EQUITY RESEARCH | September 22, 2020 | 9:41PM BST

Goldman Sachs

The following is a redacted version of the original report. See inside for details.

Green Hydrogen

The next transformational driver of the Utilities industry

In our Carbonomics report we analysed the major role of clean hydrogen in the transition towards Net Zero. Here we focus on Green hydrogen ("e-Hydrogen"), which is produced when renewable energy powers the electrolysis of water. Green hydrogen looks poised to become a once-in-a-generation opportunity: we estimate it could give rise to a €10 trn addressable market globally by 2050 for the Utilities industry alone.

e-Hydrogen could become pivotal to the Utilities (and Energy) industry, with the potential by 2050 to: (i) turn into the largest electricity customer, and double power demand in Europe; (ii) double our already top-of-the-street 2050 renewables capex EU Green Deal Bull Case estimates (tripling annual wind/solar additions); (iii) imply a profound reconfiguration of the gas grid; (iv) solve the issue of seasonal power storage; and (v) provide a second life to conventional thermal power producers thanks to the conversion of gas plants into hydrogen turbines.

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The following is a redacted version of Goldman Sachs Research's report "Green Hydrogen: The next transformational driver of the Utilities industry" originally published Sept. 22, 2020 (78pgs). All company references in this note are for illustrative purposes only and should not be interpreted as investment recommendations.

e-Hydrogen In numbers

€2.2 trn

Addressable Green Hydrogen market in Europe for Utilities by 2050E

€10 trn

Addressable Green Hydrogen market globally for Utilities by 2050E

c.65%

Estimated share of green hydrogen production cost to come from electricity (Europe)

>650x

Increase in the European electrolyser market by 2030E (vs today), based on the EU Hydrogen Strategy

>8,000x

Increase in the European electrolyser market by 2050E (vs today), based on the EU Hydrogen Strategy

Nearly 3x

Increase in European renewables annual additions vs Green Deal Bull Case (from 35 GW to 90 GW pa) until 2050E to power electrolysers

c.100%

Increase in European power demand between 2020-50E, just from electrolysers, turning clean hydrogen into the largest electricity customer

Less than €1.5/kg

Estimated cost of clean hydrogen from solar in Iberia over the longer run

Source: Goldman Sachs Global Investment Research, European Commission

Green Hydrogen: Key Conclusions

In our Carbonomics report we analysed the major role of clean hydrogen in the transition towards Net Zero as a means to decarbonise the most challenging parts of the de-carbonisation cost curve: manufacturing, heavy transport and seasonal storage. In this report we focus on the implications of green hydrogen ("e-Hydrogen") on the Utilities sector. We estimate that e-Hydrogen could give rise to a €10 trillion addressable market globally by 2050E (c.13% of global GDP 2018) for the Utilities industry. Looking out to 2050, our analysis suggests that, in Europe, green hydrogen has the potential to:

1. **Double power demand:** As electrolysis (the process that creates green hydrogen by separating water into hydrogen and oxygen) is a very electricity intensive process, we estimate that – based on the European Commission's working assumption of 500 GW electrolysers by 2050 (vs 0.1 GW today) – green hydrogen could become the largest electricity customer. Power demand for electrolysis alone could double European electricity consumption, we estimate.
2. **Double our (top of the street) EU Green Deal Bull case scenario renewable capacity estimates:** Hydrogen from electrolysis would only be clean if powered by renewable sources. As a theoretical 1 GW electrolyser would require at least 2 GW of dedicated wind/solar capacity, the EU Hydrogen Strategy implies the need for nearly 1,300 GW of dedicated, incremental renewable capacity (vs c.350 GW today in Europe, a 4x increase). This implies an effective doubling of our (top of the street) 2050 EU Green Deal Bull case for wind/solar capacity.[1]
3. **Imply a profound reconfiguration of the gas grid:** In line with the EU Hydrogen Strategy, as more parts of the economy begin to rely on hydrogen (e.g. buses, tracks, trains, factories) and as the role of hydrogen begins to become more "decentralised", H_2 molecules will need to be transported through existing gas grids. The need to compress hydrogen (the H_2 molecule has a lower energy content than natural gas per cubic meter, but a much higher energy content than natural gas per kg, as we detail later in the report) and to better seal the pipes (the molecule is thinner than gas) would necessitate a profound reconfiguration of the transport gas grid.
4. **Solve the issue of seasonal storage:** Producing hydrogen during periods of high wind/solar availability would allow the reduction in renewables curtailment and make H_2 available for moments of high power demand, especially if characterised by an abnormally low level of availability of renewables. Hydrogen could be used in fuel cells or – more likely given better economics – (converted) gas fired plants.
5. **Provide a second life to conventional thermal power producers:** With a relatively modest investment, gas power plants could be converted to burn hydrogen instead; these H2T (hydrogen turbine) power plants could be used as "peaking facilities" to

[1] Our base case (published) forecasts and valuation conservatively model the EU Green Deal to 2035; our Green Deal Bull case (published in "The case for valuing renewables to perpetuity", 24 Aug 2020) extends this out further, to 2050, to reflect full implementation - all references/comparisons to our 2050 estimates in this report are for this Green Deal Bull Case scenario.

provide backup power in periods of abnormally high demand and/or extremely low production from renewables. This would imply that the existing CCGT fleet could enjoy a "hydrogen option value", so far an area largely overlooked.

Exhibit 1: Green hydrogen could...

Potential upside of green hydrogen on European utilities sector by 2050E

Green hydrogen could..

Double power demand
Green hydrogen could become the largest electricity customer.

Double our EU Green Deal scenario RES capacity estimates
The EC's Hydrogen Strategy vs our Green Deal scenario implies the need for c. 1,300 GW of dedicated, incremental renewable capacity (vs c.350 GW today in Europe, a 4x increase).

Imply a profound reconfiguration of the gas grid
As the role of hydrogen becomes more "decentralized", its molecules would have to be transported through existing gas grids.

Solve the issue of seasonal storage
Hydrogen production would:

- allow reduction in renewables' curtailment
- cater to high power demand, especially during abnormally low availability of renewables

Provide a second life to conventional thermal power producers
With modest investment, gas power plants can be converted to H2T (hydrogen turbine) power plants and be used as "peaking facilities" for backup power

Source: Goldman Sachs Global Investment Research

We see two incremental, top down implications from the widespread use of green hydrogen:

- **Re-regulation of European power generation markets,** reflecting the 2050 target for nearly 100% of production to come from renewables (typically awarded via auctions and – mostly – remunerated under visible contracts) or from hydrogen turbines (which, in virtue of their higher costs/low utilisation rates would have to be most likely remunerated on a regulated/contracted basis).
- **Reshaping of the energy map,** with the EU target that hydrogen could approach close to c.15% of primary energy consumption by 2050 (vs less than 2% today), countries with cheap renewable sources (e.g. Iberian solar or North Sea offshore wind) could become major producers (and exporters) of this "new", clean commodity.

Exhibit 2: Green hydrogen could also lead to...

Potential upside of green hydrogen by 2050E

Use of green hydrogen for harder-to-decarbonise industries could lead to:

Re-regulation of power generation markets

Nearly 100% of production would come from:

- Renewables (typically awarded via auctions and – mostly – remunerated under visible contracts)
- Hydrogen turbines (due to higher costs/low utilisation rates, they would have to be remunerated on a regulated/contracted basis)

Reshaping of the energy map

As hydrogen may reach c.15% of primary energy consumption (vs less than 2% currently), countries with cheap renewable sources (like Iberian solar or North Sea offshore wind) could become major producers (and exporters) of such "new", clean commodity.

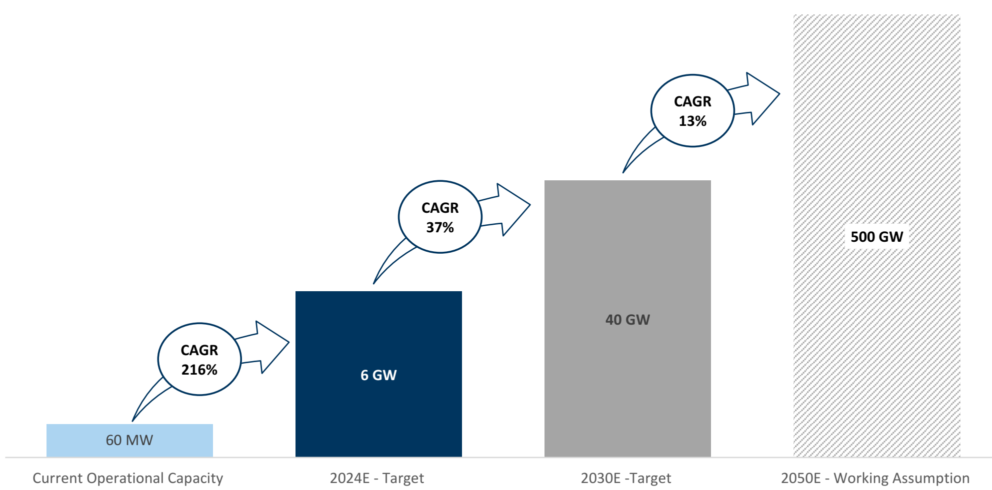
Source: Goldman Sachs Global Investment Research

Executive Summary

The EU 2030 Hydrogen Strategy: a concrete step in support of green hydrogen

On July 8, the European Commission published its 2030 Hydrogen Strategy. This is the first, concrete document which details the central role that hydrogen is to play in the European economy. The EU Hydrogen Strategy underpins the birth of an entirely new hydrogen industry largely based on green hydrogen: against the current electrolyser installed base of 0.1 GW, the EU targets 6 GW by 2024 and 40 GW by 2030, with a working assumption of 500 GW by 2050. Achieving these ambitious targets has major implications for the power demand needed to power the electrolysers – on renewables capacity and on gas infrastructure. The EU Hydrogen Strategy targets total investments of up to c.€400 bn through 2030 (with up to c.€47 bn towards electrolysers).

Exhibit 3: The EU Hydrogen Strategy to 2030 calls for a >650x increase in the electrolysis market
EU electrolyser capacity targets

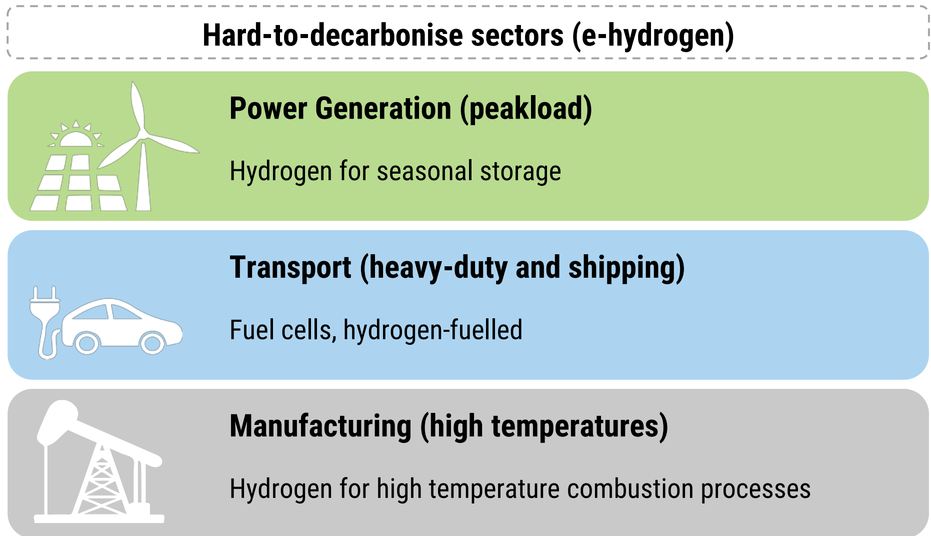


Source: European Commission, IEA, Goldman Sachs Global Investment Research

The "last mile" to reach full decarbonisation

As described in our Carbonomics report, at a high level hydrogen can be seen as an alternative fuel to diesel oil and natural gas. But hydrogen requires other sources of energy (e.g. natural gas or electricity/water) to be generated; this is why the production of hydrogen is more expensive (and less energy efficient) than natural gas or electricity, which are input costs in the production of H_2. But in an increasingly decarbonising world (where fossil fuels are likely to be increasingly banned or taxed for their emissions), hydrogen offers the potential as a key energy source to reach the "last mile" of decarbonisation.

Exhibit 4: Decarbonising the remaining 10%-20% is relatively difficult; hydrogen would be crucial here



Source: Goldman Sachs Global Investment Research

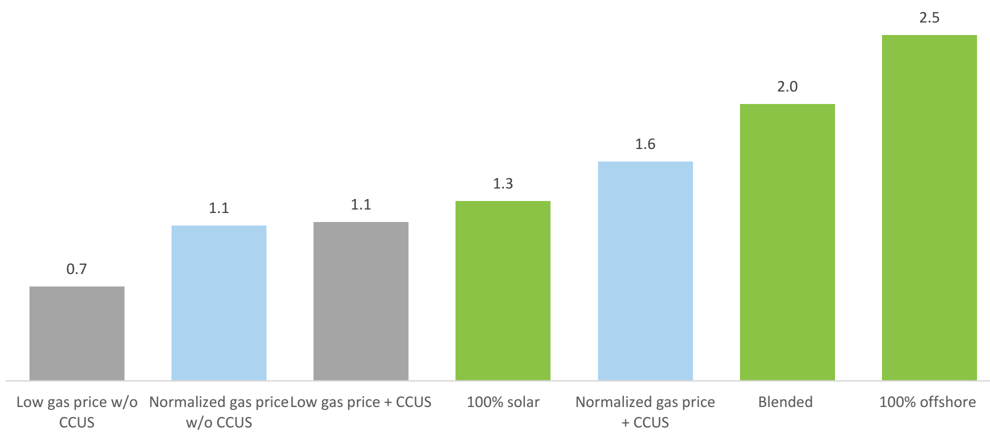
The economics: we expect steep improvements

We analyse the economics of hydrogen production under two different processes (which we detail in the section "Hydrogen: a primer"):

(i) **Blue Hydrogen** (natural gas + CCUS), which comes from natural gas and sequestrates carbon emissions; currently blue hydrogen is the cheapest "clean" alternative.

(ii) **Green Hydrogen**, which comes from electrolysis. Interestingly, our scenario analysis shows that, as renewable production gets cheaper and electrolysers become more efficient, green hydrogen costs would become increasingly competitive, although only solar-powered electrolysers are more competitive than blue hydrogen by 2050.

Exhibit 5: In 2050, our scenarios imply that only solar-powered electrolysers are more competitive than blue hydrogen
LCOH under different scenarios in 2050E (€/kg H2)



Source: IEA, ScienceDirect, U.S. Department of Energy, Company data, Goldman Sachs Global Investment Research

Addressable (global) market of €10 trillion by 2050E, >€2 trillion of which in Europe

We estimate the green hydrogen industry in Europe could attract >€2 trillion of investments by 2050 (supported by the EU Hydrogen Strategy, which we describe later in this report). This includes: (i) c.1,100-1,300 GW of dedicated renewable facilities (implying major upside to our Green Deal Bull case 2050 estimates, effectively doubling capacity and tripling annual additions); (ii) up to 500 GW electrolysers (vs 0.1 GW currently); and (iii) the reconfiguration of the gas infrastructure grid and the build-up of hydrogen-fuelled power plants to deal with backup needs and solve the problem of seasonal storage.

Exhibit 6: More than two-thirds of the investment in hydrogen in Europe to be in dedicated renewable capacity
Estimated addressable market by category in Europe, 2050E

	Capex to 2050	% of e-Hydrogen addressable market	Function
Renewables	€1.4 trn	c.65%	To power 500 GW of electrolyzers
Hydrogen power plants	€0.4 trn	c.15%	450-500 GW of peaking capacity to meet 10% of EU demand
Electrolyzers	€0.4 trn	c.15%	500 GW of electrolyzers
Gas Infrastructure	€0.1 trn	c.5%	Pipeline reconfiguration
Total	**€2.2 trn**	**100%**	

Source: European Commission, Goldman Sachs Global Investment Research

Globally, the e-hydrogen addressable market could potentially reach roughly €10 trillion in 2050, on our estimates, or c.13% of global GDP (2018).

Exhibit 7: We estimate a global addressable market for hydrogen at nearly €10trn by 2050E
Estimated hydrogen addressable global market, 2050E (selected parameters as of 2018)

	EU	USA	Asia
Electricity Consumption in PWh	2.9	3.9	10.4
Installed Capacity in GW	1,055	1,095	3,129*
Renewables Capacity in GW	312	144	480
Population in mn	447	327	4,561
GDP current prices in $ trn	15.9	20.6	31.5**
Hydrogen addressable market in €trn	**2.2**	**2.9**	**4.4**

Global addressable market → **c. €10trn**

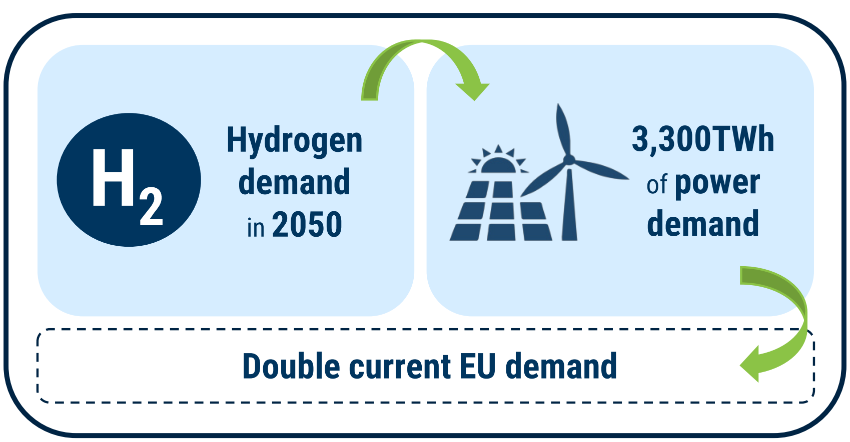
*based on aggregates for different years and excludes North Korea and Macao **excludes Palestine and Syria

Source: Enerdata, EIA, IRENA, IMF, United Nations, CIA, Burma Ministry of Electricity and Energy, Statista, Palestine Economic Policy Research Institute, World Bank, Goldman Sachs Global Investment Research

The rise of a new customer: electricity demand to double by 2050E

The production of green hydrogen is highly electricity intensive. We estimate that to achieve the 500 GW electrolysers assumption in the EU's 2050 hydrogen strategy, power demand would double vs current levels, all else being equal.

Exhibit 8: Hydrogen demand by 2050E could double the current power demand consumption in Europe

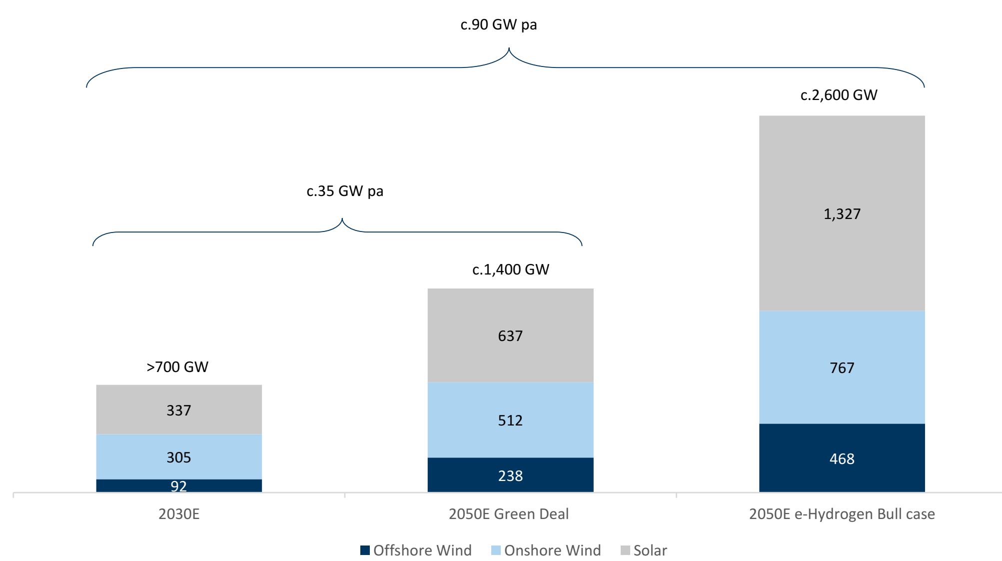


Source: Goldman Sachs Global Investment Research

Renewables: additions pa to triple vs our 2050 Green Deal estimates

To meet the power demand required for the EU's 500 GW electrolyser aspirations, we estimate some 1,100-1,300 GW of dedicated RES capacity – equivalent to incremental investments in renewables of €1.4 trillion – would be needed. This implies double our (top-of-the-street)[2] 2050 estimate of €1.2 trn capital spending. It implies nearly triple our (top-of-the-street) addition estimates for wind and solar to c.90 GW per year, starting towards the end of this decade until 2050.

Exhibit 9: Adding in the power required for hydrogen electrolysis, European RES additions would nearly triple relative to our Green Deal 2050 forecasts
Cumulative wind and solar installed base in Europe and annual additions (ex hydro) scenarios



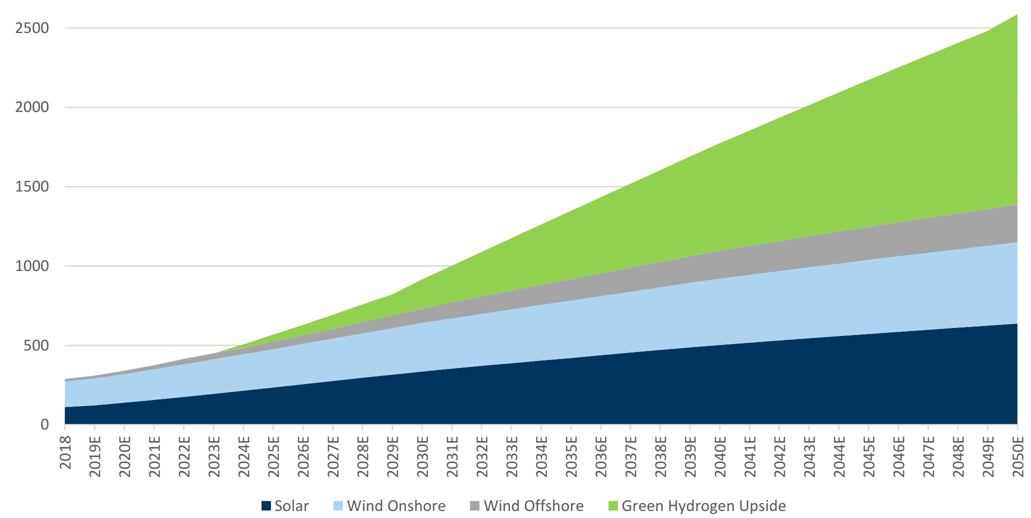
Source: Goldman Sachs Global Investment Research

The exhibit below shows the estimated evolution of wind (onshore and offshore) and solar in Europe throughout 2050. The base case estimates reflect EU Green Deal targets (the EU Green Deal Bull Case), while the upper curve shows the upside from Green Hydrogen (our e-Hydrogen Bull case). Under this new scenario, 2050E renewable capacity would double; during 2030-50E (when most of these investments would have to be carried out), annual wind and solar additions could triple vs the Green Deal scenario.

[2] Our conversations with corporates and investors suggest that the financial community has not fully captured the magnitude of the Green Deal upside potential. Our top down capacity estimates for wind and solar therefore appear amongst the highest on the street. We are also slightly above industry bodies such as the International Renewable Agency and IRENA.

Exhibit 10: Capacity additions for green hydrogen and electrolysis are double our 2050E Green Deal estimates and triple the additions during 2030-50E

Cumulative capacity additions under Green Deal 2050E and e-Hydrogen Bull case scenarios (GW)



Source: Goldman Sachs Global Investment Research

Gas grids: in need of a major reconfiguration

As hydrogen becomes increasingly decentralised (transport, factories), the demand for "hydrogen ready" infrastructure will intensify. A study released by ten of the largest European gas transport system operators estimates €27-€64 bn (€40 bn at the midpoint) of investment needed by 2040 to reconfigure gas pipelines to create a dedicated hydrogen infrastructure to move hydrogen across Europe. The study argues that the combination of centralised hydrogen production coupled with the reconfiguration of the existing gas transport grid (and storage infrastructure) would be cheaper than producing hydrogen from smaller electrolysers dedicated to on-site consumption.

Exhibit 11: An 23,000 km dedicated network to transport hydrogen across Europe estimated at c. €40bn investment (midpoint) by 2040

European Hydrogen Backbone study, initial proposed costs

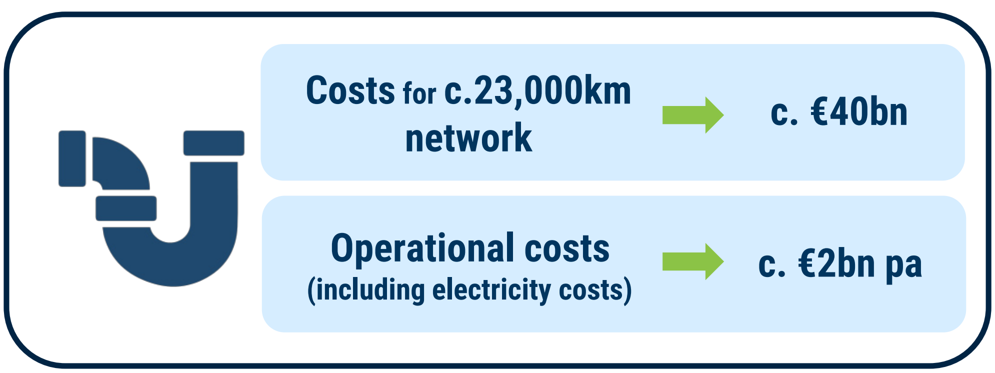


Exhibit shows midpoints of the estimated ranges of €27-64 bn and € 1.6-3.5 bn, respectively

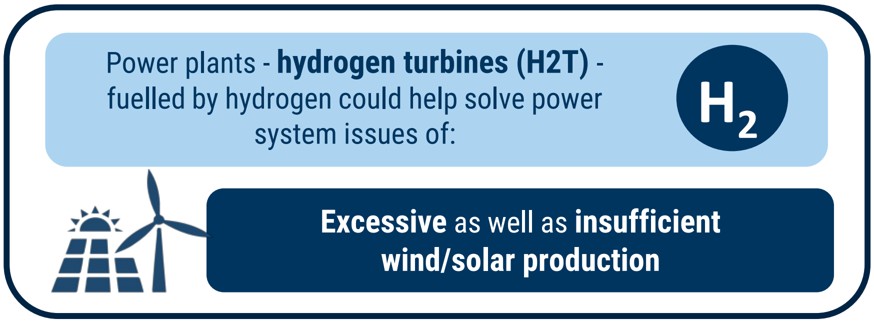
Source: European Hydrogen Backbone study (July 2020), Goldman Sachs Global Investment Research

A new wave of (regulated) power plants: a second life for legacy generators

On our estimates, once 90% of production from renewables is reached, power systems would face several challenges: (1) hours of excessive RES production and, therefore, curtailments: we estimate that at a 90% share in the power generation mix, up to 20% of the output would have to be curtailed; (2) hours of insufficient wind/solar production, which would require responsive backup generation; and (3) rising pressure on the resilience of the power grid owing to the high output volatility.

In our view, green hydrogen would solve the first two problems, whilst allowing for zero emissions. We anticipate a wave of backup power plants – Hydrogen Turbines (H2T) – fuelled by hydrogen, which would be a carbon free form of backup.

Exhibit 12: Power plants with hydrogen turbines could potentially solve some power system issues

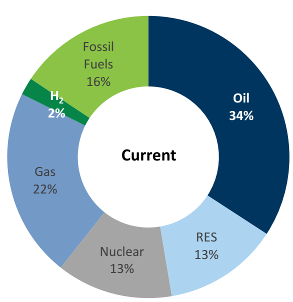


Source: Goldman Sachs Global Investment Research

Reconfiguring the energy map

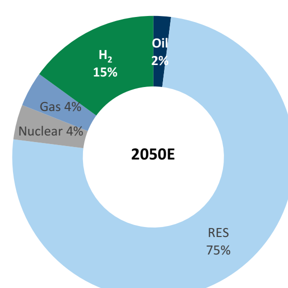
Considering the EU's overarching goal to decarbonise its economy and the requisite rise in clean hydrogen within primary energy consumption, we believe that the upstream energy map could gradually shift in favour of low-electricity cost producers such as Spain. We also believe offshore wind could be highly instrumental to support electrolysis owing to the vast potential to develop wind in the North Sea and Baltic (as demonstrated by a WindEurope study, discussed here) and to the high capacity factor of offshore wind.

Exhibit 13: Currently, hydrogen's share in EU's primary energy mix is less than 2%...
Share of different energy sources in EU's primary energy mix, 2019



Source: EEA, Goldman Sachs Global Investment Research

Exhibit 14: ...and we estimate this to reach c.15% by 2050
Share of different energy sources in EU's primary energy mix, 2050E



Source: Goldman Sachs Global Investment Research

What are the main bottlenecks and what could go wrong in our thesis?

As we demonstrate throughout the report, the green hydrogen opportunity is vast and truly game changing for the Utilities industry. Yet we identify some bottlenecks and risks, which we will be monitoring, which may delay or derail our thesis. These include:

- **Supply constraints in electrolysis**: considering the electrolysis industry is its early stages, the acceleration implied in the EU Hydrogen Strategy could create cost inflation or supply restraints in equipment, at least temporarily.
- **Permitting delays**: despite the strong policy support by the EU and the central governments in several major countries, local authorities may be (at least temporarily) overwhelmed by the strong acceleration in requests to: develop renewables, install new equipment (electrolysers, Hydrogen Turbine power plants) and upgrade gas pipelines. As seen in US Offshore or in Germany, sometimes environmental permits and local administration authorisations can create significant delays.
- **RES returns**: as discussed in several reports (European Renewable Majors: The case for valuing renewables to perpetuity), returns by the European renewables Majors remain attractive, at 7-11% on a pre-tax basis by our estimates. Although we expect marginal returns are likely to settle at 6%-7%, this is mostly due to the reduction in the cost of capital. We believe that – in the nearer term – the offshore industry could face the largest threat for two main reasons: (i) the acceleration in auctions is not due until 2023 at best, to c.15 GW pa vs c.10 GW pa during 2020-22; and (ii) the rising ambitions of European Big Oils could lead these companies to take a c.25%-35% market share in offshore, which compares with very low single digit (1%-2%, on our numbers) in onshore wind and solar.
- **Blue hydrogen economics**: currently the cost of blue hydrogen (natural gas + CCUS) is more competitive than green hydrogen owing to low gas prices, no carbon taxes and the relatively high cost of electrolysers. Although gas prices are likely to normalise to their LT average, carbon taxes on imported fuels may be introduced (as discussed already in EU papers) and the cost of renewables/electrolysers look set to fall (more details throughout the report), the (currently) better economics in blue hydrogen could ultimately lead the EU to revise ambitions in green hydrogen.

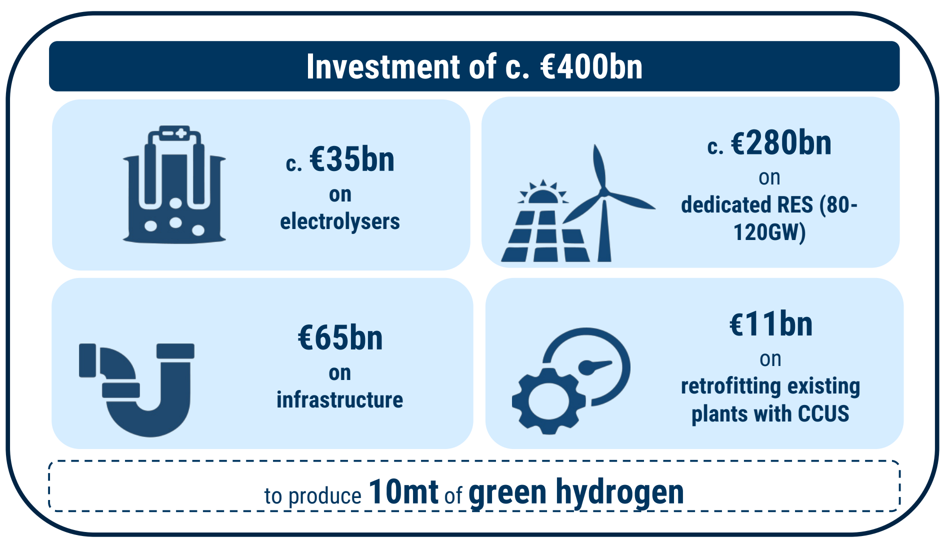
The EU 2030 Hydrogen Strategy

In July, the European Commission published its 2030 Hydrogen Strategy — the first, concrete document which details the central role that clean hydrogen is to play in the European economy. The EU Hydrogen Strategy underpins the creation of an entirely new green hydrogen industry: against the current electrolyser installed base of 0.1 GW, the EU targets 6 GW by 2024 and 40 GW by 2030, with a working assumption of 500 GW by 2050. Achieving these ambitious targets has major implications for the electricity demand needed to power the electrolysers, the incremental renewables capacity and the reconfiguration of the gas transport/storage infrastructure. The EU Hydrogen Strategy targets total investments of up to €400 bn through 2030 (up to €47 bn of which allotted for electrolysers).

The EU hydrogen targets c.€400 bn investments by 2030

On July 8, the European Commission unveiled its hydrogen strategy to support the 2050 carbon neutrality goal. This foresees investments of up to c.€400 bn (through 2030) across electrolysers, renewables (used to power the electrolysers) and gas infrastructure. The roadmap would effectively create a hydrogen ecosystem, which is largely non-existent today, thanks to a target of 40 GW of electrolysers (vs 0.1 GW currently), the reconfiguration of gas pipes and incremental wind/solar to support the creation of green hydrogen.

Exhibit 15: In its Hydrogen Strategy, the EC outlines an investment agenda of €320-458bn in hydrogen until 2030
EU hydrogen investment targets, 2030 (midpoint of target ranges shown)

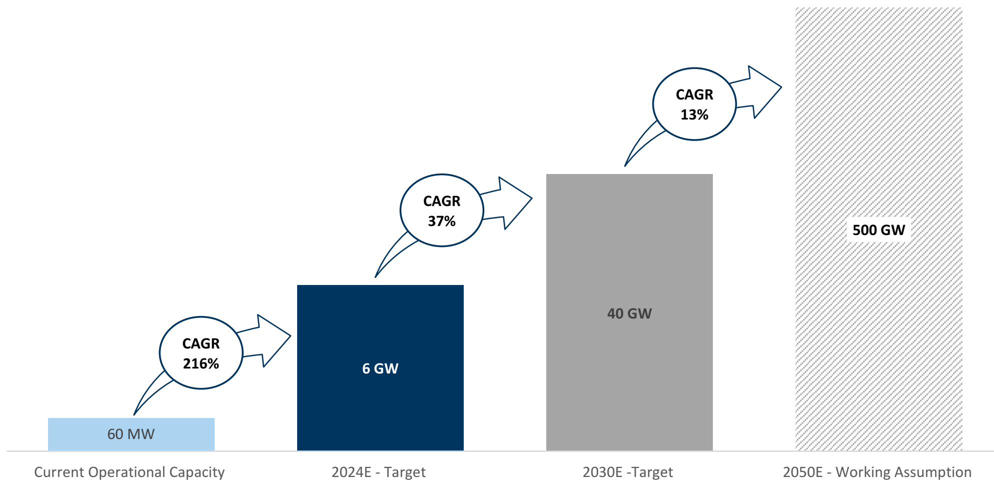


Source: European Commission, Goldman Sachs Global Investment Research

Electrolysers: >650-fold expansion in the market

The EU targets the installation of at least 6 GW of electrolysers by 2024 and at least 40 GW by 2030. Compared to the meagre capacity of 60 MW of electrolysers today, this would rapidly increase installations at a CAGR of >200% to meet 2024 targets and an incremental CAGR of >35% to meet 2030 targets.

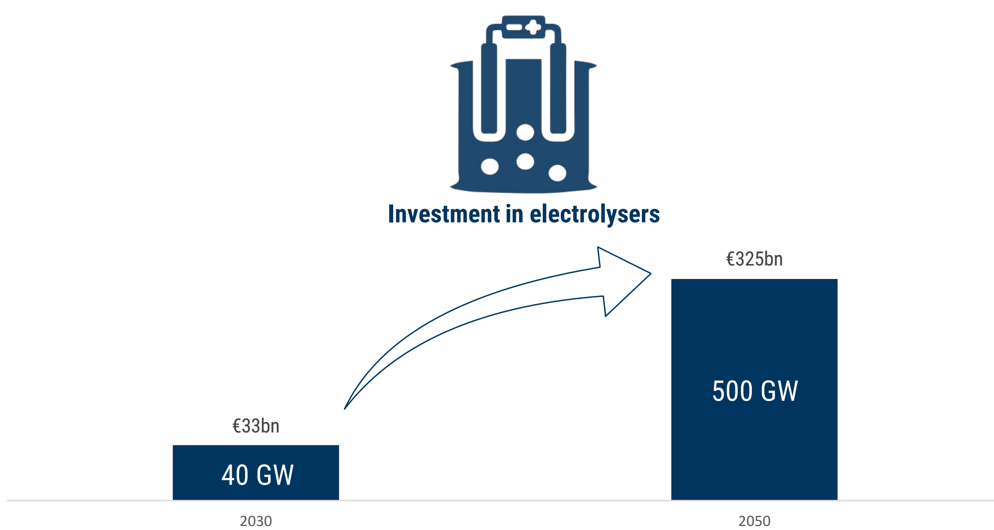
Exhibit 16: The EU Hydrogen Strategy implies >650x increase in the electrolysis market by 2030
EU Hydrogen Strategy electrolyser capacity targets



Source: European Commission, IEA, Goldman Sachs Global Investment Research

The strategy outlines investments in electrolysers of c.€33 bn to 2030 (at the midpoint of the target range), which would increase exponentially to c.€325 bn by 2050 as renewable hydrogen technologies reach maturity and are deployed on a larger scale.

Exhibit 17: The EU Hydrogen Strategy targets c.€325 bn cumulative investment in electrolysers by 2050
EU Hydrogen Strategy electrolyser investment targets (midpoint of target ranges shown)

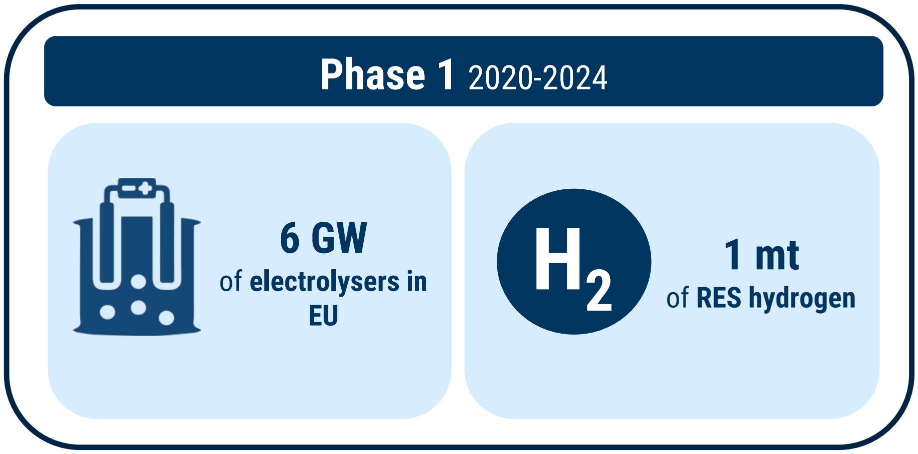


Source: European Commission, Goldman Sachs Global Investment Research

Phase 1: "cleaning up the existing hydrogen production"

The first phase of EU Hydrogen Strategy covers 2020-2024. In this phase, the EU plans to decarbonise existing hydrogen production through installation of at least 6 GW electrolysers. Hydrogen would continue to be used in the refining oil industry and in the fertilizing industry.

Exhibit 18: In phase 1, EU plans to install at least 6 GW of electrolysers to produce up to 1 mn tonnes of renewable hydrogen
EU Hydrogen Strategy electrolyser targets



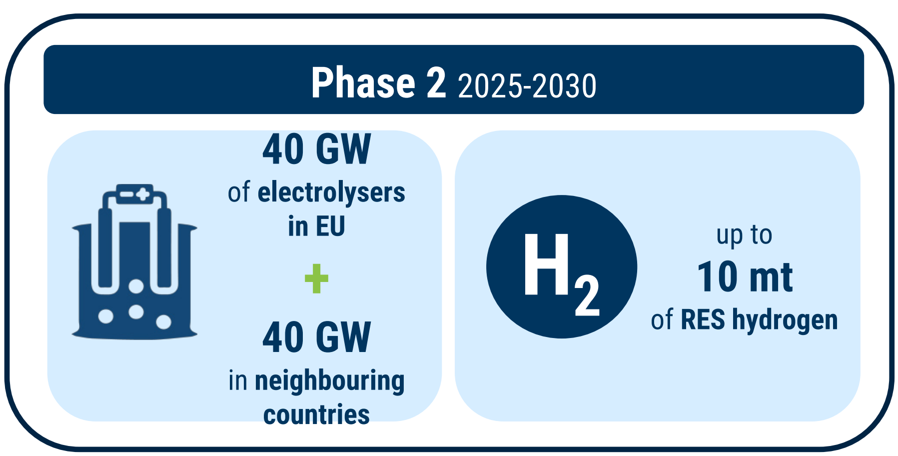
Source: European Commission, Goldman Sachs Global Investment Research

Phase 2: using hydrogen in industrial processes and for transport

In the second phase, covering 2025 and 2030, EU targets the installation of least 40 GW of renewable hydrogen electrolysers by 2030 (plus 40 GW in neighbouring countries) to be able to utilise up to 10 mn tonnes of renewable hydrogen.

In this phase, hydrogen is expected to be increasingly used in industrial processes (e.g. steel) and in transport (e.g. trucks, rail, maritime). Hydrogen would also start playing a role balancing a RES-based electricity system by providing flexibility (transforming electricity into hydrogen where renewables are abundant and cheap) and by being used for daily/seasonal storage.

Exhibit 19: In phase 2, EU plans to install at least 40 GW of electrolysers to produce up to 10 mn tonnes of renewables hydrogen
EU Hydrogen Strategy electrolyser targets



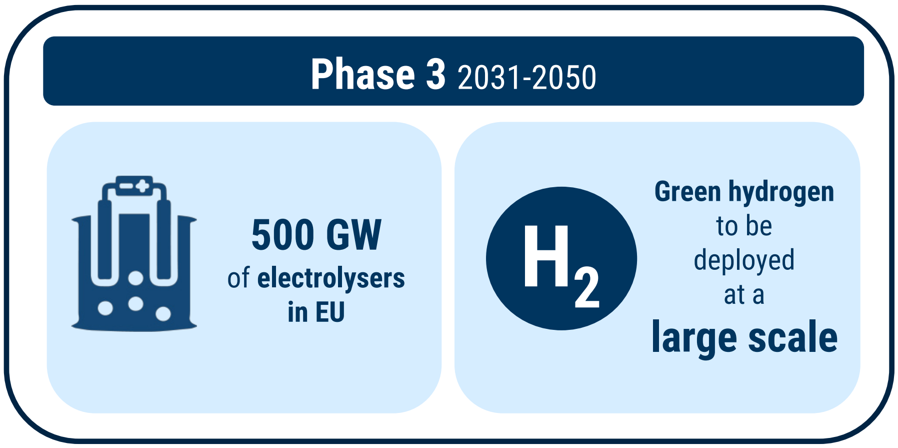
Source: European Commission, Goldman Sachs Global Investment Research

Phase 3: a more comprehensive use of hydrogen in the economy

The third part of EU Hydrogen Strategy covers 2030 and 2050, when renewable hydrogen technologies are expected to reach maturity and be deployed at a large scale to reach a wider range of sectors in the economy (aviation, shipping, commercial buildings and hard-to-decarbonise industrials).

This phase would require a massive increase of RES production, as the EC anticipates c.25% of renewable electricity might be used for renewable hydrogen production by 2050. The EC's working assumption is 500 GW electrolysers by then.

Exhibit 20: In phase 3, c. 25% of renewable electricity would be used to produce green hydrogen which will be deployed at a large scale
EU Hydrogen Strategy electrolyser targets

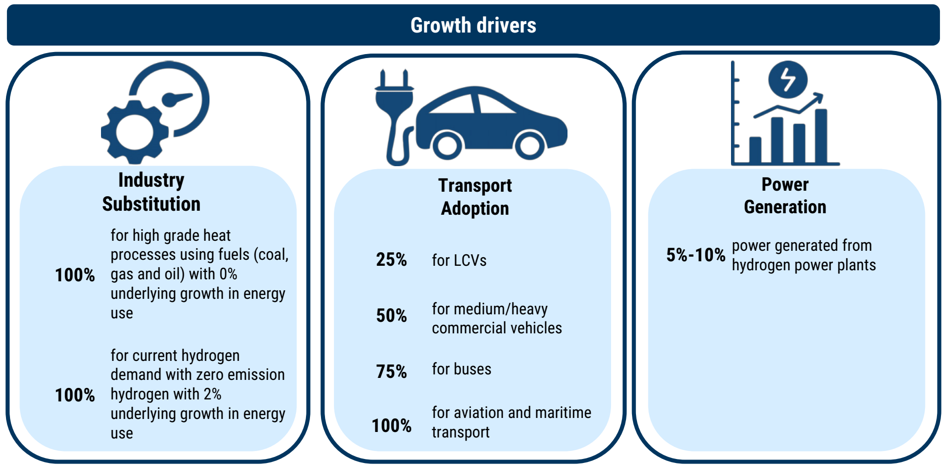


Source: European Commission, Goldman Sachs Global Investment Research

Hydrogen bottom up demand

We estimate that in a scenario where hydrogen adoption becomes highly widespread in Europe to meet the EU's 2050 ambitions, incremental demand from Europe alone would roughly be c.15% more than present *global* demand. Our Bottom Up hydrogen demand analysis outlines how hydrogen demand in Europe could grow to a multiple of what it is today, driven by: (i) widespread adoption of fuel cells to decarbonise the transport sector, with uptake for buses/trucks, ships and planes looking particularly promising; (ii) the decarbonisation of industrial processes through the adoption of zero emission hydrogen as both a substitute to grey hydrogen currently being used and as an alternative to coal, gas and oil as a fuel for high grade heat processes; and (iii) the adoption of hydrogen as the source of energy, which we estimate could supply up to 5%-10% of European power demand.

Exhibit 21: Hydrogen demand growth drivers
Bottoms Up hydrogen demand model



Source: Goldman Sachs Global Investment Research

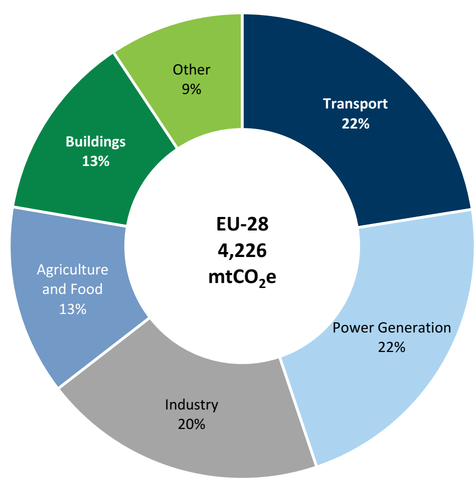
Hydrogen: the "last mile" to reach Net Zero

As described in our Carbonomics report, at a high level, hydrogen can be seen as an alternative fuel to diesel oil and natural gas. But hydrogen requires other sources of energy (e.g. natural gas or electricity/water) to be generated; this is why the production of hydrogen is more expensive (and less energy efficient) than natural gas or electricity, which are input costs in the production of H_2. In an increasingly decarbonising world (where fossil fuels are likely to be increasingly banned or taxed for their emissions), hydrogen offers the potential as a key energy source to reach the "last mile" of decarbonisation.

Why Green Hydrogen: tackling the "last mile" of decarbonisation

In our Green Upside report, we demonstrated that the immense task of fully decarbonising the European economy - the main objective of the EU Green Deal - can be summarized into an exercise of bringing to net zero five main segments of the economy: power generation (>20% of EU emissions), transport (>20% of emissions), manufacturing/industrial processes (c.20%), heating (c.15%) and agriculture/food production (>10%).

Exhibit 22: GHG emissions in EU-28 accounted to >4,000mtCO2e in 2018
EU-28 GHG emissions by sector (mtCO2e, 2018)



Source: EEA, Goldman Sachs Global Investment Research

Thanks to its properties and its clean nature, clean hydrogen (green and blue + CCUS) appears particularly suitable for the hard-to-decarbonise ("last mile") parts of the economy such as: (1) heavy-duty transport; (2) industrial processes that require high-temperature-combustion (e.g. steel factories); and (3) seasonal storage in power generation.

We see a particularly central role for green hydrogen (or as we refer it to, e-Hydrogen);

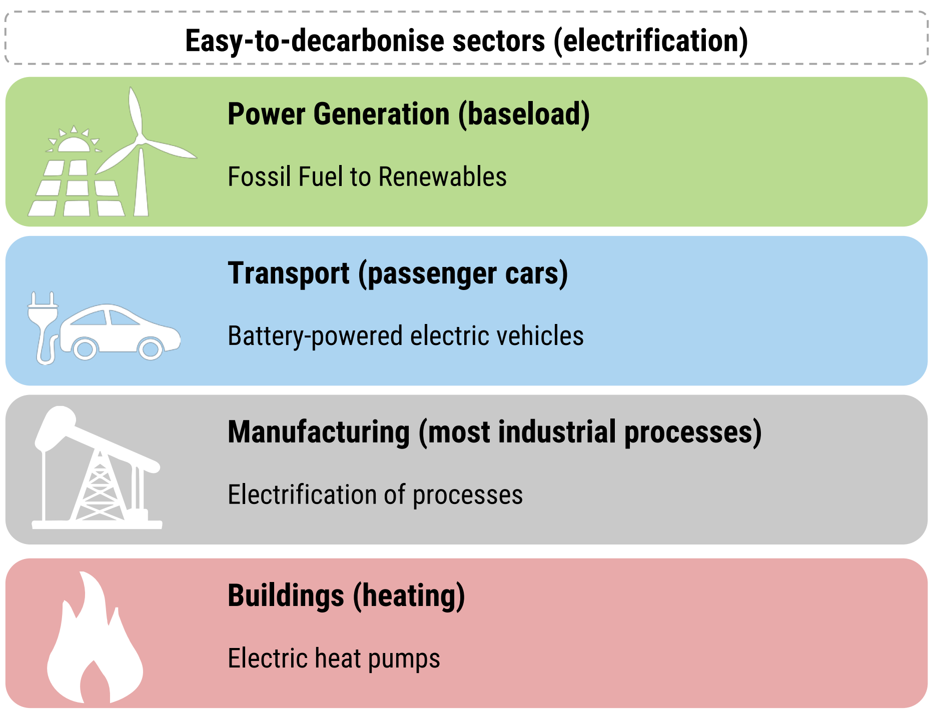
this is H_2 created via electrolysis, a process that utilises electricity to break up water (H_2O) into hydrogen (H_2) and oxygen. Electrolysis is very electricity intensive and more expensive than the equivalent blue hydrogen (which is produced via natural gas). Electrolysis generates no emissions and releases oxygen as byproduct.

Easy parts of the economy to decarbonise

As described in our previous research, decarbonising c.80% of the economy can be seen as a relatively straightforward exercise as technologies are widely available, at reasonable (or attractive) costs. For instance:

- **Power generation** can be mostly decarbonised thanks to the transition to renewables (wind/solar) in lieu of fossil fuel power plants.
- **Transport** can partly be addressed (passenger cars) thanks to the rising offering of battery powered, electric vehicles.
- **Heating** could gradually become electric thanks to heat pumps and overall consumption could be greatly reduced via energy efficiency measures.
- **Manufacturing** processes (where high temperatures are not needed) can also be largely electrified.

Exhibit 23: Decarbonising c.80% of the economy can be seen as a relatively straightforward exercise as technologies are widely available, at reasonable (or attractive) costs
Easy-to-decarbonise sectors



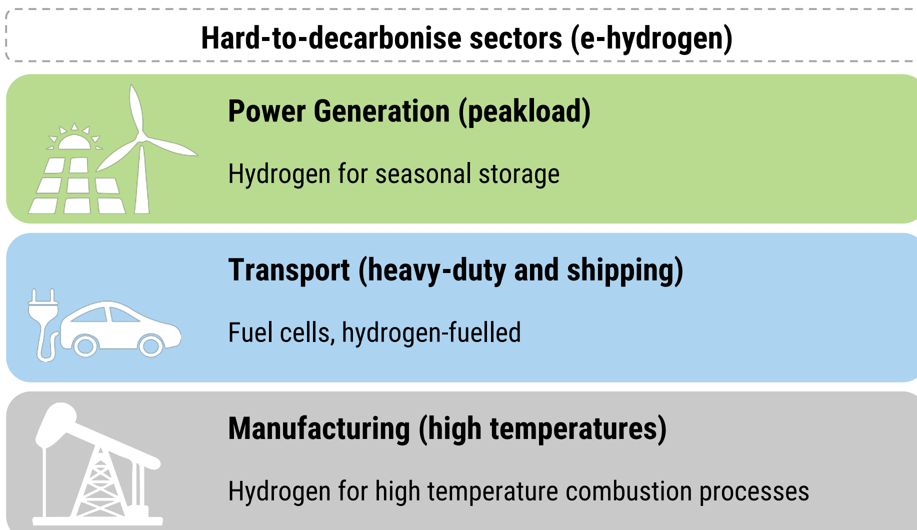
Source: Goldman Sachs Global Investment Research

What is harder to decarbonise: the "last mile"

What is much trickier to decarbonise is the last 10%-20% of the economy ("the last mile", as we define it). We highlight three areas that may heavily rely on hydrogen, to reach net zero:

- **Power generation**. We can't envisage a power system 100% powered by RES as this would: (i) increase the risks of blackouts during moments of low wind/solar production; and (ii) lead to major output curtailments, during periods of low demand and excess production. Hydrogen-fuelled power stations could allow for seasonal storage and act as backup to the power system.
- **Heavy duty transport.** It may also be hard to fully electrify heavy-duty vehicles and ships owing to the theoretical weight of batteries needed for it. Hydrogen (thanks to fuel cells) appears a much more suited technology for this purpose, as we detail later. Hydrogen/fuel cell buses, trucks and ships could largely help achieve the full decarbonisation of transport.
- **High temperature combustion processes.** We also believe that some industrial processes requiring high temperatures (e.g. steel, ceramic) may still require a fuel to burn: clean hydrogen could be burnt in industrial processes creating no emissions.

Exhibit 24: Decarbonising the remaining 10%-20% is relatively difficult: hydrogen would be crucial here
Hard-to-decarbonise sectors



Source: Goldman Sachs Global Investment Research

Blue hydrogen also likely to play a large role...

As described in our Carbonomics report, blue hydrogen (derived from natural gas, featuring carbon capture, CCUS, as we detail in our Technical Appendix) could also play an important role globally. Currently, blue hydrogen is on average cheaper than the green alternative. The advantages we see in favour of green hydrogen – especially in Europe – include the lack of reliance on imported fuel (natural gas) and the support to the domestic "green industry". Also, as gas prices in Europe potentially normalise, and economies of scale could potentially reduce the costs of electrolysis (as already seen in the past ten years: costs have fell by c.60%), the economics of e-hydrogen could continuously improve vs blue.

The e-Hydrogen economics: expect steep improvements

We analyse the economics of hydrogen production under two different processes (which we detail in the section "Hydrogen: a primer"): (i) Blue Hydrogen (natural gas + CCUS), which comes from natural gas and sequestrates carbon emissions — currently blue hydrogen is the cheapest "clean" alternative; and (ii) Green Hydrogen, which comes from electrolysis. Interestingly, our scenarios show that, as renewable production gets cheaper and electrolysers become more efficient, green hydrogen costs would become increasingly competitive, although only solar-powered electrolysers are more competitive than blue hydrogen by 2050.

Our methodology: two processes, seven scenarios

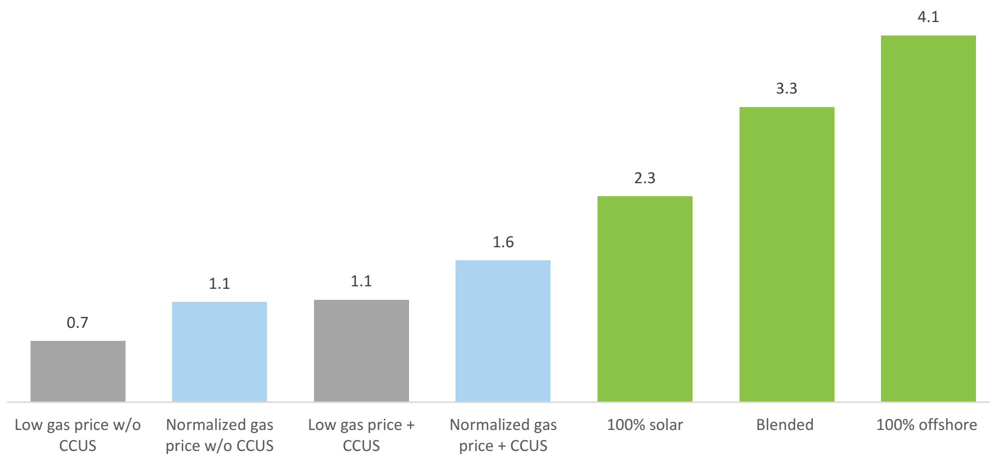
In our analysis of the production of blue hydrogen, we explore production prices with carbon capture, utilisation and storage technologies (CCUS) and without CCUS. We model two scenarios for natural gas prices: (i) Our "low gas price scenario" assumes prices of €12/MWhg for TTF; this is consistent with the recent trough price (for the one-year forward curve) during 2020. (ii) Our "normalised gas price scenario" reflects a price for TTF of price of c.€20/MWhg, in line with the 10-year average before the covid outbreak. Since Steam Methane Reformation, the process for generating blue hydrogen, has been around for a while and achieved scale, we do not model variation in its capital expenditure and efficiency over our time horizon (to 2050).

The green hydrogen modeling is under three scenarios: (i) electrolysis from 100% Southern European solar, which is currently the cheapest form of renewable energy; (ii) electrolysis from 100% offshore wind, which is at the moment the most expensive form of renewable energy; and (iii) electrolysis from a blend of RES sources: offshore wind 40%, solar 40% and onshore wind 20%.

Blue hydrogen still way cheaper than green hydrogen, for now

Currently, the average levelised cost of green hydrogen (LCOH) of c.€2.5-4/kg is significantly more expensive than any blue hydrogen alternative. Indeed, even assuming a return of gas prices in line with long-term historical levels and including CCUS, blue hydrogen would still cost about €1-1.5/kg.

Exhibit 25: At present, producing green hydrogen is more expensive than blue hydrogen
LCOH under different scenarios in 2020E (€/kg H2)



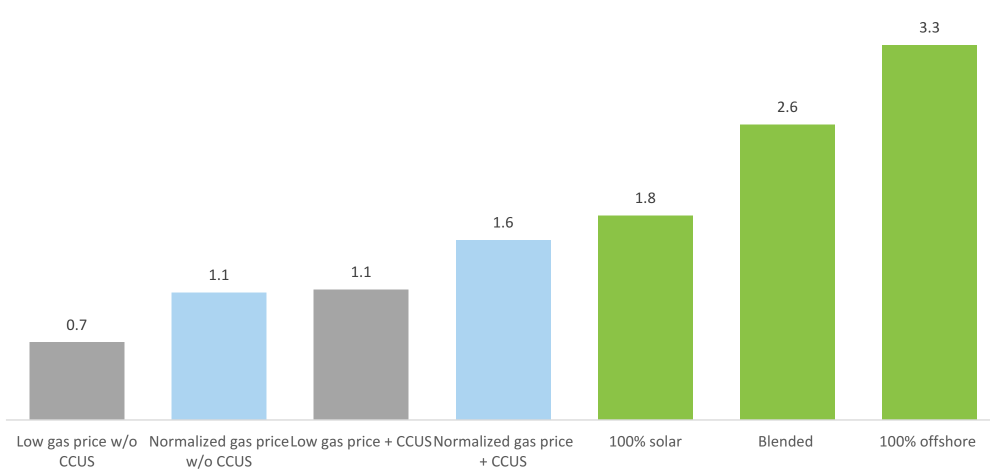
Source: IEA, ScienceDirect, U.S. Department of Energy, Company data, Goldman Sachs Global Investment Research

By 2030, solar-powered electrolysis would almost be competitive

By 2030, we estimate the LCOH of green hydrogen produced from solar in the South (the cheapest RES source) would become more competitive, at less than €2/kg. This is still higher than our blue hydrogen estimate, assuming a normalisation in gas prices by then. Over time, the LCOH of green hydrogen is primarily affected by two factors: (i) the cost of electricity, as this accounts for about 80% of the LCOH, and (ii) the cost of electrolysers seeing sizeable cost reductions, thanks to improving scale (during the past ten years, the cost of electrolysers has declined by 60%, according to the IEA).

Our analysis could actually prove conservative as we don't assume any carbon costs for natural gas; in a decarbonising (net zero) world, imports of natural gas could face carbon costs, which would worsen the economics.

Exhibit 26: Technological advancement and scale to bring down green hydrogen's LCOH
LCOH under different scenarios in 2030E (€/kg H2)



Green bars = green hydrogen scenarios; blue & grey = blue hydrogen scenarios

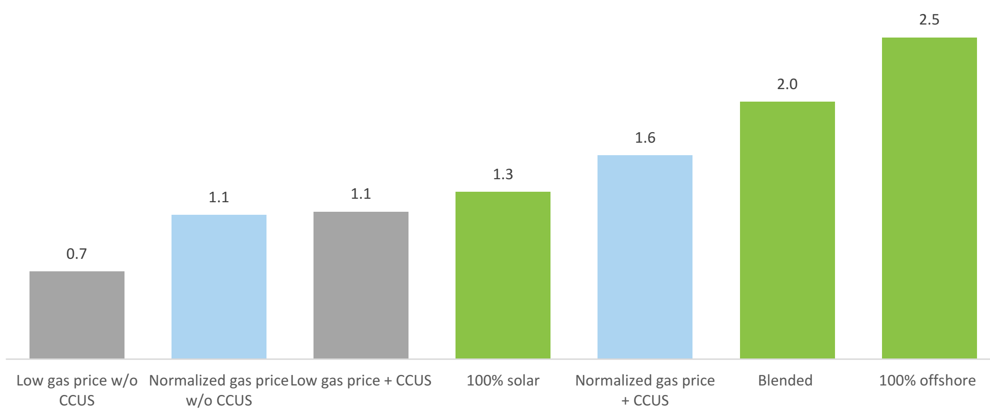
Source: IEA, ScienceDirect, U.S. Department of Energy, Company data, Goldman Sachs Global Investment Research

The end game: green hydrogen competitiveness to improve greatly

By 2050, we expect the LCOH of green hydrogen produced 100% from solar to be competitive vs blue hydrogen. Blended costs would still be more expensive than normalised gas prices + CCUS. Once again, we think our analysis could actually prove conservative as we don't assume any carbon costs for imported natural gas and assume c.5% annual decline in electrolyser capex (consistent with the drop seen in the past ten years, but this could be underestimating the price drop as the scale of these machines is set to increase at a greater rate than in the past decade).

Exhibit 27: In 2050, our scenarios imply that LCOH of hydrogen produced via electrolysis using 100% solar energy would be very competitive

LCOH under different scenarios in 2050 (€/kg H2)



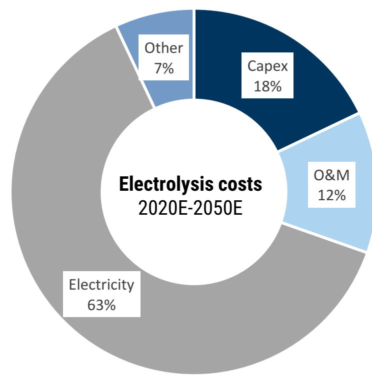
Green bars = green hydrogen scenarios; blue & grey = blue hydrogen scenarios

Source: IEA, ScienceDirect, U.S. Department of Energy, Company data, Goldman Sachs Global Investment Research

Electricity input costs are c.65% of the total cost of producing green hydrogen

Our electrolysis cost estimate shows that, on average during 2020 and 2050, electricity inputs costs would account for about 65% of the cost of producing green hydrogen via electrolysis.

Exhibit 28: Electricity accounts for c.65% of the cost of producing green hydrogen via electrolysis (GSe)
Estimated electrolysis cost (2020-50E average)



Source: ScienceDirect, Company data, IEA, U.S. Department of Energy, Goldman Sachs Global Investment Research

Addressable market for Utilities of c.€10 trillion globally by 2050E

We estimate the green hydrogen industry in Europe could attract >€2 trillion of investments by 2050 (supported by the EU Hydrogen Strategy) for Utilities. This includes: (i) 1,100-1,300 GW of dedicated renewable facilities (implying a near doubling of our bullish Green Deal estimates for 2050); (ii) up to 500 GW electrolysers (vs 0.1 GW currently); (iii) the reconfiguration of the gas infrastructure grid and the build-up of hydrogen-fuelled power plants to deal with backup needs and solve the problem of seasonal storage; and (iv) the development of Hydrogen Turbines to replace up to 500 GW of CCGTs and provide clean, reliable, backup power. Globally, the e-hydrogen addressable market could potentially reach roughly €10 trillion, on our estimates, or c.13% of global GDP (2018).

e-Hydrogen: more than €2 trn addressable market (2050E), just in Europe

Setting up 500 GW of electrolysers by 2050 (consistent with the assumptions made by the EU in the Hydrogen Strategy paper, which compares with a total European market of just 0.1 GW today, nearly non-existent) could create an addressable market to the magnitude of €2.2 trillion, we estimate. This is based on the following breakdown:

- **Dedicated renewable assets (c.65% of the addressable market)**. As electrolysis is a very electricity intensive process (power prices account for c.80% of the total electrolysis costs), we estimate that each 1 GW of electrolysers would require about 2 GW of RES dedicated capacity. This 2-to-1 ratio implies c.€1.4 trillion incremental RES investments by 2050, we estimate, double our Green Deal RES capex 2050 forecast. Incremental renewables would account for about 65% of the addressable e-Hydrogen market (40% offshore, 40% solar, 20% onshore, as we detail later).
- **Electrolysers (c.15%).** The build up of electrolysers at about 15% of the total addressable market.
- **Gas infrastructure (c.5%).** The remaining 5% would be needed to repurpose the gas transport/storage infrastructure and allow for upgrades to better seal gas pipes to prevent any leaks (hydrogen molecules are thinner than natural gas, and so far a blend of 7-8% has been attempted, though there are tests which suggest there could be a blend of up to 15% with minimal investment).
- **Hydrogen Turbine Power Plants (H2T, c.15%).** The construction of hydrogen-fuelled power plants and the conversion of existing gas plants accounting for nearly 15% of this addressable market.

Exhibit 29: We expect more than two-thirds of the investment to be for dedicated renewable capacity
Estimated addressable market by category in Europe (€ trn)

	Capex to 2050	% of e-Hydrogen addressable market	Function
Renewables	€1.4 trn	c.65%	To power 500 GW of electrolyzers
Hydrogen power plants	€0.4 trn	c.15%	450-500 GW of peaking capacity to meet 10% of EU demand
Electrolyzers	€0.4 trn	c.15%	500 GW of electrolyzers
Gas Infrastructure	€0.1 trn	c.5%	Pipeline reconfiguration
Total	**€2.2 trn**	**100%**	

Source: European Commission, Goldman Sachs Global Investment Research

A global addressable market of nearly €10 trillion by 2050E

On our estimate, the addressable market of e-Hydrogen in the US would be larger than in Europe (€2.9 trn vs €2.2 trn), and the Asian one would be double Europe's.

In market sizing, for Europe we carried out detailed cost estimates on: wind/solar capacity needed as dedicated input into electrolysis; the electrolysers needed by 2050; and the power plants fuelled by hydrogen and the gas infrastructure. To estimate US and Asia, we simply grossed up the European estimates in proportion to the GDP differential between these regions. Although the global estimate is not comprehensive and bottoms up as our European estimate, we believe it provides a valid guesstimate of the global e-hydrogen addressable market.

Exhibit 30: The global addressable market for hydrogen could reach nearly €10trn by 2050E
Estimated addressable global market, 2050E (selected parameters as of 2018)

	EU	USA	Asia
Electricity Consumption in PWh	2.9	3.9	10.4
Installed Capacity in GW	1,055	1,095	3,129*
Renewables Capacity in GW	312	144	480
Population in mn	447	327	4,561
GDP current prices in $ trn	15.9	20.6	31.5**
Hydrogen addressable market in €trn	**2.2**	**2.9**	**4.4**

Global addressable market → **c. €10trn**

*based on aggregates for different years and excludes North Korea and Macao **excludes Palestine and Syria

Source: Enerdata, EIA, IRENA, World Bank , IMF, United Nations, CIA, Burma Ministry of Electricity and Energy, Statista, Palestine Economic Policy Research Institute, Goldman Sachs Global Investment Research

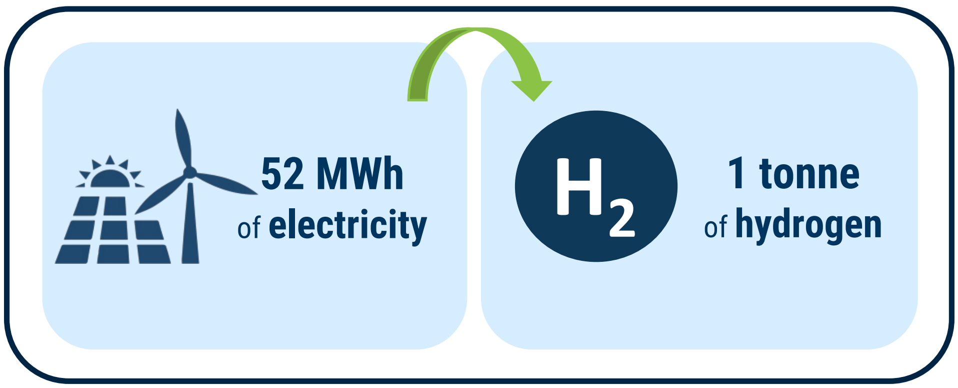
Electrolysis set to double power demand in Europe

The production of green hydrogen is highly electricity intensive. Electricity, we estimate, accounts for about 65% of the total electrolysis costs (2020-2050E average). We estimate that to achieve the 500 GW electrolysers assumption in the EU's 2050 energy strategy, power demand would double vs current levels, all else being equal.

Electrolysis is a very electricity intensive process

Data by Hydrogenics and the IEA show that to generate 1 tonne of hydrogen, some 52 MWh of electricity (plus 10 litres of water) are needed.

Exhibit 31: 52 MWh of electricity is needed to generate 1 kg of hydrogen



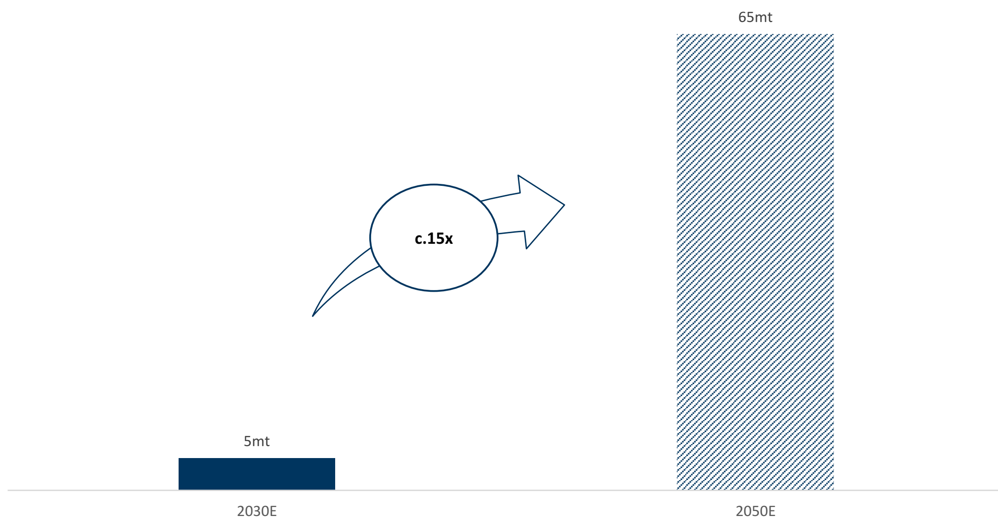
Source: IEA, Hydrogenics

To put this into perspective, if we were to replace all the hydrogen currently produced worldwide (c.70-75 mt) with green hydrogen, the new supplies of electricity would exceed the current power consumption in Europe (c.3,500 TWh).

Hydrogen could become the largest electricity client: power demand to double by 2050E

As discussed earlier, the EC target for the European electrolysis market is to reach 40 GW by 2030 vs 0.1 GW currently. By 2050, the working assumption is 500 GW. On our estimates, this would imply c.5 mt of hydrogen production by 2030 and c.65 mt by 2050.

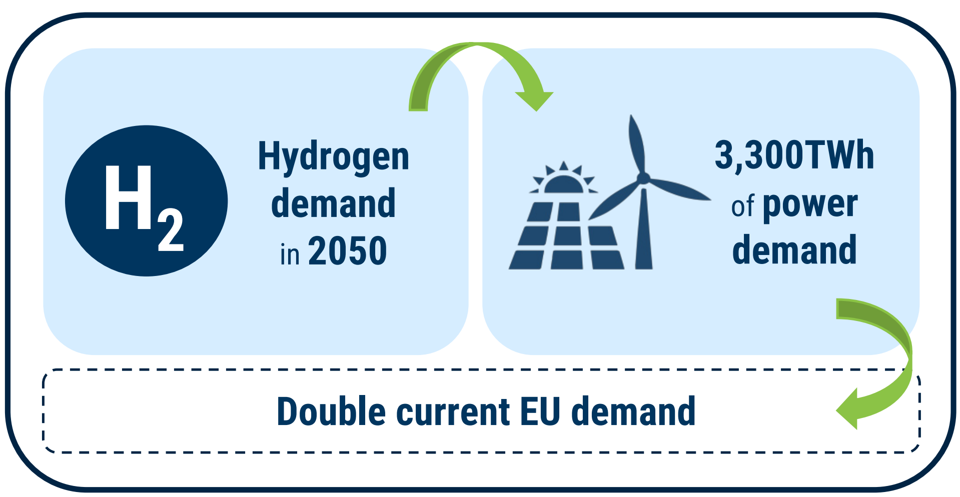
Exhibit 32: By 2050, the European electrolysis market reaching 500 GW would imply c.65 mt of hydrogen production
Estimated hydrogen production evolution (m tones)



Source: Goldman Sachs Global Investment Research

Based on the ratio expressed above (1 tonne of H_2 requires 52 MWh of electricity), this would imply >3,300 TWh of power demand, roughly doubling current consumption in Europe.

Exhibit 33: Hydrogen demand in 2050E could double current power demand consumption
Estimated EU power demand, 2050E



Source: Goldman Sachs Global Investment Research

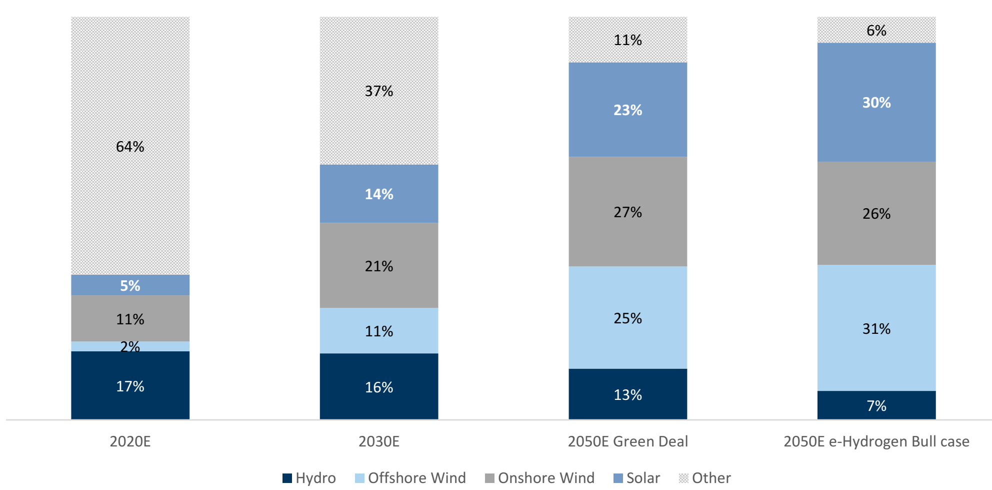
RES additions p.a. may triple vs the Green Deal scenario

To meet the power required for the EU's 500 GW electrolyser aspirations, we estimate some 1,100-1,300 GW of dedicated RES capacity – equivalent to incremental investments in renewables of €1.4 trillion – would be needed. This implies double our (top-of-the-street) Green Deal estimate of €1.2 trn capital spending by 2050. It also implies nearly triple our (top-of-the-street) addition estimates for wind and solar to c.90 GW per year starting towards the end of this decade until 2050.

European RES: from 35% to nearly 90-95% of production

In 2019, about 35% of the power generated in Europe came from renewables (hydro, offshore/onshore wind, solar). By the end of the decade, we estimate that the share of RES in the system could approach 65% and, by 2050, c.95%. The following exhibit details two RES scenarios for 2050: our Green Deal Bull case and an e-Hydrogen Bull case, that is adding the incremental RES required to power electrolysis.

Exhibit 34: European renewables could supply c.95% of power by 2050E vs c.35% currently
Renewable technologies breakdown in the European generation mix (percentage)

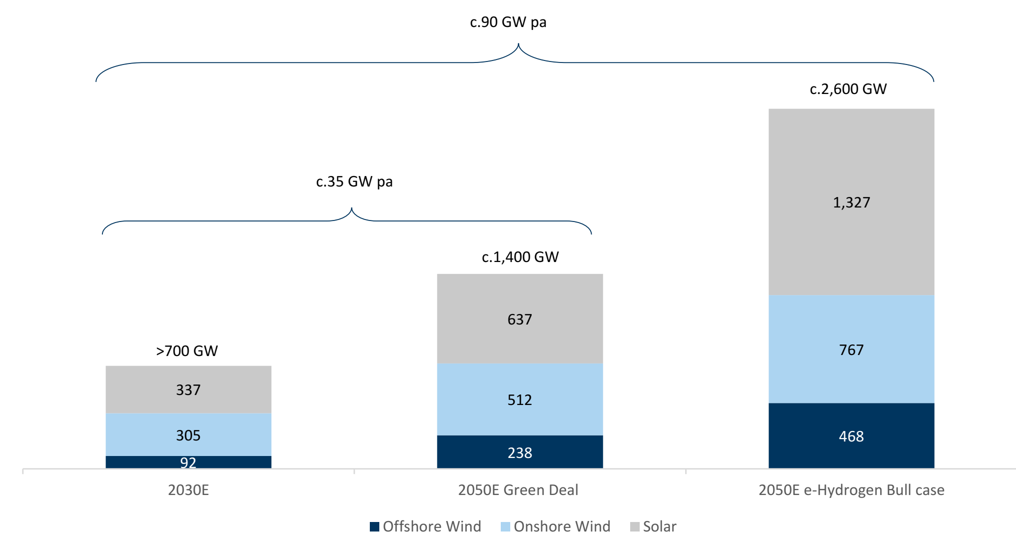


Source: Goldman Sachs Global Investment Research

e-Hydrogen implies nearly tripling of annual RES additions in Europe by 2050E

As explained earlier, the creation of green hydrogen via electrolysis is a very electricity intensive process. By 2050, we estimate that – to satisfy the 500 GW of electrolysers assumed by the EU in their "net zero" strategy – the amount of wind and solar in the system would have to double to nearly 2,600 GW vs our (already top of the market) 2050 Green Deal estimates. This e-hydrogen 'bull case' would imply, relative to Green Deal scenario of 35 GW annual additions of wind/solar through to 2050, an acceleration to c.90 GW pa.

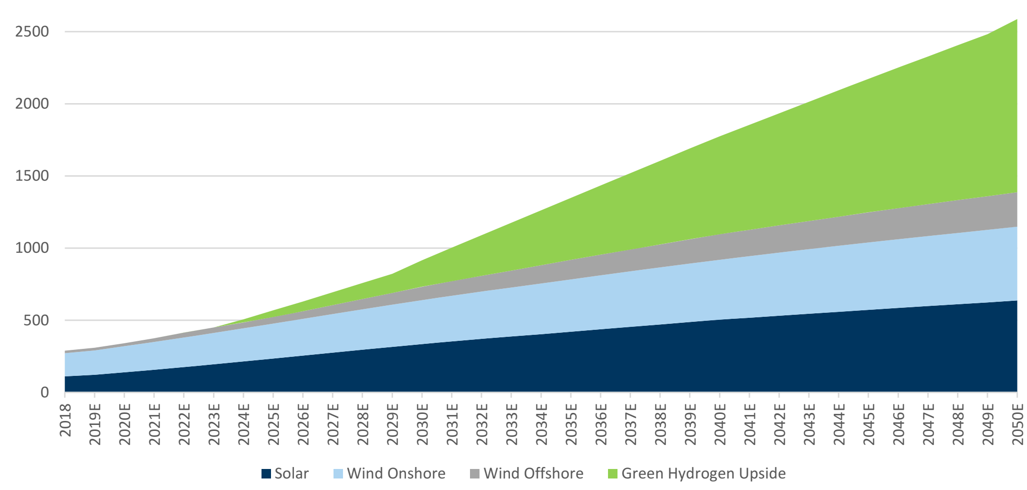
Exhibit 35: European wind and solar annual additions would nearly triple relative to our 2050E Green Deal forecasts under an e-hydrogen scenario
Cumulative wind and solar installed base in Europe and annual additions scenarios



Source: Goldman Sachs Global Investment Research

The exhibit below shows the evolution of wind (onshore and offshore) and solar in Europe throughout 2050. The base case estimates reflect EU Green Deal targets (under our EU Green Deal scenario), while the upper curve shows the upside from Green Hydrogen. Under this new scenario, 2050E renewable capacity would double; during 2030-50 (when most of these investments would have to be carried out), annual wind and solar additions could triple vs the Green Deal scenario.

Exhibit 36: Capacity additions for green hydrogen and electrolysis are double our 2050E Green Deal estimates and triple the additions during 2030-50E
Cumulative capacity additions under Green Deal 2050E and e-Hydrogen Bull case scenarios (GW)



Source: Goldman Sachs Global Investment Research

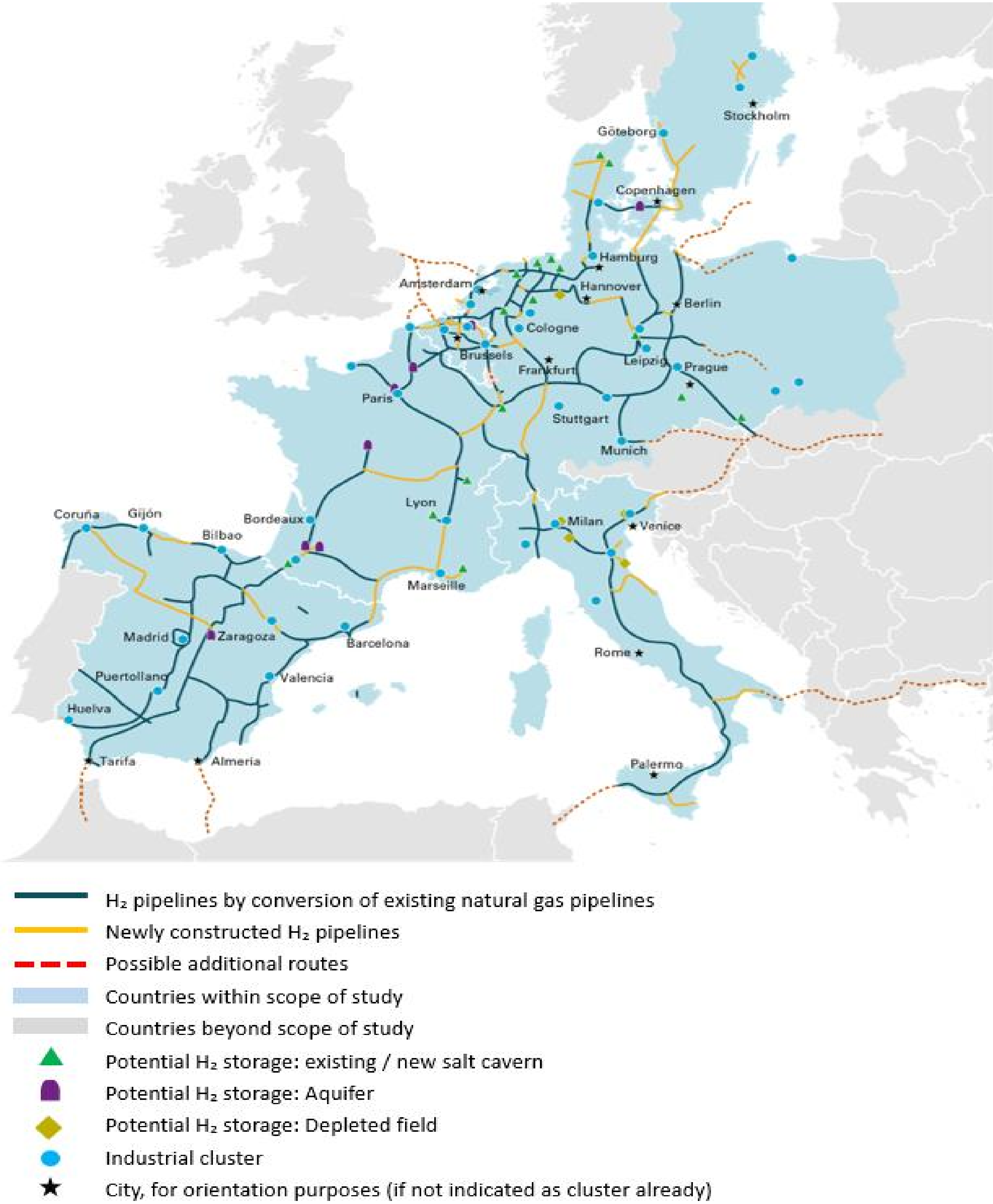
Gas grids need major reconfiguration

As hydrogen becomes increasingly decentralised (transport, factories), the demand for "hydrogen ready" infrastructure will intensify. A study released by ten of the largest European gas transport system operators along with two renewable industry associations estimates €27-€64 bn (midpoint €40 bn) of investment needed by 2040 to reconfigure gas pipelines to create dedicated hydrogen infrastructure to move hydrogen across Europe. The study argues that the combination of centralised hydrogen production coupled with the reconfiguration of the existing gas transport grid (and storage infrastructure) would be cheaper than producing hydrogen from smaller electrolysers dedicated to on-site consumption.

Gas pipeline reconfiguration, c.€40bn (at midpoint) investment opportunity

A study released by ten European gas TSOs estimates that establishing a dedicated pan-European hydrogen pipeline network (the "European Hydrogen Backbone") could require €27-€64 bn of investments by 2040. Once completed, this envisioned network would stretch from the Nordics to southern Italy and Spain, with extensive coverage in key areas of renewable energy production (e.g. the North Sea and Spain). Crucially, about 75% of the networks is expected to rely on existing gas transport infrastructure.

Exhibit 37: About 75% of the proposed European hydrogen network would rely on existing gas transport infrastructure
'European Hydrogen Backbone' initial proposed hydrogen pipeline



Source: European Hydrogen Backbone study (July 2020), Goldman Sachs Global Investment Research

The European Hydrogen Backbone analysis estimates potential costs for a nearly 23,000 km European network at between €27 bn and €64 bn, putting the mid-point at €40 bn, with the wide range largely explained by the still uncertain cost of compression stations. The cost of operating the hydrogen network is estimated in the region of €1.6-3.5 bn (or c.€2 bn at the midpoint) per annum including electricity costs.

Exhibit 38: An 23,000 km dedicated network to transport hydrogen across Europe estimated at c.€40 bn investment (midpoint) by 2040
European Hydrogen Backbone study, initial proposed costs

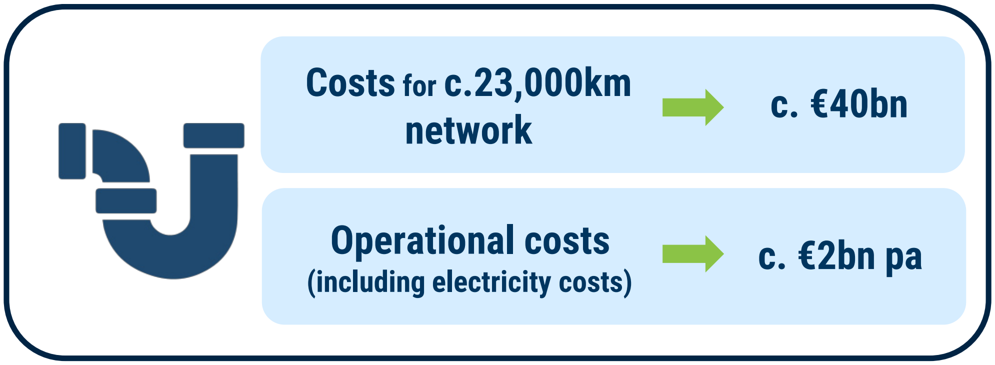


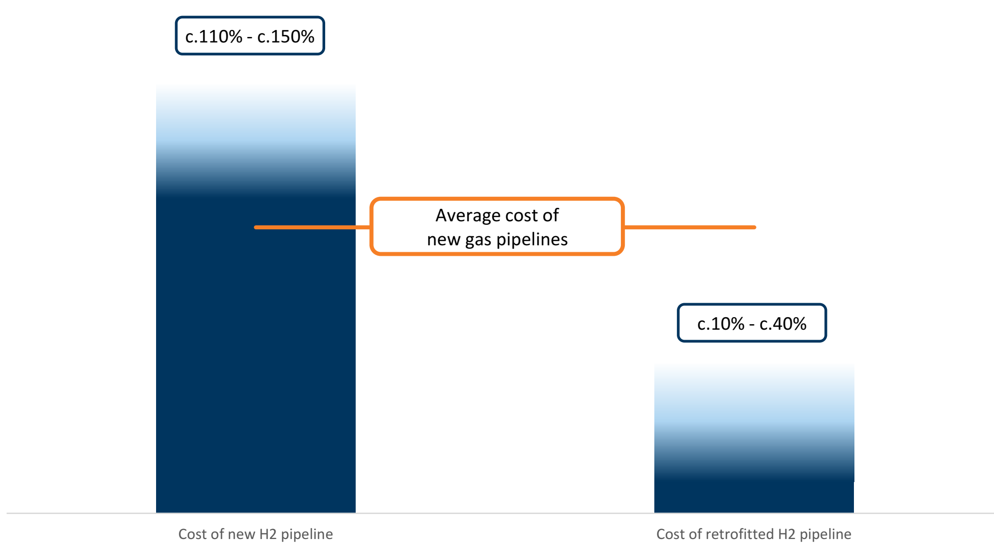
Exhibit shows midpoints of the estimated ranges of €27-64 bn and €1.6-3.5 bn, respectively

Source: European Hydrogen Backbone study (July 2020), Goldman Sachs Global Investment Research

Repurposing anticipated to be much cheaper than building a new hydrogen grid

The European Hydrogen Backbone study argues that the retrofitting of the existing gas infrastructure to constitute about two-thirds of the hydrogen network will be crucial for cost containment. It estimates retrofit costs at c.10%-40% of the capex required for a gas pipeline - significantly cheaper than the cost of new hydrogen transport infrastructure, which is estimated at c.110%-150% of the cost of a natural gas pipeline.

Exhibit 39: Retrofitting existing gas pipelines for hydrogen use could contain the incremental cost of the European Hydrogen Backbone
Cost of hydrogen pipelines as % of comparable gas pipelines



Source: European Hydrogen Backbone study, Goldman Sachs Global Investment Research

In several countries, gas TSOs are already experimenting with blending to assess asset readiness - a few examples in the exhibit below.

Exhibit 40: Several projects are currently underway to assess asset readiness with rest to blending gases

Partners	Location	Project description
Snam	Italy	Experimental project that injects 5% of hydrogen into the natural gas network
Gas Networks Ireland (GNI)	Ireland	GNI plans to test hydrogen suitability and blends of the fuel with natural gas and renewable gases on its network.
ATCO	Canada	Project which will inject up to 5% of hydrogen into Fort Saskatchewan's residential natural gas network
Cadent (main), Northern Gas Networks, Keele University, the Health and Safety Executive (HSE) Science Division, ITM-Power and Progressive Energy	United Kingdom	HyDeploy is a pilot project to inject up to 20% hydrogen into Keele University's existing natural gas network
Engie, AREVA H2Gen, CEA, CETIAT, Dunkirk Urban Community, ENGIE Ineo, GNVERT, GRDF, INERIS, McPhy, and STDE	France	GRHYD is a power-to-Gas demonstration project that tests the injection of 6-20% of hydrogen in the residential natural gas network
Snam and Baker Hughes	Italy	Project to test Baker Hughes' turbine, which will be powered by a blend of upto 10% of hydrogen, at Snam's gas compressor station in Istrana

Source: The Irish Times, respective company press releases, compiled by Goldman Sachs Global Investment Research

A new wave of (regulated) power plants: Hydrogen Turbines

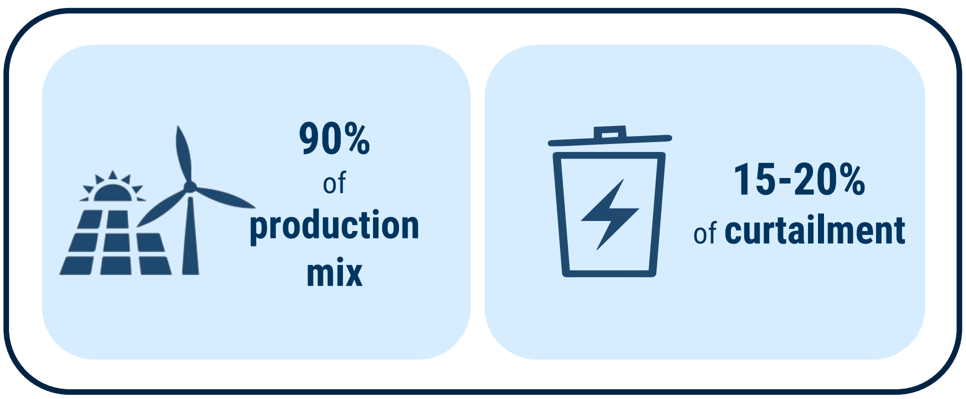
On our estimates, once 90% of production from renewables is reached, power systems would face several challenges: (1) hours of excessive RES production and, therefore, curtailments: we estimate that at a 90% share in the power generation mix, up to 20% of the output would have to be curtailed; (2) hours of insufficient wind/solar production, which would require responsive backup generation; and (3) rising pressure on the resilience of the power grid owing to the high output volatility.

In our view, green hydrogen would solve the first two problems whilst allowing for zero emissions. We anticipate a wave of backup power plants – Hydrogen Turbines (H2T) – fuelled by hydrogen, which would be a carbon free form of backup. We investigate the main economics.

e-hydrogen potential to solve the issue of seasonal storage

We estimate that, once renewables reach 90% of the power production mix, about 15%-20% of the output from renewables would have to be curtailed as it would be produced during hours of insufficient demand.

Exhibit 41: We estimate that once RES reaches 90% of the power production mix, c.15%-20% of renewable curtailment would have to occur



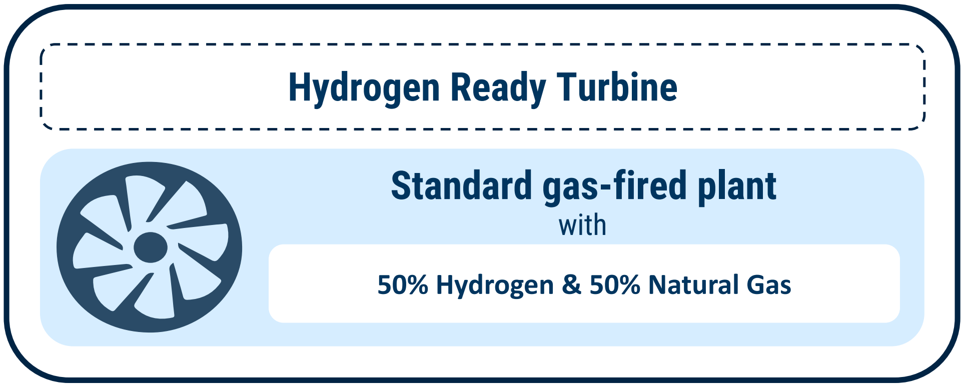
Source: Goldman Sachs Global Investment Research

Under the assumption of a properly interconnected European network (a key condition to freely transfer excess wind and solar output), the excess renewables output could be utilised in the electrolysis process. Crucially, during hours of excess renewables production, hydrogen could be produced and stored for periods of poor renewable production. This would ultimately provide a major backup to the system.

The rise of hydrogen-ready turbines

Currently, standard CCGT plants can burn up to 20% hydrogen without significant intervention. Hydrogen-ready turbines could potentially play a big role in decarbonising power generation systems. HRT can be thought of as "standard" gas-fired power plants which can burn fuel that contains a hydrogen component of up to 50% (as per data from General Electric and Siemens, and other pilot projects are underway). Blending green hydrogen (which has oxygen and steam/water as byproduct) with natural gas could halve emissions from gas plant.

Exhibit 42: HRTs are essentially standard gas-fired plants with some adjustments

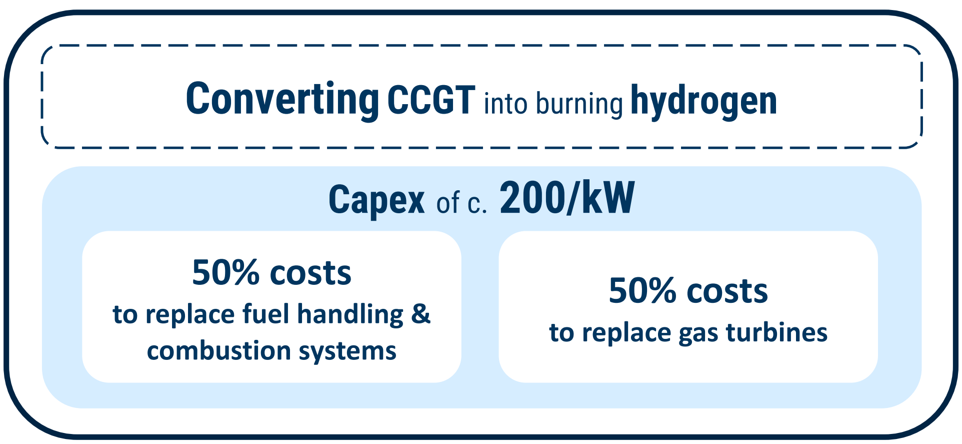


Source: Goldman Sachs Global Investment Research

Full CCGT conversion into hydrogen vs Hydrogen Turbines (H2T)

Recently, power generators such as Uniper and RWE announced the intention to convert standard gas plants into hydrogen power plants. We estimate that to fully convert an existing CCGT into burning hydrogen, capex per kW could be c.€200/kW, evenly split between costs to replace the fuel handling & combustion systems and to replace the gas turbine.

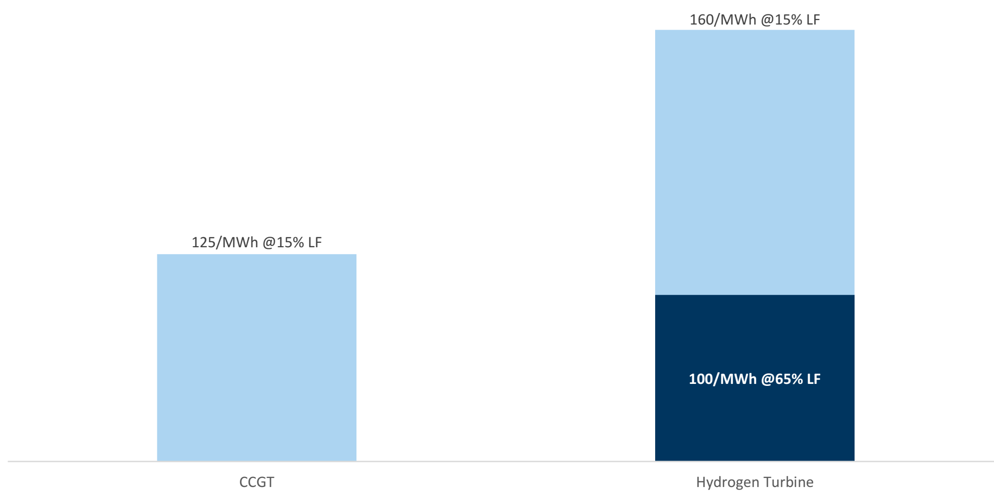
Exhibit 43: We estimate converting an existing CCGT into burning hydrogen could cost c.€200/kW



Source: Goldman Sachs Global Investment Research

Newly built hydrogen turbines (H2T) would have similar construction costs to CCGTs (we assume €675/kW), similar opex and similar efficiency (55%-60% for new ones, closer to 50% for converted ones). The exhibit below shows our estimates for the levelised cost of electricity for CCGTs vs H2T, assuming 15% load factors, €20/MWh gas price (10-year average before the crisis), €30/t carbon (closer to the current forward curve) and €1.5/kg hydrogen cost (GSe). Our analysis implies that gas-fired plants would still have lower break-even costs.

Exhibit 44: Hydrogen Turbines LCOE at €160/MWh, assuming 15% load factor, and still at €100/MWh even if utilised as baseload
LCOE for Conventional CCGTs vs Hydrogen Turbines

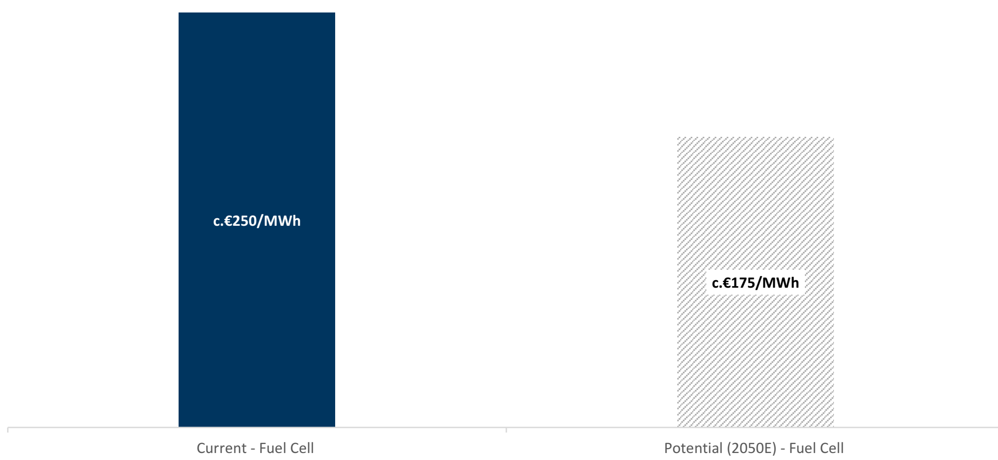


Source: Goldman Sachs Global Investment Research

Electricity generation from fuel cells may be too expensive for now

We estimate that power generation from fuel cells currently costs €250/MWh (at 15% load factor), still well above any other peaking technology. This would rest on fuel cells capex of c.€5,000/kW. Assuming economies of scale (likely to halve fuel cell capex/kW costs) and falling clean hydrogen costs per kg, we estimate that fuel cells could potentially breakeven at €175/MWh. This would still be more expensive than Hydrogen Turbines.

Exhibit 45: Potential breakeven cost for fuel cells is well "out of the money"
Fuel Cells full generation cost at €175-250/MWh (it assumes 15% Load Factor)



Source: Goldman Sachs Global Investment Research

Heading towards the re-regulation of power markets?

In our view, the above-mentioned technologies (Hydrogen Turbines and Fuel Cells) are unlikely to be developed on a competitive/merchant basis with LCOEs in excess of €150/MWh well above the current (baseload) power curves of below €50/MWh. Also, an investment decision to develop such technologies could prove highly risky owing to uncertainties on several fronts: (i) the evolution of capacity factors, given the uncertainty on the evolution of the share of renewables in the mix; (ii) the outlook on gas/carbon prices, which would make an opportunity cost vs CCGTs very hard; and (iii) the outlook on hydrogen prices. This is why we believe that these technologies are likely to be developed under a capacity mechanism/regulated system.

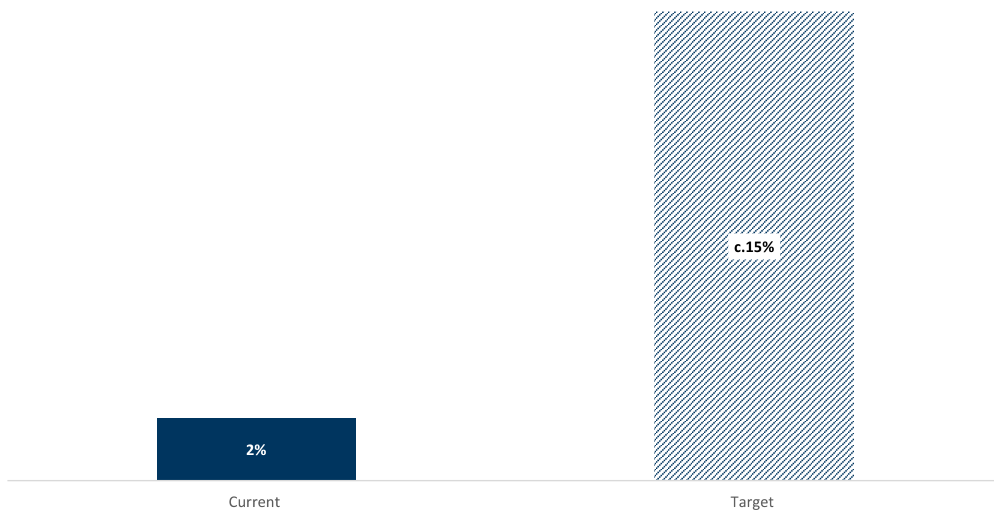
Reconfiguring the energy map

Considering the EU's overarching goal to decarbonise the economy and the rise in clean hydrogen within primary energy consumption, we believe that the upstream energy map may be gradually shifting in favour of low-electricity cost producers such as Spain.

Hydrogen could near c.15% of primary energy consumption by 2050

Hydrogen's current share in EU's primary energy mix stands at a low single digit of less than 2%. The EU envisions a climate-neutral economy by 2050 and projects hydrogen's share to approach close to c.15% by 2050.

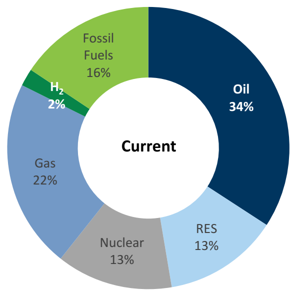
Exhibit 46: EU envisions hydrogen's share in the primary energy mix to approach close to c.15%
Hydrogen's share in EU's primary energy mix



Source: European Commission, Goldman Sachs Global Investment Research

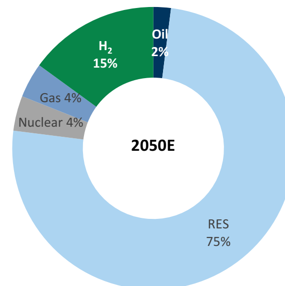
Currently, Europe's primary energy mix is dominated by non-renewables which contribute c.85% of the primary energy mix as shown in Exhibit 47. Out of this, the share of oil and petroleum products is the highest at 34% followed by natural gas at 22%. However, this would change substantially by 2050. The share of renewables would grow from the current 13% to 75% by 2050, on our estimates (Exhibit 48). Accounting for the EU's targeted hydrogen share of c.15%, non-renewables would end up contributing only 10% of the total primary energy by 2050.

Exhibit 47: Currently hydrogen's share in EU's primary energy mix is less than 2%
Share of different energy sources in EU's primary energy mix



Source: EEA, Goldman Sachs Global Investment Research

Exhibit 48: Hydrogen's share in EU's primary energy mix is expected to approach close to c.15% by 2050 under the EU Hydrogen Strategy
Share of different energy sources in EU's primary energy mix



Source: EEA, Goldman Sachs Global Investment Research

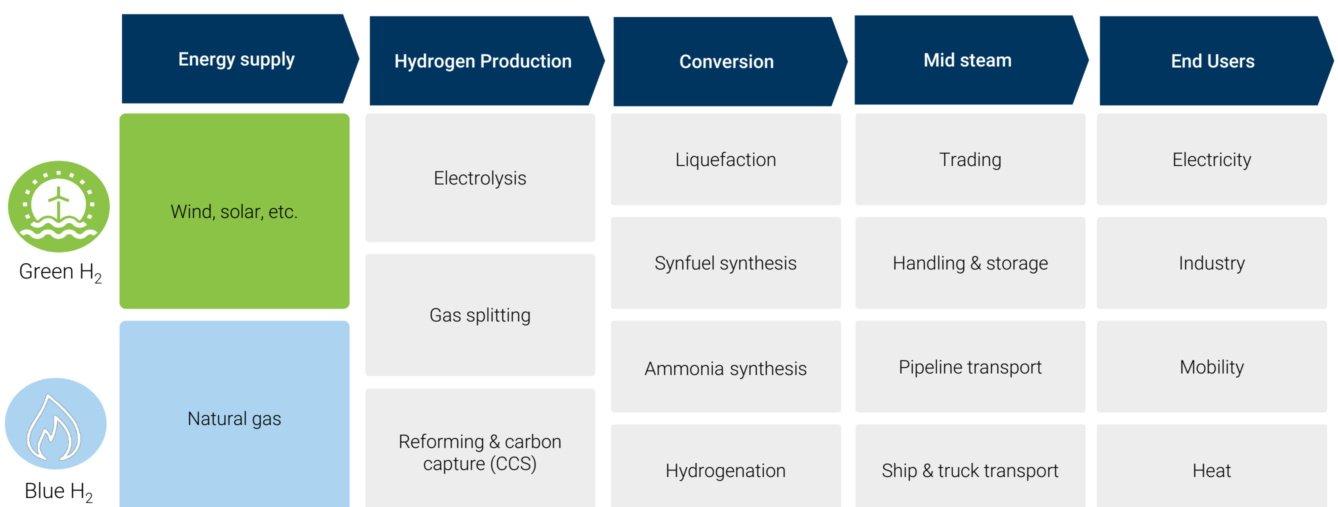
Southern Europe could become a major producer/exporter of hydrogen

In virtue of the abundance of renewable sources and the ability to produce from solar at very attractive costs (c.€15/MWh by 2025E, about 1/3 of the current power price), we think Iberia is well positioned to become a major producer and exporter of green hydrogen. This logic could also apply to Italy, where solar levelised costs are still below €20/MWh.

Utilities could develop new business models across the H_2 value chain

As explained by Uniper during its 1H results, utilities could gain exposure to clean hydrogen (green/blue) across the entire value chain: as seen in the following exhibit, utilities might generate hydrogen, convert it (e.g. liquefy), transport it and sell it to end users.

Exhibit 49: Utilities could gain exposure to clean hydrogen across the entire value chain

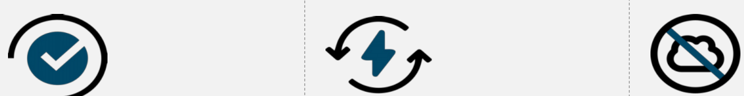


Source: Uniper, Goldman Sachs Global Investment Research

Hydrogen: a primer

We provide an overview of key technical features of hydrogen as well as the current state of the hydrogen economy, outlining where hydrogen comes from and how it is being used. We identify three key advantages of hydrogen as a source of energy: (i) **availability:** unlike fossil fuels, hydrogen is plentiful – in fact, it is the most common chemical element in the universe; (ii) **energy density:** a kilogram of hydrogen has nearly three times the energy content of gasoline and more than twice that of gas; and (iii) **zero emissions throughout:** hydrogen can easily be produced with no carbon emissions (using renewable electricity to split water molecules) and causes no greenhouse gas emissions when it is converted into other forms of energy.

Exhibit 50: Three key advantages of hydrogen as a source of energy



Availability
Hydrogen is the most common element in the universe;

Energy Density
A kilogram of hydrogen has nearly three times the energy content of gasoline and more than twice that of gas;

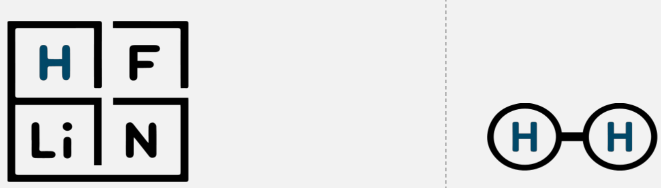
Zero Emissions Throughout
Hydrogen's production and conversion to other forms of energy causes no GHG emissions

Source: Hydrogen Europe, Live Science, World Nuclear Association, Goldman Sachs Global Investment Research

Hydrogen: Shaping the Universe

Hydrogen (H_2) is nature's simplest chemical element, and the lightest. Hydrogen is also the most common element: about 75% of all matter in the universe (by mass) is made up of hydrogen.

Exhibit 51: Hydrogen is nature's lightest and most common element



Hydrogen is nature's lightest element with - in its most common form - **an atomic weight of merely 1.**

c.**75%** of all matter in the universe (by mass) is made up of hydrogen.

Source: Merriam-Webster, University of Illinois, Goldman Sachs Global Investment Research

Energy content much higher than fossil fuels (and batteries)

Being the lightest element, hydrogen also has one of the highest energy contents per unit of mass. Given its lightweight and thin molecules, the energy content of hydrogen per cubic meter is roughly one-third of natural gas. Yet once compressed, hydrogen's energy content per kilogram is nearly 2.5x greater than natural gas.

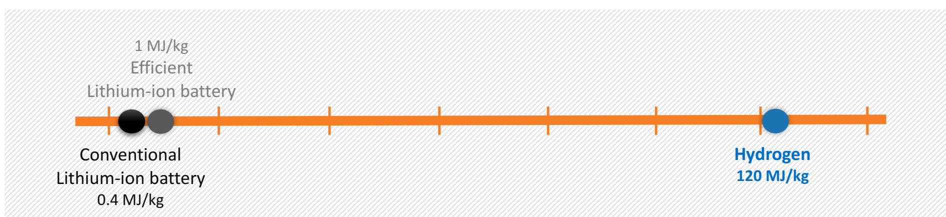
Exhibit 52: Hydrogen's energy density is significantly higher than that of fossil fuels

MJ = Megajoule, kg = Kilogram

Source: IEA, Goldman Sachs Global Investment Research

This superior energy content per kg is a particular advantage in the field of mobility. A comparison with conventional lithium-ion batteries shows that hydrogen has about 200x higher energy density. Even when compared to some of the most efficient batteries on the market, hydrogen's energy density is still >100x higher.

Exhibit 53: Hydrogen has about 120-300 times the energy density of lithium-ion batteries



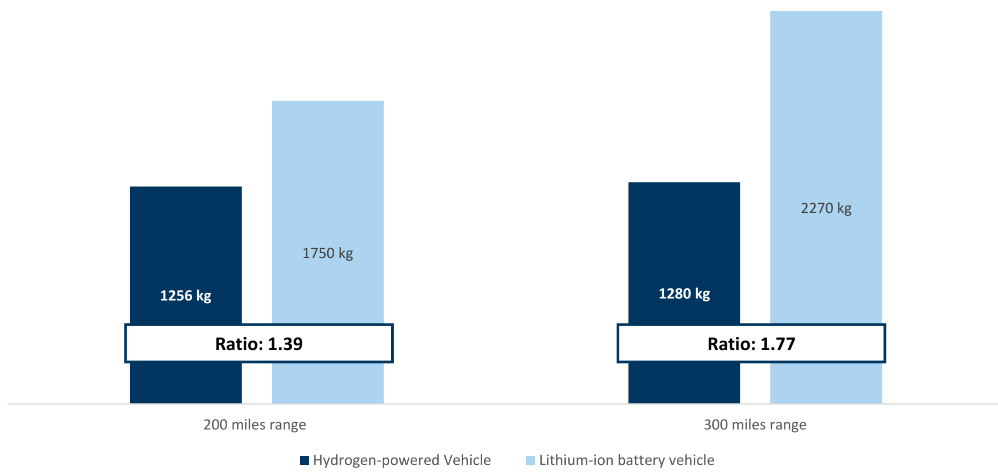
MJ = Megajoule, kg = Kilogram

Source: University of Washington, IEA, Goldman Sachs Global Investment Research

Hydrogen's properties suggest it could turn into the preferred fuel choice for heavy-duty vehicles (buses, trucks, trains) thanks to its higher energy content per kg. Based on a study comparing the weight ratio for batteries powered by lithium vs hydrogen, shown in the exhibit below, we draw two key conclusions:

1. **Fuel Cell vehicles are much lighter** than the battery equivalent and the weight gap increases per amount of energy required, or per range required. The study found that a truck powered by a lithium-ion battery could weigh up to 50% more than the hydrogen-equivalent.
2. **The weight of EVs changes meaningfully** as function of the range of the vehicle. By contrast, the study suggests that the weight of a hydrogen car would stay broadly the same.

Exhibit 54: Weight of a lithium-ion vehicle increases significantly as the vehicle range increases
Ratio of weight of a lithium-ion battery vs hydrogen powered vehicle

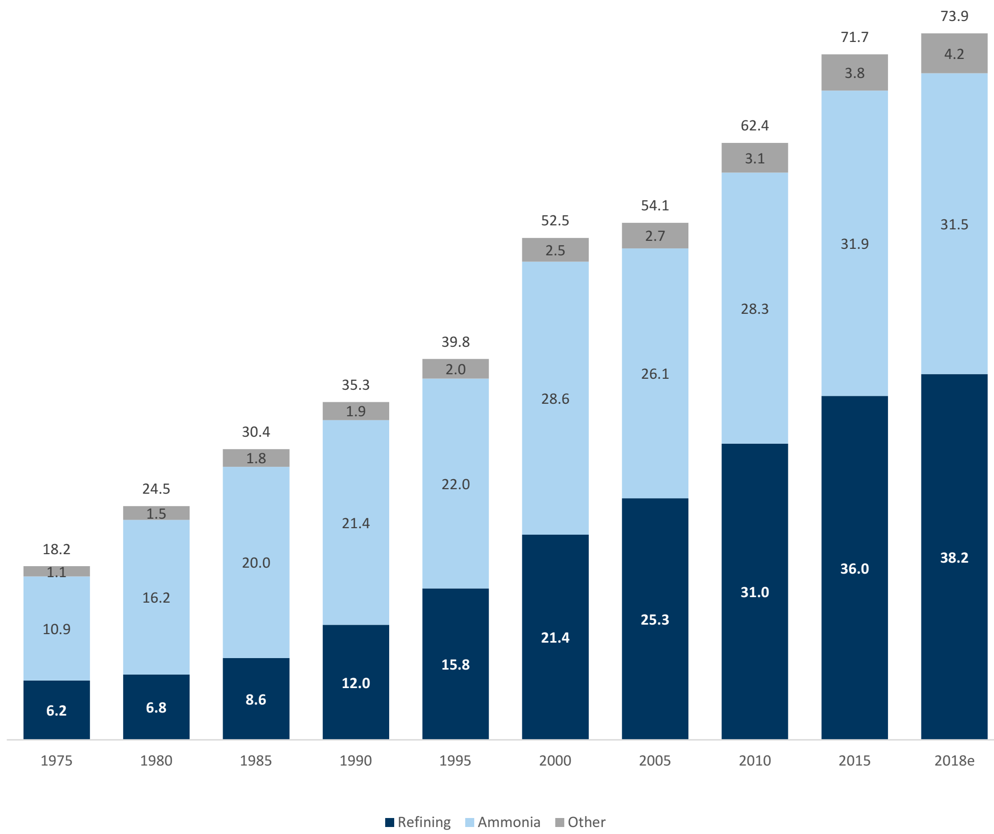


Source: "Fuel Cell and Battery Electric Vehicles Compared" (2009), Goldman Sachs Global Investment Research

The Hydrogen Economy: Uses

Pure hydrogen consumption in 2018 amounted to c.75mt with pure hydrogen being used mostly for two specific activities: refining (of petroleum and petrochemical products) and ammonia (a key feedstock in the production of fertilizer). These two use cases consume >95% of global hydrogen demand.

Exhibit 55: Ammonia and refining consume >95% of the world's pure hydrogen demand
Global demand for pure hydrogen by sector (in Mt)



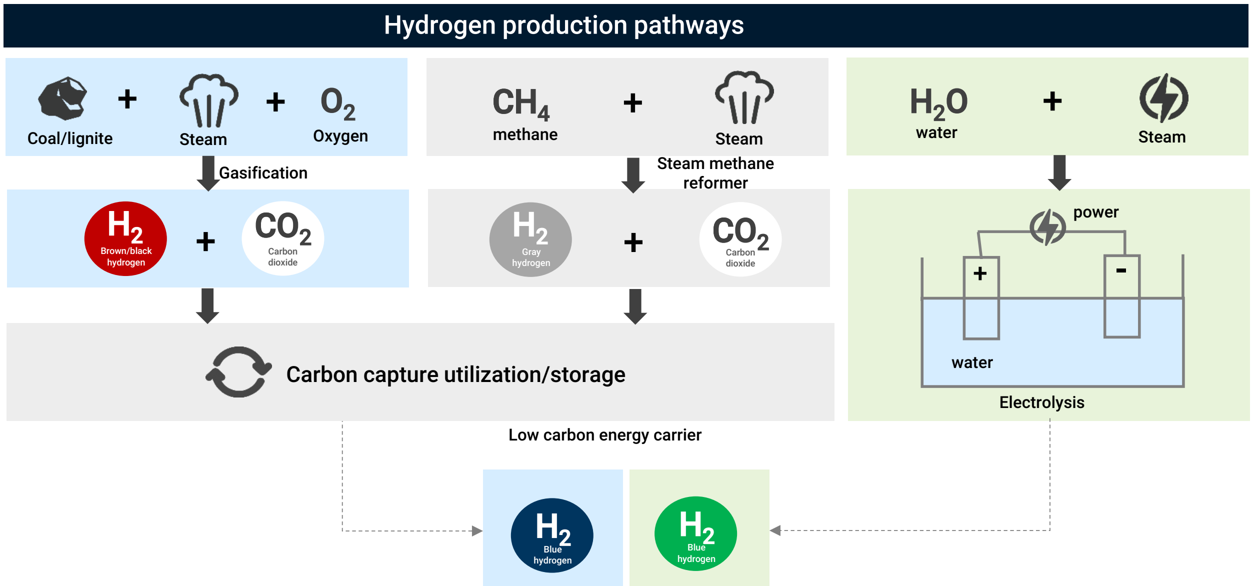
Source: IEA

We estimate that Europe is currently responsible for 20% of global hydrogen demand. This means that Europe consumed c.15 mt of pure hydrogen (based on 2018 data above).

The Hydrogen Economy: Production

From a chemical perspective, the production of hydrogen consists simply in isolating H_2 from more complex molecules. Today, there are two main approaches to do this: (i) **black/brown/grey hydrogen**, which uses steam to separate H_2 from carbon in many fossil fuels (hydrocarbons) including coal, lignite and methane, and can be turned into **blue hydrogen** by capturing carbon emissions at the source; and (ii) **green hydrogen**, which uses electricity to split hydrogen from oxygen in water molecules (a process called electrolysis).

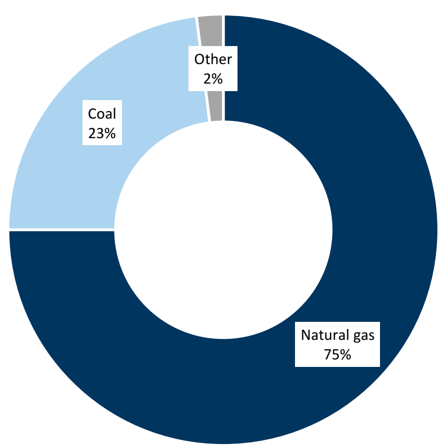
Exhibit 56: There are two main pathways for the production of hydrogen: the separation of hydrogen from hydrocarbons and the isolation of hydrogen in water molecules



Source: S&P Global Platts, Goldman Sachs Global Investment Research

Over 98% of hydrogen is produced from fossil fuels, with natural gas (methane) accounting for about two-thirds of global supply. As yet, electrolysis plays a very marginal role, supplying about 1% or less of global demand.

Exhibit 57: Over 98% of the global hydrogen is produced from fossil fuels
Sources of global hydrogen production (%), 2018

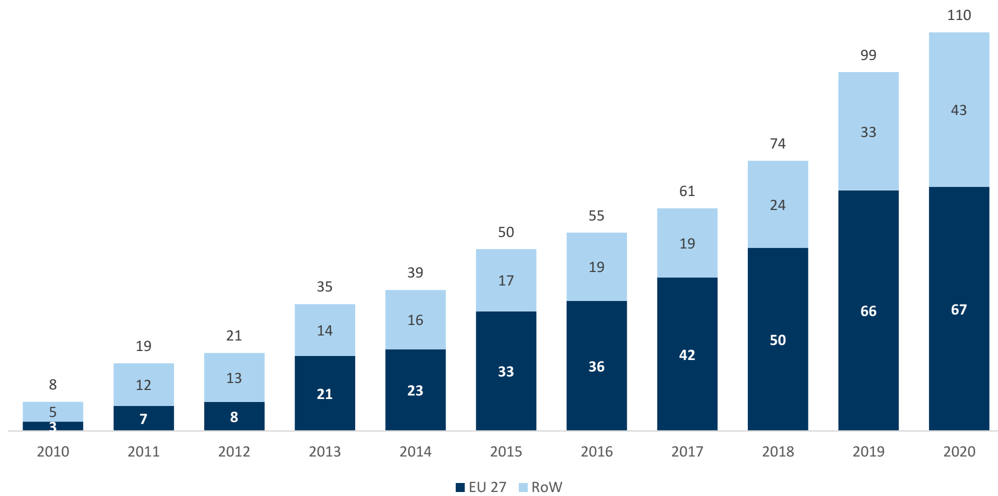


Source: IEA, Goldman Sachs Global Investment Research

Green Hydrogen: A niche technology set for a major acceleration

Currently, hydrogen electrolysis is a very niche technology and the total capacity commissioned in the world is just over 100 MW with c. 60% of that installed in the EU.

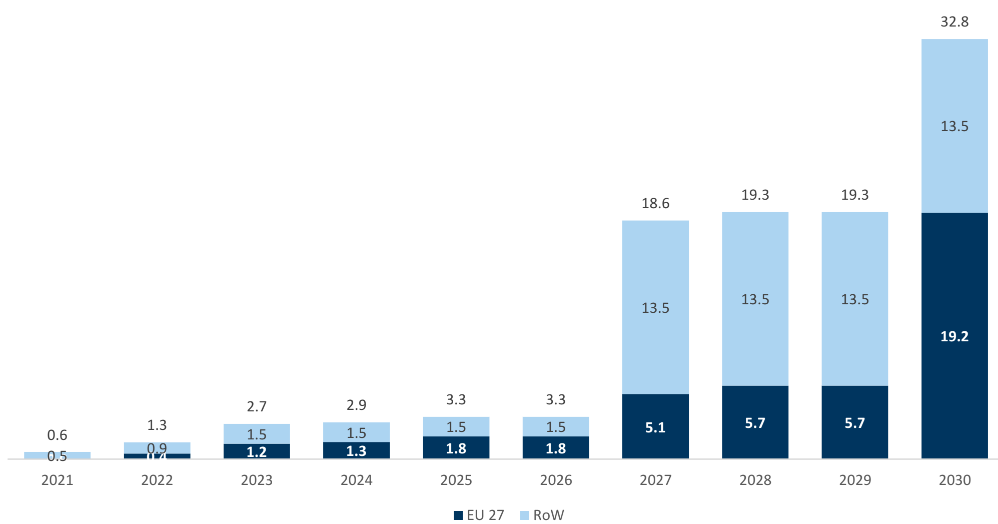
Exhibit 58: The EU accounts for c. 60% of the current global electrolysis capacity
Electrolysis capacity evolution (MW)



Source: IEA, Goldman Sachs Global Investment Research

However, the technology is set for rapid growth. As per IEA, the announced projects that are to be commissioned in the forthcoming decade could grow the global electrolysis capacity by multiple times over the coming years. It could increase from 100 MW currently to 30 GW by 2030 with Europe still accounting for a major proportion of that capacity.

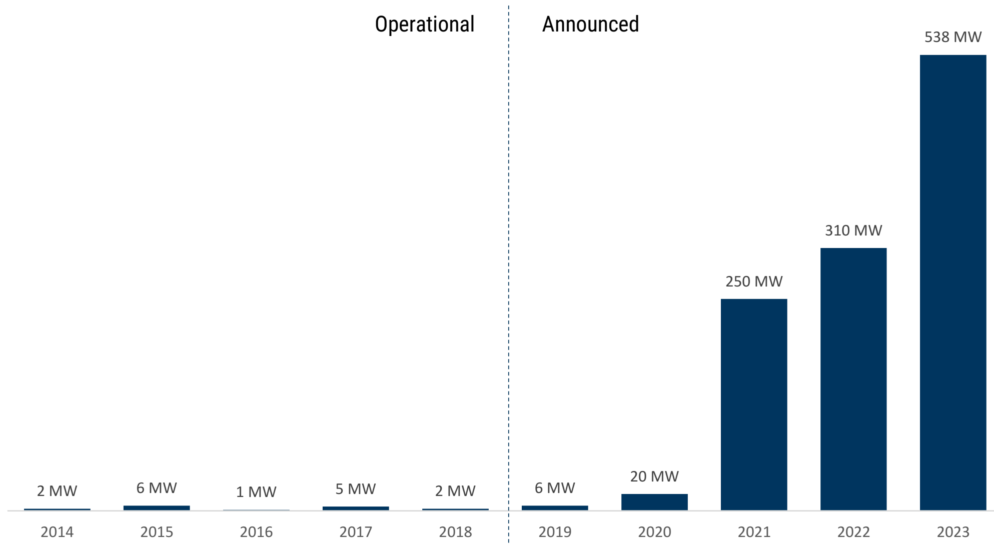
Exhibit 59: Europe could still account for around 60% of the global electrolysis capacity by 2030
Announced project capacity due to be commissioned (GW)



Source: IEA, Goldman Sachs Global Investment Research

The rapid acceleration in the average size of the projects being commissioned will also contribute to the rapid growth of the technology. As per IEA, a 500+ MW hydrogen electrolysis project is scheduled to be commissioned as early as 2023 representing a multi-fold increase from the current project capacity.

Exhibit 60: A 500+ MW electrolysis project is expected to be commissioned as early as 2023
Globally largest electrolysis project capacity evolution (MW)

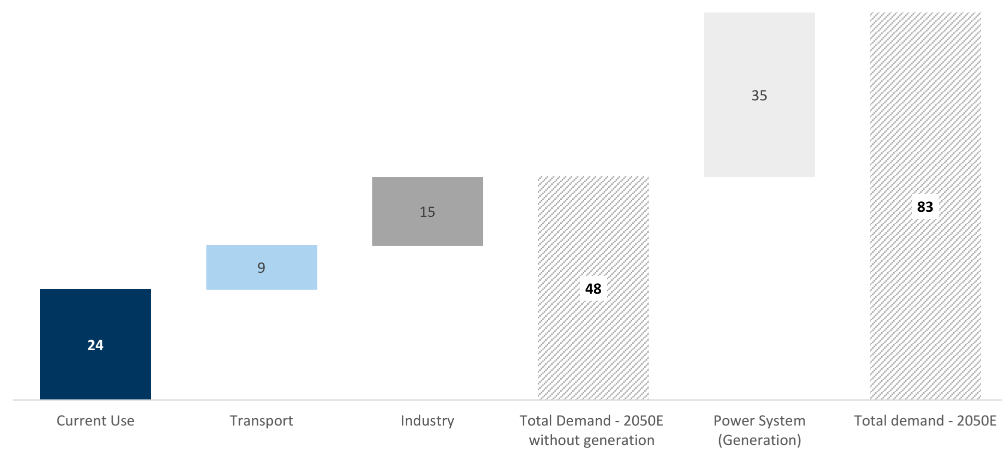


Source: IEA, Goldman Sachs Global Investment Research

Detailed e-hydrogen uses and production analysis

The current global demand for pure hydrogen stands at c. 75mtpa. As per our analysis, the demand for pure hydrogen in EU itself is expected to reach c. 85mtpa by 2050.

Exhibit 61: Hydrogen demand could reach c.85 mtpa in EU by 2050E
Sector-wise demand for hydrogen by 2050E in EU (mtpa)



Source: Goldman Sachs Global Investment Research, IEA, Eurostat, Fuel Cells Research and Joint Undertaking, IPIECA, Hydrogen Euro, ACE, UK Department of Transport , Hellenic Shipping New, Eurocontrol

Current hydrogen needs

As we mentioned earlier, pure hydrogen consumption in 2018 amounted to c.75mt, with hydrogen being used mostly for two specific activities: refining (of petroleum and petrochemical products) and ammonia (a key feedstock in the production of fertilizer). These two use cases consume >95% of global hydrogen demand.

We assume that c.20% of global pure hydrogen demand, coming from Europe, is currently fully decarbonised (blue/green hydrogen) and this demand is likely to grow between 1-3% per year.

Hydrogen needs for transport

Road transport

We estimate hydrogen consumption from road transport (commercial vehicles and buses) could reach 4mn tonnes of hydrogen by 2050.

Number of buses amounted to 0.8mn in EU in 2019. By 2050, assuming an underlying growth rate of 1% pa, a higher share of fuel cell penetration (75%) and a fuel cell consumption of 8.5 H2g/km; total hydrogen consumption for this subgroup could reach 0.4mt by 2050.

Number of light commercial vehicles in EU reached 33mn in 2018, and we assume it could grow by 1% pa until 2050. Taking a 25% fuel cell penetration and a fuel consumption of 9.9 H2g/km (average between passenger cars and medium/heavy commercial vehicles), total hydrogen consumption by this sub-category in 2050 would amount to 2.2mt.

Medium/heavy commercial vehicles in EU totaled 6.6mn in 2018. Assuming an underlying growth rate in the vehicles number of 1% pa until 2050, a 50% fuel cell penetration and a fuel cell consumption of 11.6 H2g/km; total hydrogen consumption for medium/heavy commercial vehicles would reach 1.4mt by 2050.

Air transport

Domestic aviation in EU currently consumes c.7 mn tonnes of fuel (kerosene) and we expect it to grow in line with domestic traffic growth to 2050 (>2% pa). This would imply 3.8mt of hydrogen consumption from air transport by 2050, if we assume 100% fuel cell penetration rate. We assume a 55% efficiency factor for hydrogen in our forecast.

Maritime transport

EU maritime transport uses c.6.5mn tonnes of fuel (oil) per year. Domestic navigation accounts of 80% of yearly consumption, with the rest coming from fishing activities. Assuming that EU domestic navigation energy needs would modestly grow (<1% pa) and would be broadly flat in case fishing activities (-0.5% pa), we estimate that EU maritime transport could consume 1.7mt of hydrogen by 2050. We assume 100% fuel cell penetration and a 55% efficiency factor for hydrogen in our forecast.

Hydrogen needs for industry

We identified six energy-intensive industries (iron and steel, petrochemicals, non-ferrous metals, pulp and paper and construction) of which c.40% of the energy demand is for high-grade heat. Hydrogen offers benefits in its ability to generate high temperatures using process setups similar to today's for these processes which consumed c. 2.5mn TJ of energy (gas, fossil fuels and oil) in 2018. We expect these energy demands to remain broadly flat until 2050.

We forecast hydrogen demand by 2050 from industrial activities assuming an average fuel efficiency factor of c.40%, in line with the ones found in fossil-based power plants (gas, coal and oil), and a hydrogen efficiency factor of 55%. This leads us to a hydrogen demand of c.15mt by 2050 with: (i) 4.7mt to replace gas, (ii) 6.8mt to replace fossil fuels, and (iii) 3.3mt to replace oil.

Hydrogen needs for power system

We estimate hydrogen demand from power systems could be c.35mt. We assume 5%-10% of the power in 2050 could be generated from hydrogen.

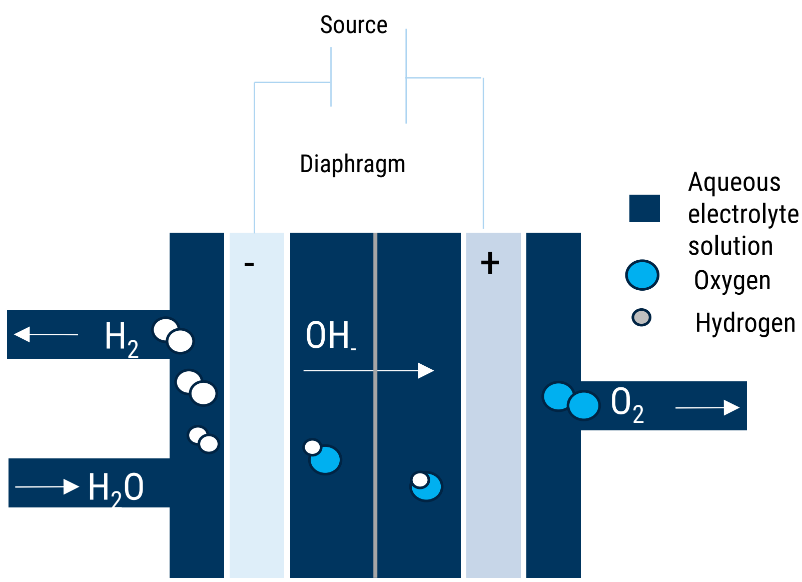
Technical Appendix - Green Hydrogen

Green hydrogen is produced through process called electrolysis - the separation of water molecules into hydrogen and oxygen by using an electric current. There are two common processes used today to undertake electrolysis: alkaline electrolysis and proton electron membrane (PEM) electrolysis.

Alkaline Electrolysis

Alkaline electrolysis makes use of two electrodes submerged in an alkaline electrolyte solution (such as potassium or sodium hydroxide), which are separated by a non-conductive porous membrane called a diaphragm. When electricity is run through the electrodes and water is pumped in against the negative electrode, hydrogen is separated from negatively charged hydroxide ions, which move through the diaphragm towards the positive electrode, where they release their negative charge to become oxygen molecules.

Exhibit 62: Alkaline electrolysis process



Source: BloombergNEF, Goldman Sachs Global Investment Research

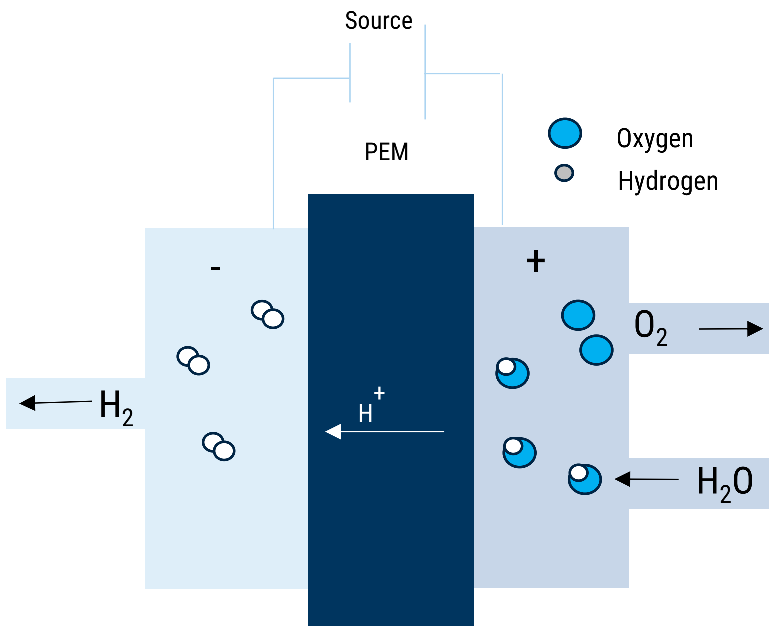
Compared to PEM electrolysis, the alkaline method offers key advantages including:

- It relies on convenient catalysts - electrolyte solutions are widely available and cheap to produce.
- Cheap inputs also mean that a large part of the cost of an alkaline electrolyser is labour - this in turn implies significant economies of scale.
- Electrolyte solutions are easily exchangeable and have minimal corrosive impact on the electrodes, implying relatively long useful life of the electrolyser.
- Alkaline electrolysis produces highly pure H_2 as hydrogen does not easily diffuse in the electrolyte solution.

PEM electrolysis

In contrast with alkaline electrolysis which makes use of electrolyte solutions to catalyse the separation of hydrogen from water molecules, PEM electrolysers use a solid polymer membrane which absorbs positively charged hydrogen atoms (separated from oxygen using electricity) and allows them to flow into a separate tank where they bond back together into H_2 molecules.

Exhibit 63: PEM electrolysis process



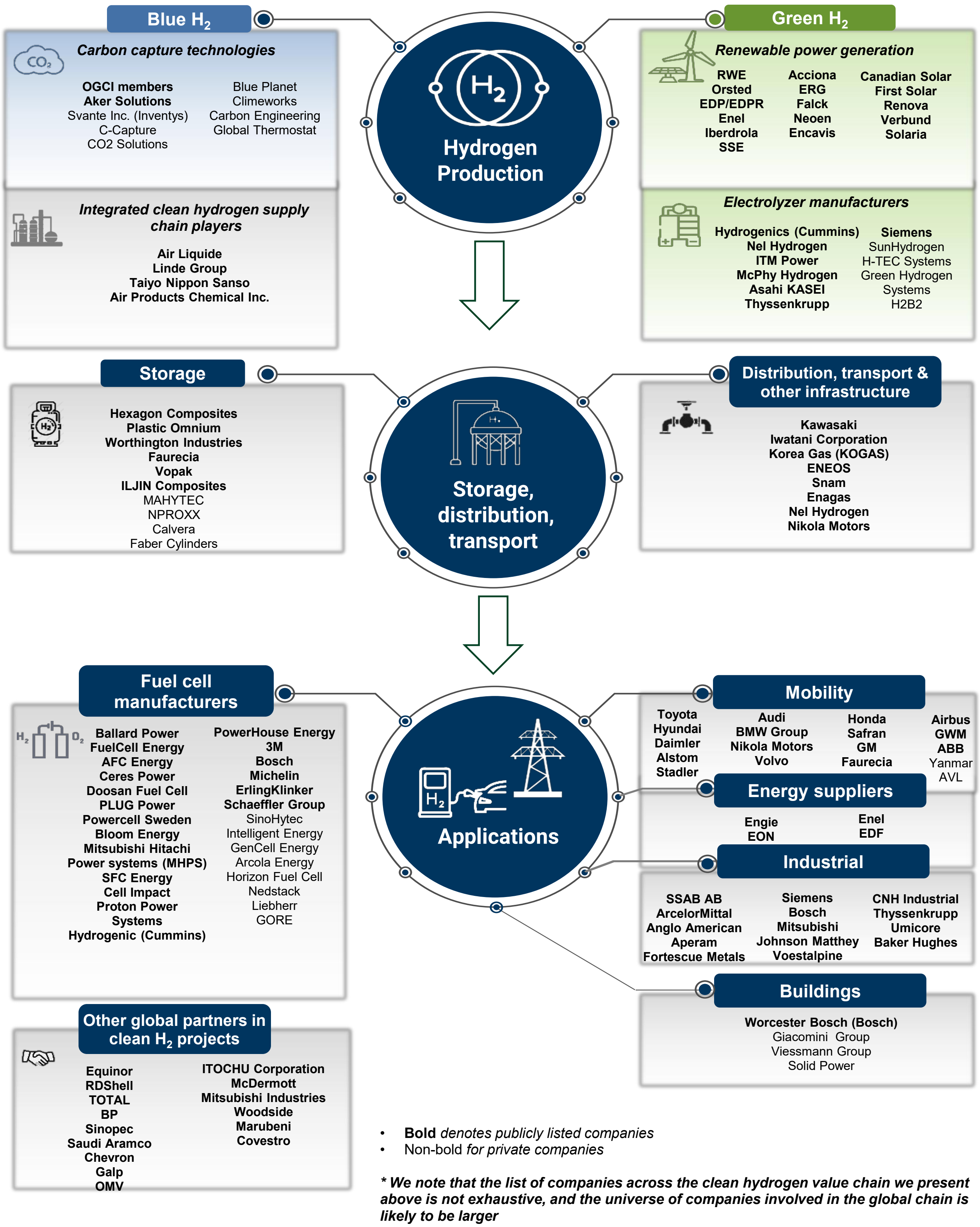
Source: BloombergNEF, Goldman Sachs Global Investment Research

According to our analysis based on some studies (e.g. IEA, IRENA), key advantages and disadvantages of PEM electrolysis include:

- PRO: higher purity of output compared to alkaline machines.
- PRO: fast response times, which make PEM electrolysers suitable to provide grid balancing services and allow PEMs to better deal with the volatility of renewable output (resulting in higher efficiency).
- PRO: very small scale can be achieved and installation is simple, making PEM electrolysers easy to bring onsite.
- CON: PEM electrolysers are more expensive.
- CON: what makes PEM electrolysers more expensive are the materials used, meaning that there are limited economies of scale on large installations.

The Clean Hydrogen Ecosystem

Exhibit 64: Clean hydrogen ecosystem



Source: Company data, Goldman Sachs Global Investment Research

Current hydrogen initiatives

Exhibit 65: Several projects for hydrogen production and end-use are currently underway

Partners	Location	Capacity	Project description
Neoen Australia	Australia	50 MW	The Hydrogen Superhub plans to combine 50 MW electrolyzer with 125 MW of wind, 150 MW of solar PV and 130 MW/400Mwh of battery storage.
InterContinental Energy, Vestas, CWP Energy Asia and Pathway Investments	Australia	12 GW	Asia Renewable Energy Hub is a plan of 15+ GW of wind and solar generation to produce green hydrogen
Voestalpine, Verbund, Siemens, APC, K1-MET and ECN (part of TNO)	Austria	6 MW	H2FUTURE involves installation and operation of an electrolyzer at Voestalpine Linz steel plant
Fluxys, Parkwind and Eoly	Belgium	25 MW	Power-to-gas installation to convert renewable electricity into green hydrogen under Hyoffwind project
Port of Oosende, DEME Concessions and MV	Belgium	50 MW	HyPort is a green hydrogen production project
Orsted	Denmark	2 MW	H2RES project plans to have a 2 MW electrolysis plant powered from two 3.6 MW offshore wind turbines
Meyer Burger, European Energy, Hydrogenics and Ecosolifer	Europe	800,000 tonnes	Silverfrog involves construction of 2 GW PV and 2 GW elecrtrolyzer production plants along with deployment of 10 GW of PV, 5 GW of wind for supply to a 10 GW electrolyzer system to produce green hydrogen
Engie and Air Liquide	France	10,440 tonnes	HyGreen Provence project plans to generate 1.3 TWh of solar electricity annually from 900 MW of solar project capacity to power electrolysis of green hydrogen on an industrial scale.
RWE	Germany	100 MW	Project to develop 100 MW electrolyzer to produce green hydrogen for Thyssenkrupp's steel mill
Uniper, VNG Gasspeicher (VGS), ONTRAS Gastransport, DBI Freiberg and Terrawatt Planungsgesellschaft	Germany	35 MW	Plan to set up a plant to produce green hydrogen from energy from wind farms
Shell and ITM Power	Germany	1,300 tonnes	Installation of 10 MW PEM electrolyzer at Shell Rhinelans's refinery under REFHYNE project.
RWE, OGE, BP and Evonik	Germany	100 MW	GET H2 involved establising 2 power-to-gas plants for electrolysis to produce hydrogen and includes transportatiion and end-use applications
Gasunie, TenneT and Thyssengas	Germany	100 MW	Power-to-gas plant for production of hydrogen under ELEMENT EINS
Orsted	Netherlands		Green H2 projects linked to bid for Holland Coast South 3&4 wind projects
Shell, Gasuine and Groningen	Netherlands	800,000 tonnes	NortH2 involved establishment of 3-4 GW of offshore wind capacity by 2027 and 10 GW by 2040 for hydrogen production
Nouryon, Gasunie, McPhy, BioMCN and DeNora	Netherlands	3,000 tonnes	Djewels is a 20 MW electrolyzer project to produce hydrogen and methanol from renewable sources
RWE and Innogy	Netherlands	100 MW	Project for construction of hydrogen plant in RWE's Eemshaven power station with renewable energy supply from Innogy's Westereems wind farm
BP, Nouryon and Port of Rotterdam	Netherlands	45,000 tonnes	Plans for 250 MW green hydrogen electrolysis pnt
Currently not selected	Portugal	1 GW	H2Sines is a government-approved hydrogen cluster plan in Sines for an initital electrolysis pilot of 10 MW, which will evolve to 1 GW, and green generation capacity of 1.5 GW
Air Products, ACWA Power and Neom	Saudi Arabia	237,250 tonnes	Green hydrogen based ammonia production facility whch will be powered by renewable energy
SSAB, Vattenfall and LKAB	Sweden	NA	HYBRIT is a pilot project to replace coal used in steel-making with green electricity and hydrogen
Orsted, ITM Power, Phillips 66 and Element Energy	United Kingdom	100 MW	Gigastack project plans to explore 100 MW electrolysis system and demonstrate production of low-cost green hydrogen from offshore wind farms
POLA, Toyota, Kenworth and Shell	United States of America	NA	Zero-Emission and Near Zero-Emission Freight Facilities (ZANZEFF) project aims to develop a hydrogen fuel-cell-electric technology framework for freight facilities to structure operations for future goods movement.
EDF Germany, Holcim Germany, OGE, Ørsted, Raffinerie Heide, Stadtwerke Heide, thyssenkrupp Industrial Solutions and Thüga, Region Heide development agency and Westküste University of Applied Science	Germany	30 MW	WESTKÜSTE 100 is a large-scale hydrogen project which will be used to evaluate future scale-ups.
Enagas	Spain	32 MW	Plans to build a hydrogen hub with a production capacity of 12 tonnes of green hydrogen per day powered by 150 MW solar PV plant.

Note this list is not exhaustive

Source: S&P Platts, Company data, Project data, PV Magazine, Fuel Cells Works , ENTSO-G, respective company press releases, El Economista, compiled by Goldman Sachs Global Investment Research

Disclosure Appendix

Reg AC

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