel.	Vienna Stock Exchange	VOE.VI	4.0	●
Fortescue Metals	The miner announced its five-year, AU$19.1 million investment in hydrogen research being done by the Commonwealth Scientific and Industrial Research Organization, or CSIRO, in November 2018. This year, Fortescue Metals Group and ATCO Australia signed an agreement to explore the deployment of hydrogen vehicle fuelling infrastructure in Western Australia.	Australian Securities Exchange	FMG.AX	31.8	●
Anglo American	In 2019, Anglo American announced an agreement with ENGIE to develop and fuel the world's largest hydrogen-powered mine haul truck. This project is part of Anglo American's approach to sustainable mining, FutureSmart MiningTM, and focuses on technological advances to address mining's major sustainability challenges. The company is one of the 13 inaugural members of the Hydrogen Council.	London Stock Exchange	AAL.L	28.9	
ArcelorMittal	ArcelorMittal is developing a new project at its Hamburg, Germany site aimed at the first industrial scale production and use of Direct Reduced Iron (DRI) made with 100% hydrogen as the reductant, with an annual production of 100,000 tonnes of steel. The company aims to source de-carbonized hydrogen from renewable sources to be used on a demonstration scale. The use of hydrogen in the iron ore reduction process is part fo the company's ambition to cut CO_2 emissions by 30% by 2030.	Euronext Amsterdam	MT.AS	12.6	
Mitsubishi Heavy Industries	Through its subsidiary Primetals Technologies, Mitsubishi Heavy Industries is developing technologies that allow for the direct reduction of iron ore using high-purity hydrogen, significantly reducing the carbon footprint of the steel-making process. The company is planning a pilot plant for testing to be constructed at the Voestalpine steel plant in Stahl Donawitz, Austria.	Tokyo Stock Exchange	7011.T	8.1	
Umicore	A supplier of automotive and homogeneous chemical catalysts, Umicore has developed catalysts for a broad range of Polymer Electrolyte Membrane (PEM) fuel cell technologies.	Euronext Brussels	UMI.BR	12.2	
Baker Hughes	Baker Hughes announced its commitment to reduce its emissions by 50% by 2030 and achieve net zero by 2050 whilst investing in a wide range of advanced technologies. As part of this commitment, the company signed an agreement with H2U to deploy hydrogen-fired gas turbines at Port Lincoln in Australia.	NYSE	BKR	16.0	
Aperam	Aperam is a global producer of stainless, electrical and specialty steel. Its products include coated stainless steel for bipolar plates in the production of PEM fuel cells.	Euronext Amsterdam	APAM.AS	2.4	
Energy Suppliers					
Engie	ENGIE aims to operate across the entire value chain of renewable hydrogen, from carbon-free power generation to the three key end uses: mobility, industry and energy storage. Engie is one of the partners in the Hympulsion project in the Auvergne Rh□ne Alpes Region, which expects to deploy 20 green hydrogen-filling stations in the region by the end of 2021.	Euronext Paris	ENGIE.PA	31.1	
E.ON	E.ON launched its "Green gas from green power" initiative that seeks to convert and store energy produced by renewable sources into hydrogen gas. The company plans to implement Power-to-Gas (P2G) plants, which will convert locally produced energy from wind and solar into hydrogen gas & synthetic methane which can then be fed directly into gas distribution grids.	Frankfurt Stock Exchange	EONGn.DE	30.6	
EDF	EDF is leading the Hydrogen to Heysham (H2H) consortium in the UK, which seeks to use the low carbon, low cost electricity from the Heysham nuclear power station to produce hydrogen gas in bulk from electrolyzers. The hydrogen produced could then be used for various applications including powering vehicles, supplying industrial processes and even to inject it into the UK gas network.	Euronext Paris	EDF.PA	31.1	
Enel	Enel announced it would launch a green hydrogen business in 2021, with plans to develop green hydrogen production facilities supplied with electricity from its renewables pipeline around the world.	Milan Stock Exchange	ENEI.MI	91.5	
Buildings					
Worcester Bosch (Bosch)	Worscester Bosch, a subsidiary of the Bosch group, has developed a prototype hydrogen-fired boiler for household and commercial applications.	National Stock Exchange of India	BOSH.BO	5.3	●
Giacomini Group	Giacomini has developed the H2ydroGEM, a hydrogen-powered domestic boiler that can be used for household heating applications, based on a catalytic burner which produces thermal energy during the reaction process.	N/A			
Viessmann Group	Viessman Group has developed the Vitovalor series of hydrogen-fuelled boilers and heating systems, providing simultaneous heating and hot water using fuel cell technology to convert hydrogen into energy. The company's hydrogen-based boilers have mostly domestic/household applications.	N/A			
SOLIDpower	The SOLIDpower Group develops, manufactures and markets fuel cell systems for generating power and heat in residential and commercial buildings at locations in Italy, Germany, Switzerland and Australia.	N/A			
Other global partners in clean hydrogen projects					
Equinor	Equinor is leading a project to develop one of the first global large-scale facilities to produce hydrogen from natural gas in combination with carbon capture and storage (CCS). The project, called Hydrogen to Humber Saltend (H2H Saltend), provides the beginnings of a decarbonized industrial cluster in the Humber region, the UK's largest by emissions.	Olso Stock Exchange	EQNR.OL	49.0	
RDShell	This year, the firm's Netherlands arm published plans to construct new wind farms in the North Sea, with a total capacity of 3-4MW, in order to feed the electrolyzer of a "mega-hydrogen" facility in Eemshaven. The wind facility and hydrogen hub would be completed in 2030 according to the plan. RDShell, Dutch gas grid operator Gasunie and the port of Groningen are the founding partners of the NorthH2 project, with the trio looking for others to join the consortium during the one-year feasibility study. They hope to develop a "European Hydrogen Valley" cluster. The company also has a wide chain of global hydrogen fueling stations.	London Stock Exhange/ Euronext Amsterdam	RDSa.AS/ RDSb.L	125.5	
TOTAL SA	TOTAL is one of the 13 inaugural members of the Hydrogen Council. According to the company, TOTAL's German arm has opened one of the most modern stations in Karlsruhe. In 2019, the company signed a cooperation agreement with the Sunfire cleantech company to integrate capture waste heat and CO_2 at a German refinery to create synthetic methanol and hydrogen to be used to reduce energy and transport emissions.	Euronext Paris	TOTF.PA	102.4	

** Other global partners in clean hydrogen projects and members of the hydrogen council are involved in a wide range of activities.*
Whilst in this list we cover a borad range of companies involved in all parts of the hydrogen supply chain, we note that the list is not exhaustive.

Source: Company data, Thomson Reuters Datastream, Goldman Sachs Global Investment Research

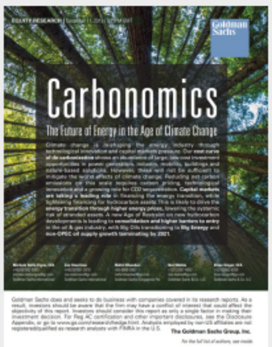
Related research

Carbonomics: The green engine of economic recovery

June 16, 2020

Clean tech has a major role to play in the upcoming economic recovery. Leveraging our Carbonomics cost curve, we estimate that clean tech has the potential to drive US$1-2 tn pa of green infrastructure investments and create 15-20 mn jobs worldwide, through public-private collaboration (e.g., "The Green Deal"). Renewable power will become the largest area of spending in the energy industry in 2021, on our estimates, surpassing upstream oil & gas for the first time in history, driven by bifurcating cost of capital (up to 20% for long-term oil projects, down to 3-5% for renewables).

By Michele Della Vigna, CFA, Zoe Stavrinou, Alberto Gandolfi, Ajay Patel, Sharmini Chetwode, Ph.D, Evan Tylenda, CFA, Derek R. Bingham and Neil Mehta



Carbonomics: The Future of Energy in the Age of Climate Change

Dec 11, 2019

Climate change is re-shaping the energy industry through technological innovation and capital markets pressure. Our cost curve of de-carbonization shows an abundance of large, low-cost investment opportunities in power generation, industry, mobility, buildings and nature-based solutions. However, these will not be sufficient to mitigate the worst effects of climate change. Reducing net carbon emissions on this scale requires carbon pricing, technological innovation and a growing role for CO2 sequestration.

By Michele Della Vigna, CFA, Zoe Stavrinou, Nikhil Bhandari, Neil Mehta, Brian Singer, CFA, Geydar Mamedov, Mark Wiseman, CFA, Bruno Amorim, CFA, Baden Moore, Duncan Milligan, Sahar Islam, Derek R. Bingham, Tristyn Martin, Vinit Joshi, Karl Blunden, CFA

Carbonomics Q&A: Five key questions from investors

Feb 3, 2020

Five key questions emerged from meetings with more than 100 investors on our 'Carbonomics' analysis, which we address in detail in this follow-up:

1. What technologies could meaningfully change the shape of the carbon abatement cost curve?
2. If energy storage fails to innovate, can carbon storage be the solution?
3. How important is carbon pricing?
4. What carbon price is required to achieve net zero carbon?
5. Are we facing a stranded assets crisis?

By Michele Della Vigna, CFA, Zoe Stavrinou, Derek R. Bingham

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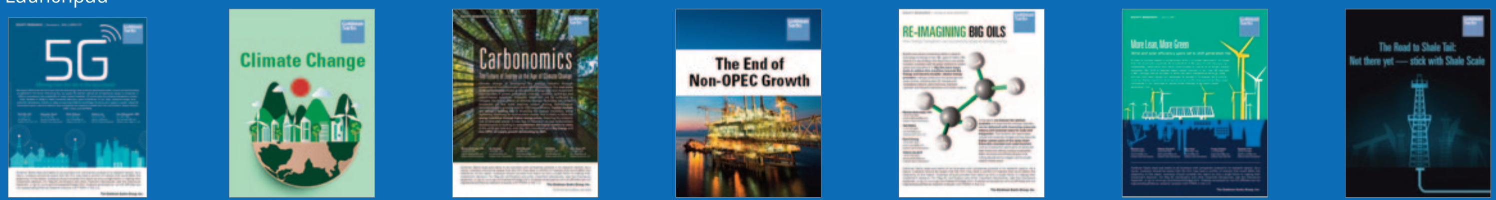

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