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Laying the foundations of a low carbon hydrogen market in Europe

Hydrogen as the cornerstone of energy transition

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EXECUTIVE SUMMARY

The 2020s will be the pivotal decade for tackling climate change. If the Paris Agreement goal of limiting warming to 1.5°C and delivering net zero is to be achieved, this will now require a five times increase in the rate of global decarbonization (some 12%) every year until 2030.[1] The creation of a low carbon hydrogen economy can play a critical role in accelerating this transition.

Hydrogen is regarded by many as the 'Swiss army knife' of the green energy future with the potential to replace hydrocarbons in many applications and sectors where emissions are hard to abate. Hydrogen molecules can help store energy to support intermittent energy flows from renewables. It can act as a fuel in heating where electrification is not possible or not cost effective. And it can serve as a feedstock in power generation and in industrial processes requiring intense heat (think of steel production for example).

However, how can the significant potential of this green energy fuel be realized? After all, while the technology may be mature (fuel cells helped propel the first man to the moon), the industry and supply chains are nascent and immature. Establishing a low carbon hydrogen economy will require a number of building blocks. These range from stimulating demand in target sectors to establishing a global trading market in hydrogen akin to the growth of LNG.[2] And all this will need to be underpinned by a strong and enabling regulatory framework implemented by governments in order to deliver the EU goal of a low carbon hydrogen economy.

1 PwC Net Zero Economy Index 2020: https://www.pwc.co.uk/services/sustainability-climate-change/insights/net-zero-economy-index.html
2 Liquefied Natural Gas

Overview of the current and potential hydrogen market

Low carbon hydrogen is widely acknowledged as an abundant, clean, versatile and convenient energy carrier and as a result, it is now regarded as a key part of the energy transition. Hydrogen's potential as a fuel source has been considered from time-to-time for decades, but without much progress. The recent commitments by countries and international organizations to curb and achieve net zero carbon emissions, paired with the consistent scale up of renewable capacities, as well as the ongoing reduction in renewable power costs, have finally delivered the necessary impetus. This is particularly the case for low carbon hydrogen which can be used as an alternative to natural gas (*see Exhibit 1, next page*).

EXHIBIT 1

There is a potential to replace natural gas with H_2 thanks to similar properties, lower CO_2 output and natural abundance

Hydrogen properties

Hydrogen characteristics

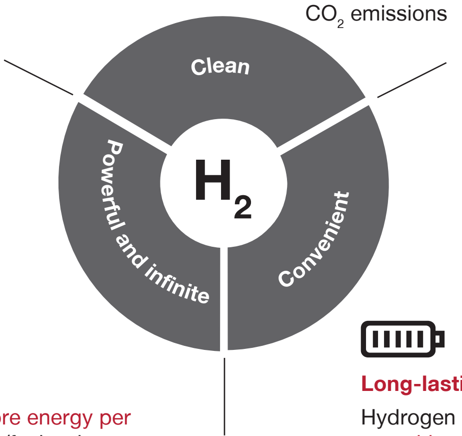
With no carbon in it, hydrogen emits no CO_2 nor pollutants when consumed. Depending on the way it is generated, it can be a zero carbon solution

A way to decarbonize end uses of energy

Used as a substitute to fossil fuel or blended with natural gas through injection into gas grids, hydrogen has the potential to reduce CO_2 emissions

Endless

Hydrogen is the most abundant element in the universe



Transportable using several technical options

Not easy to transport when pure, but H_2 could be mixed or liquefied to facilitate large volume transportation

High energy density

Hydrogen has much more energy per unit mass than other gas/fuels, almost 3 times more than gasoline

Long-lasting storage

Hydrogen can be stored in large quantities and for long periods

Natural gas properties

GHG emissions

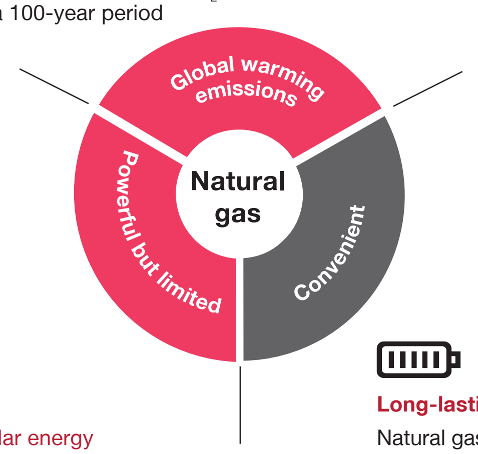
The drilling and extraction of natural gas and its transportation in pipelines results in the leakage of methane, primary component of natural gas that is 34 times stronger than CO_2 at trapping heat over a 100-year period

Clean power producer

Gas fired power plants achieve high energy efficiency ratios (>60%) but produce a significant amount of CO_2

Limited resources

Given the current rate of production and current known reserves, we have about 52.8 years worth of reserves left



Easily transportable in large volumes

Natural gas already benefits from large developed networks of transportation routes around the world

High energy density

Natural gas has a similar energy density to gasoline

Long-lasting storage

Natural gas can be found, transported and stored in liquid form

Advantages
Drawbacks

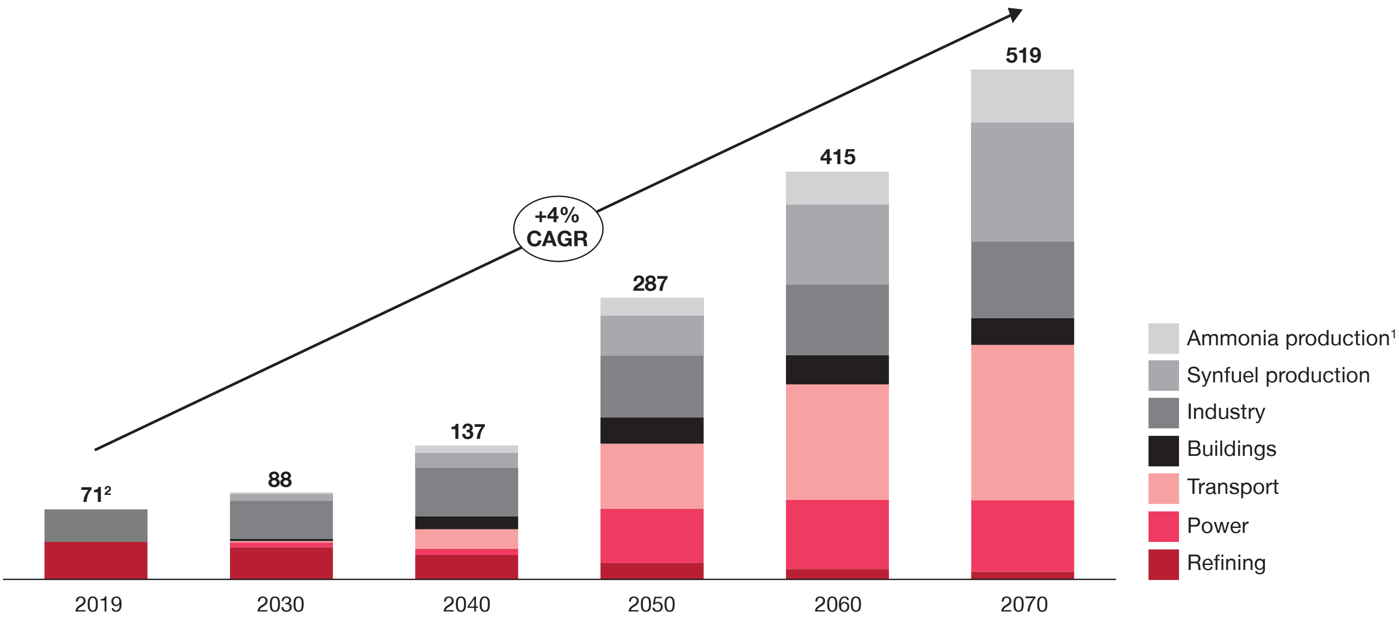
Source: Strategy& analysis

According to the International Energy Agency's (IEA) Sustainable Development Scenario (SDS) projections, global demand for hydrogen is expected to increase sevenfold to 520 MtH_2 by 2070, from around 70 MtH_2 in 2019 (*see Exhibit 2*). Assuming a corresponding decline in fossil alternatives and a low carbon production of hydrogen, this would contribute to global CO_2 emissions from the energy sector and industrial processes reaching zero (carbon neutrality) by 2070.

EXHIBIT 2

In the SDS scenario, worldwide demand for hydrogen is expected to increase sevenfold to 520 MtH_2 by 2070

Global hydrogen demand by sector in the SDS scenario, 2019-2070 – in MtH_2



H_2 Sector usages in 2070

- **In the Sustainable Development Scenario, the global hydrogen demand increases by 7x to reach 520 MtH_2 by 2070 with:**
  - **Transportation** (cars, trucks, ships) accounting for 30%
  - **Synthetic kerosene** production for aviation accounting for 20%
  - **Industry** (steel, chemicals) accounting for 15%
  - **Power generation** accounting for 15%
  - **Ammonia production** accounting for 10%
  - **Buildings** (space and water heating) representing 5%
  - **Other** uses (refining) account for <5%
- The increase in the H_2 demand is driven by the CO_2 emission reduction targets in all economies

1. Ammonia production refers to the fuel production for the shipping sector. Hydrogen use for industrial ammonia production is included within the industry use
2. A further 45MtH_2 is used in the industry without prior separation from other gases

Source: IEA, Strategy& analysis

Of course hydrogen is not something that has just been discovered. With 70 MtH_2 produced a year, it is a market worth some $100bn (*see Exhibit 3*). Demand largely comes from industrial customers and Asia is the biggest market (48%), followed by the Americas (22%) and Europe (18%). The refining and chemicals industries account for more than 80% of hydrogen demand. In refineries, hydrogen is used to lower the sulphur content of diesel fuel, so demand has been sustained by higher diesel consumption globally and stricter sulphur-content regulations.

In the chemicals industry, hydrogen is used to make two major and widely used chemical compounds: ammonia and methanol. Ammonia is the primary resource of the fertilizer industry.

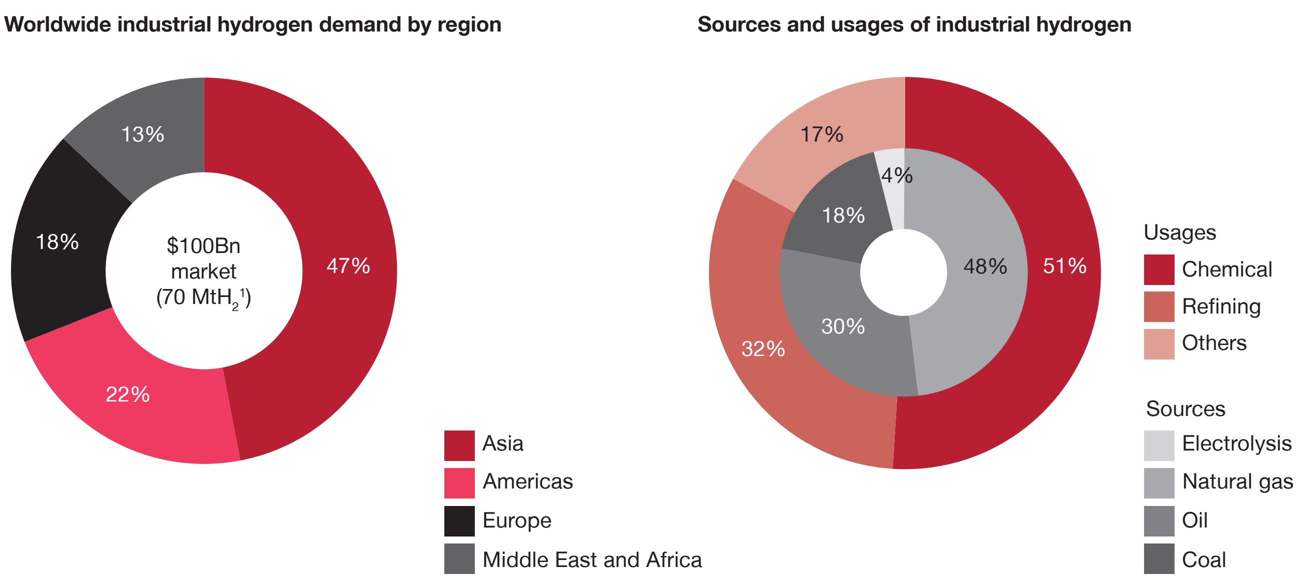
The challenge is that almost 95% of the hydrogen consumed today is produced from fossil fuels, with coal gasification and steam methane reforming the most common methods. In these processes, a fossil fuel input, namely coal or gas, reacts with steam to produce carbon monoxide, carbon dioxide and hydrogen. Unless the CO_2 is captured, used or stored, these traditional ways of manufacturing hydrogen are harmful to the environment, releasing about 10kg of CO_2 for each 1kg H_2 produced.

So hydrogen can only deliver on its promise to sustainably decarbonize the global economy if carbon emissions are minimized in the production process. There are several ways to achieve this. Low carbon hydrogen can be produced at scale with the help of renewables such as wind, solar or hydro, as well as biogas and nuclear power but also through conventional fossil fuel energy sources coupled with carbon capture and storage (CCS) solutions. These themes are developed further in the 'Building Block 2' section. However, stimulating demand is one of the first and key building blocks for developing a hydrogen economy.

EXHIBIT 3

Global demand for H_2 is a ~$100Bn market in 2020

Worldwide demand for H_2 by region versus sources and industrial usage



1. 70 MtH_2 is equivalent to ~200 MTOE (Million tons of Oil Equivalent)
Sources: IRENA 2018, Bloomberg, Afhypac, CNCCEF.org, IEA, Strategy& analysis

BUILDING BLOCK 1

Stimulating demand for low carbon hydrogen

As countries and industries increasingly look to low carbon hydrogen as a fuel source and feedstock, we expect a far more diverse customer base for hydrogen to develop. Different sectors will follow their own decarbonization pathway and timeline, depending on the maturity of low carbon hydrogen production technologies, the complexity of adapting their existing processes and the regulation and economic incentives available. The availability of alternative and competing technologies will also be a factor (the electrification of light passenger vehicles being a case in point).

However, rather than target a plethora of sectors, governments pursuing a low carbon hydrogen economy may need to focus their efforts adhering to some broad principles, namely:

- Focusing on industrial clusters which are hard to decarbonize and where there is scale (a variety of large and diverse industry players) and existing infrastructure that can be utilized (such as pipelines)
- If those clusters are located near ports and coastlines this will also be critical to accessing a growing international trading market in hydrogen
- Partnership models will be an enabling platform to promote hydrogen solutions. These partnerships will often be made between corporates looking to build capabilities in hydrogen and syndicate the investment cost and risk. Local governments can also be part of these alliances

> "The first main challenge in the near future is to incentivize demand by developing subsidies to encourage and not to force targeted industries to switch to green H_2."
>
> **Europe industry representative**

Many sectors can pursue a low carbon hydrogen future. However, there are some sectors that should be prioritized, especially those where there is no viable alternative technology to accelerate decarbonization. Taking the latter into account, sector prioritization might reflect the following:

1 The refining industry …

is likely to start using low carbon hydrogen as a substitute for the conventional hydrogen produced from coal and gas. As a next step, the industry is planning to use low carbon hydrogen to manufacture synthetic fuels in combination with captured carbon, among other applications. Compliance with existing renewable energy regulations (Renewable Energy Directive II) and economic incentives may accelerate this change.

2 In the steel industry, …

direct reduction of iron – using hydrogen to remove oxygen from iron ore in its solid state, without melting it in the blast furnace – offers a promising path to decarbonization for a sector that produces 1.85 tons of CO_2 for each ton of steel, according to the World Steel Association. The technology is being tested by steel manufacturers in demonstration projects already and should reach maturity by the mid-2020s before being scaled up (*see Exhibit 5, page 10*).

3 In power generation, …

hydrogen blended with natural gas or pure hydrogen can power gas turbines and engines to decarbonize the sector. Gas turbine and gas engine manufacturers are currently addressing the technical challenges caused by hydrogen combustion, such as higher flame propagation speeds and nitrogen dioxide emissions, to design fully hydrogen-compatible turbines and engines by 2030, in line with the objectives of industry body EUTurbines. This move will open up new ways for power generation companies to further decarbonize their operations and mitigate the risks of stranded assets they can no longer use as a result of tightening emissions regulations (*see Exhibit 4, page 9*).

4 The cement industry ...

is an interesting case, because one third of its CO_2 emissions are linked to the fuel source needed to heat the process and trigger the calcination reaction. Hydrogen could be used as a primary source instead in this case. The remaining two-thirds of CO_2 emissions are directly linked to the calcination process itself. Several carbon reduction levers have been identified by the (cement) industry in order to meet its obligations, including improving energy efficiency, reducing the clinker-to-cement ratio or using alternative binding materials, and also capturing carbon emissions for long-term storage or use. The latter is a particularly strong opportunity for this sector: green hydrogen could be combined with the carbon captured by cement makers to produce chemical compounds such as ammonia or methanol. This highlights the potential for cross-sector collaboration in the low carbon hydrogen market.

5 In the transport sector ...

heavy-duty mobility, such as freight trucking is likely to offer consumption volumes of hydrogen as a fuel that could be large enough to trigger economies of scale. Large fleets and pre-planned routes will also ease the need to quickly develop a wide network of hydrogen refueling stations. While some car manufacturers invest heavily in light vehicles, they are facing an uphill battle, including individual cars, because cheaper low carbon electric vehicles are already available. Hydrogen is likely to become cost-competitive in transport before other sectors because the cost of diesel and gasoline is typically higher than the cost of the natural gas used in other industries. Over time, governments will need to respond to an increased use of hydrogen and synfuels as a fuel for vehicles and replace the taxes they raise from petrol and diesel sales today. Thus, potential future taxes levied on hydrogen could in turn impair its cost competitiveness. However, we do not believe this will happen until the switch to hydrogen is well established, as governments do not want to hinder the progress of the transport industry.

EXHIBIT 4
The energy sector is gearing up to increase the amount of hydrogen used as a fuel for power and heat generation

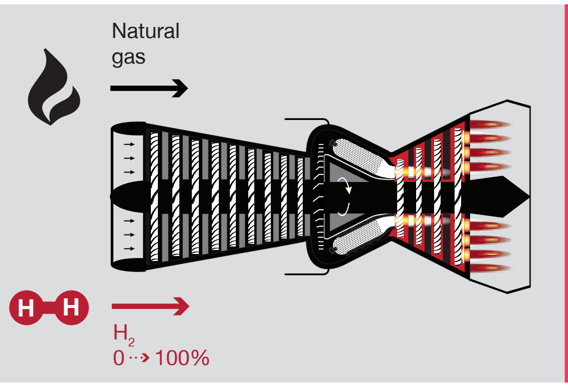
Energy – power and heat generation optionality are increasing H_2 capability (selected examples)

Gas TSO – Hydrogen blending

Gas Transmission System Operators (TSOs) are setting up working groups and carrying out experiments to increase the level of hydrogen in natural gas with targets of 10% by 2030 and up to 20% later on

The aim is to mobilize equipment manufacturers and downstream users, to assess externalities of injecting H_2 into the network, to integrate infrastructure development needs and to define and implement a framework for experimenting and operating hydrogen clusters

GRYDH and Jupiter are two demonstrator projects testing such concepts in France

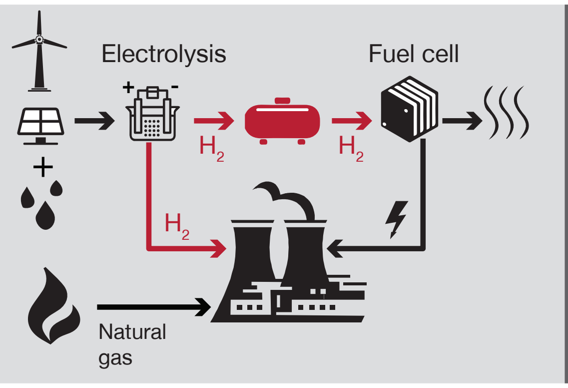


GT manufacturers – H_2 capability

Gas turbine (GT) as well as gas engine manufacturers (e.g. GE, Siemens, Jenbacher) are developing new fuel flexible units as enablers for a low carbon energy mix and also to ensure the sustainability of their business in a carbon free energy ecosystem

GT hardware modifications will be required due to specific H_2 properties. For example, it takes 3x more volume flow of H_2 to provide the same energy as natural gas and as the flame speed of H_2 is about 10x faster

Members of the industry body EUTurbines have signed a commitment to increase H_2 capability in GT to at least 20% in 2020 and to 100% by 2030



Verbund – “Hotflex” pilot plant

In the Mellach pilot plant in Austria, excess wind and solar power can be taken from the grid and converted into H_2 by high-temperature electrolysis. This “green” hydrogen (40 Nm3/h) is mixed with natural gas to drive the two gas turbines and gas engines

A special feature of the plant is that it can operate in reverse mode as a fuel cell. The plant is thus able to produce electricity and heat

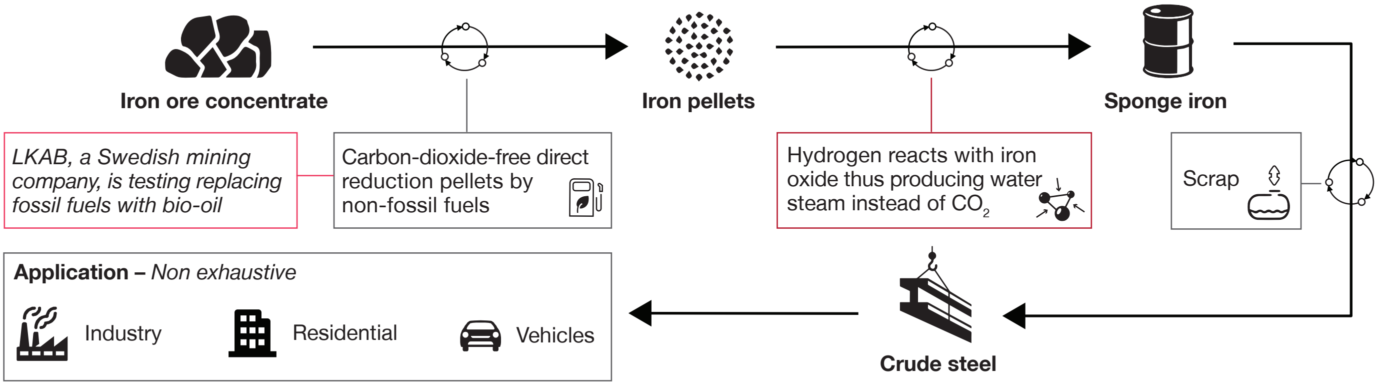
Verbund will test this fuel cell operating mode primarily as a possibility for self or emergency power supply of its power plant

Sources: GRTGaz, Siemens-energy.com, ge.com, Strategy& analysis

EXHIBIT 5

Green hydrogen is tested to be used as a replacement for coke and coal to decarbonize the steel industry

Iron and steel making industry – Process example and use cases



Arcelor Mittal use case

- Multinational steel production company Arcelor Mittal is partnering with the University of Freiberg to develop a production plant that uses hydrogen for iron ore reduction in Hamburg
- Though testing will be done with grey and blue hydrogen, the company plans to transition to green hydrogen as it becomes more widely available
- It aims to achieve the separation of H_2 with a purity of more than 97% from the waste gas of the existing plant, using 'pressure swing absorption' process
- It estimates a demonstration scale of around 110,000 tons of hydrogen-based iron ore reduction
- Hydrogen technology is just part of the company's €250 million investment into carbon dioxide avoidance
- Commissioning is estimated to start in 2023

The HYBRIT initiative: Hydrogen breakthrough ironmaking technology

- HYBRIT is an initiative founded by three Swedish companies: steel manufacturer SSAB, mining company LKAB, and energy company Vattenfall
- It aims at exploring the use of hydrogen in steel production, that will be generated from renewable electricity. The decarbonized hydrogen will be used in place of coke[1] and coal, and will react with Iron Oxide
- A HYBRIT Development AB pilot plant began construction during summer 2018 at the SSAB site in Luleå, Sweden, with €44 million in funding assistance from the Swedish Energy Agency
- The pilot phase is expected to last until 2024, followed by a demonstration phase from 2025 to 2035

1. Coke is a hard, porous, nearly pure carbon product made by heating coal in the absence of air. Coke acts as both a fuel and reducing agent in the blast furnace, forming carbon monoxide when burned

Sources: Company website; Strategy& analysis

Stimulating the supply of low carbon hydrogen

To accelerate the development of low carbon hydrogen and drive the displacement of hydrocarbons in energy-intensive industries, the top priority is to bridge the price gap between mature carbon-emitting technologies and newer, cleaner hydrogen technologies. The cost of the electricity input accounts for 60 to 70% of green hydrogen's variable costs, so access to cheap and abundant renewable energy to power electrolyzers is of paramount importance. Experts interviewed by Strategy& said that green hydrogen could become cost-competitive at scale when the levelized cost of energy (LCOE) in renewables falls below $20/MWh. This is likely to happen in scale by 2030 as countries around the world invest significantly in renewable energy and reduce the LCOE.

In the meantime, electrolyzer OEMs are working hard to make electrolyzers more efficient and achieve economies of scale that will also contribute to lower variable costs. We also expect that that polymer electrolyte membrane (PEM) technology will be more efficient than alkaline (ALK) and this will also bring down costs.

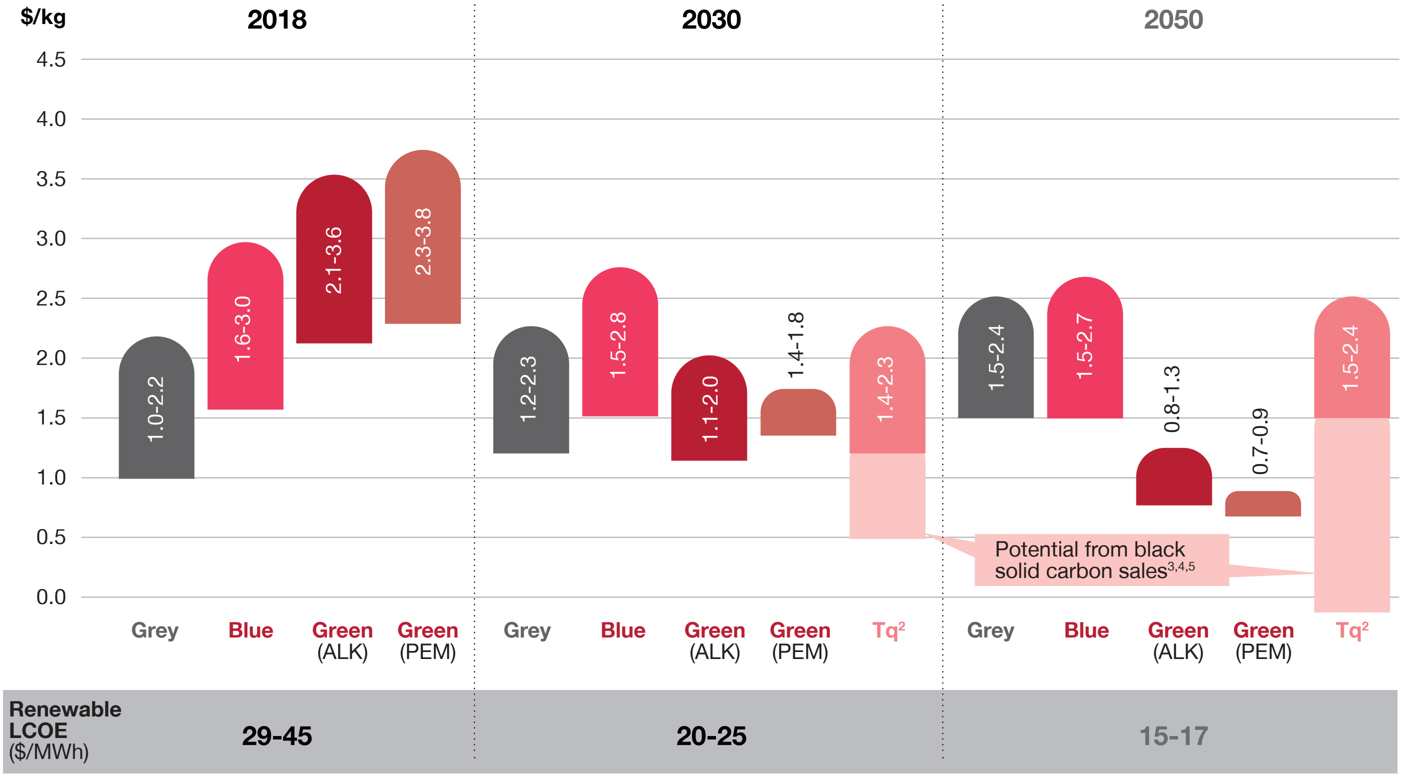
Today, it takes about 55 kWh of electricity to produce 1kg of hydrogen. CAPEX improvement is expected as electrolysis technology becomes more mature, however there might be a significant CAPEX difference between relatively cheap electrolyzers produced in Asia (<$500/kW) and the ones produced in Europe. This gap also reflects the technology used, with PEM electrolyzers being more CAPEX intensive than ALK electrolyzers (*see Exhibit 6, next page*).

> "The variable cost of H_2 is mostly driven by the cost of the main input: electricity."
>
> **Electrolyzer manufacturer**

EXHIBIT 6

Green H_2 could become cost competitive by 2030 given expected cost optimization and CO_2 price increase

Strategy& market model on global hydrogen cost development by technology[1]



Key insights on cost perspective	
	• **Green hydrogen:** – Cost structure is mainly driven by OPEX (local electricity prices) for electrolyzers, with green electricity expected to become cheaper (~$33/MWh) and electrolyzers more efficient (~50kWh/kg H_2) thus decreasing OPEX – Cumulative production volumes are doubling about every two years and could lead to up to 70% cost decrease (CAPEX improvement) – CO_2 (respectively natural gas) price is expected to rise to ~$50/t (respectively to reach at least $7/GJ) and will make green H_2 more competitive • **Blue hydrogen:** – Decarbonizing natural gas bears additional costs of $55-80/t CO_2 • **Turquoise hydrogen:** – Hydrogen produced from natural gas using molten metal pyrolysis technology – Shows comparative advantage where CCUS is not applicable for political or geographic reasons, but is in early development stage (e. g. BASF pilot)

1. Cost assumptions based on greenfield projects, excluding cost for electrolyser and building cooling requirements
2. Turquoise costs mainly driven by natural gas price
3. Current prices for solid black carbon range from 400-2000 €/t
4. Assuming a black carbon revenue between 500 and 700€/t turquoise hydrogen could be produced at zero cost
5. Carbon black use cases: tires, rubbers, construction material

Sources: BNEF (2019), IEA (2019), Energy Conversion and Management: X (2020) and Strategy& Research (2020)

However, the expected boom in demand for green hydrogen will significantly increase the need for renewable energy capacity. To illustrate this point, for the EU to produce 10 MtH_2 from electrolysis in 2030, it would consume about 550 terawatt hours (TWh) of renewable energy (on the basis that 1kg H_2 requires about 55 kWh today) – more than the annual electricity consumption of France, which was 460 TWh in 2020.

Some countries with large renewable energy potential could supply parts of Europe with green energy to power electrolyzers. They may also decide to produce green hydrogen and export it to other countries. (*See Exhibit 7* for an overview of the main potential exporting and importing countries of the future global hydrogen trading market).

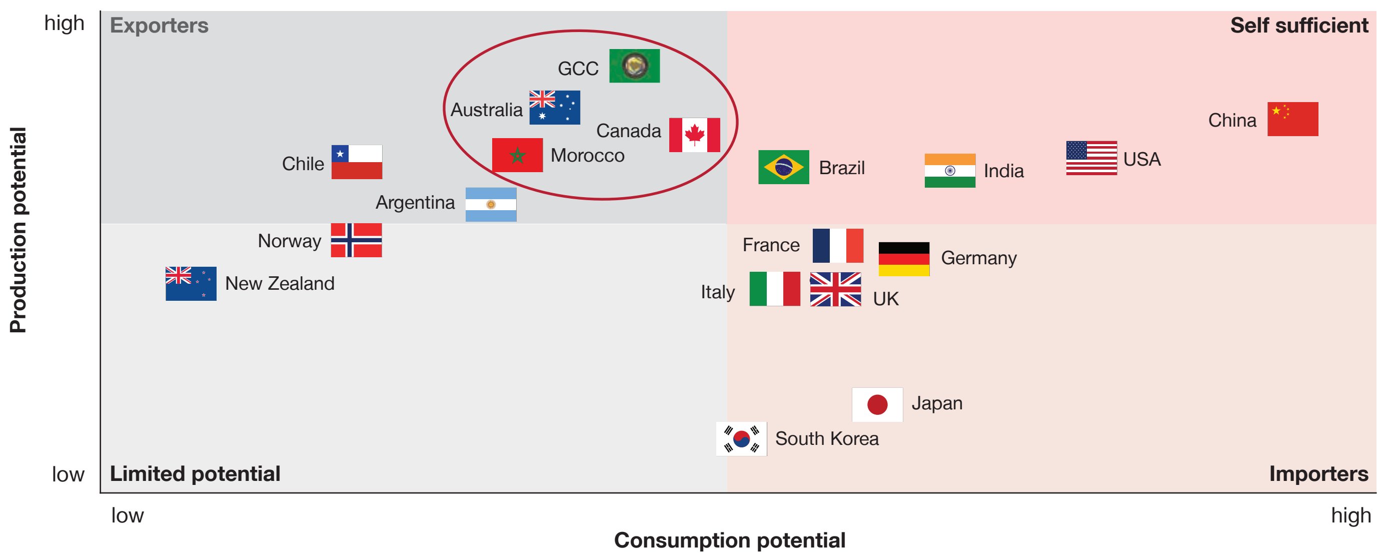
Water is another critical resource needed to power electrolyzers. The quantities will be huge, as it takes up to 22 liters of water to produce 1kg H_2. In dense industrial areas, there might be some constraints to accessing a sufficient quantity of water to feed the electrolyzers and meet industrial needs.

And just a final concluding thought on supply and the role of 'blue' hydrogen, that is hydrogen produced from gas using carbon capture technology. While the end goal in supply must be clean and renewables-sourced hydrogen, 'blue' hydrogen will have an important role to play as a bridge technology to generate sufficient low carbon hydrogen volumes until 'green' hydrogen production will be available at scale. We see this in cases such as in the Netherlands but also the UK where for example Equinor and Uniper together with a dozen of partners have formed the Zero Carbon Humber consortium to generate hydrogen from gas using carbon capture technology. The carbon dioxide will be exported and stored underground in the North Sea.

EXHIBIT 7

GCC[1], Australia, Canada and Morocco have a high potential to export large H_2 volumes to Asian and European countries

Green hydrogen production/consumption potential by country



1. GCC: Gulf Cooperation Council is a regional intergovernmental political and economic union consisting of all Arab states of the Persian Gulf: Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates.
Source: Strategy& analysis

Connecting supply and demand – transportation and storage

Hydrogen transportation is key to connecting demand and supply.

Transporting hydrogen through the existing gas infrastructure is one option. As already referenced, gas transmission system operators in Europe estimate they could blend up to 10% hydrogen with natural gas without facing many technical challenges. A maximum of 20% blending seems achievable with minor adaptations to the gas network, but beyond that, it would be more cost-efficient to have a dedicated hydrogen infrastructure.

However, the economic model around blending has yet to be clarified. Injecting an expensive molecule into cheap natural gas is often seen as a value destruction mechanism. There are also projects that demonstrate the technical feasibility of using hydrogen in heating, such as plans set out by UK grid companies to deliver the country's first hydrogen town by 2030.

As natural gas volumes are expected to decrease, gas pipes could be repurposed to transport hydrogen and this would prevent TSOs being saddled with stranded assets. Eleven European gas TSOs published a European hydrogen 'backbone' study that envisions the development of hydrogen transportation infrastructure.[3] The latter ranges from regional networks formed around hydrogen hubs, to an interconnected pan-European network made up of approximately 75% retrofitted existing gas infrastructure and 25% new hydrogen pipes, extending to a total length of about 23,000km by 2040. The cost of this infrastructure development has been estimated at €64bn (*see Exhibit 8, next page*).

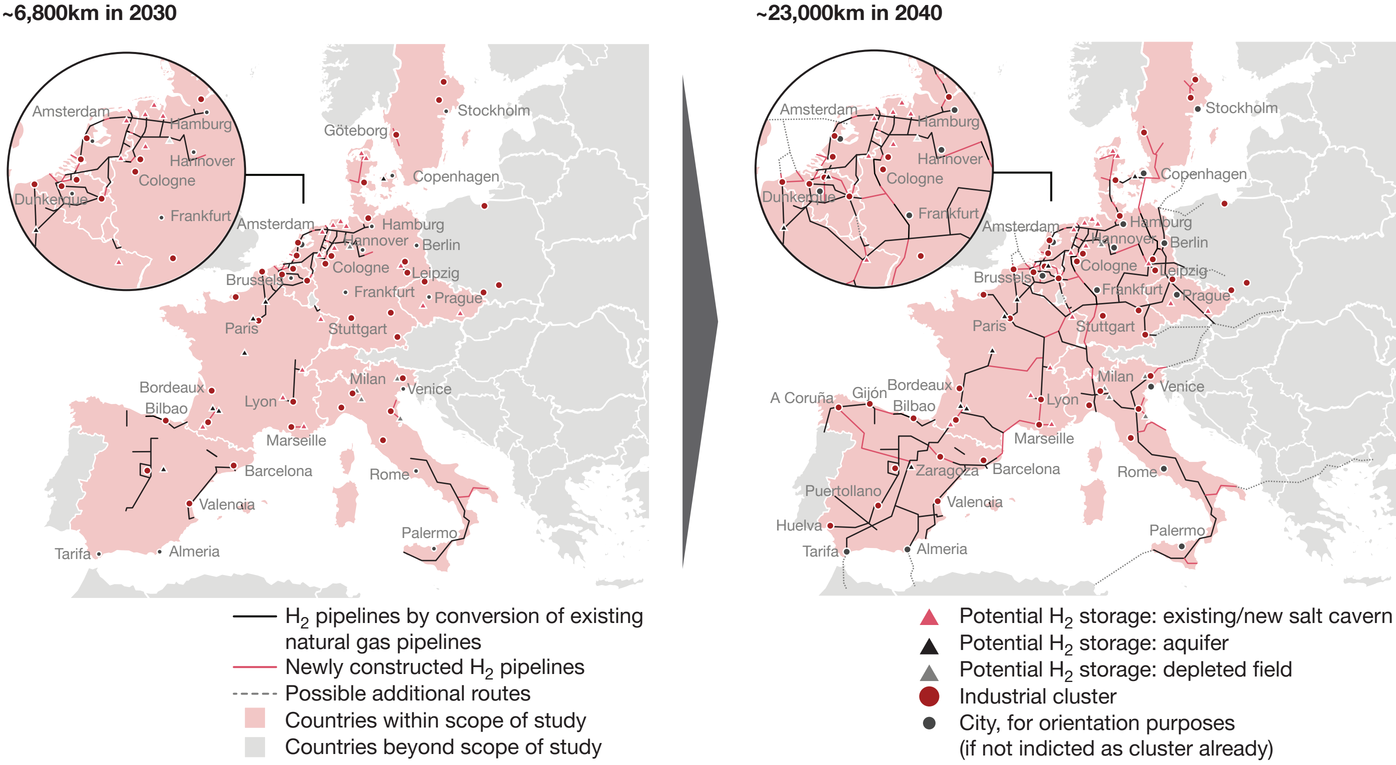
3 European Hydrogen Backbone

> From 2025, national and transnational infrastructure will be needed to connect hydrogen clusters and ecosystems."
>
> **Leading pipe manufacturer**

EXHIBIT 8

Infrastructure is critical to support H_2 market growth and will represent an investment of up to €64Bn by 2040

European hydrogen backbone development to connect supply and demand



- Regional backbones are expected to form in and around first-mover hydrogen supply and demand hubs, or “hydrogen valleys” (e.g. industrial clusters, ports, cities, pilot projects and commercial hydrogen developments)
- Today, small-scale dedicated hydrogen networks of approximately 1,600 km in length exist in Europe to transport fossil-based, “grey” hydrogen between industrial clusters

- By 2040, the hydrogen backbone could have a total length of 22,900 km, consisting of approximately 75% retrofitted existing gas infrastructure and 25% of new hydrogen pipelines
- The network should be able to adequately meet the 1130 TWh of annual hydrogen demand in Europe by 2040 (ambitious scenario)

CAPEX and OPEX levels required by 2040

CAPEX in €Bn	Low[1]	High[1]
Pipeline cost	17	28
Compression cost	10	36
Total investment	27	64

OPEX in €Bn/yr	Low	High
Operations and maintenance	0.7	1.1
Electricity cost	0.9	2.4
Total OPEX	1.6	3.5

- The €27 to €64Bn investment bracket covers the full capital cost of building and retrofitting of natural gas pipe. *This amount is a fraction of the hundreds of billions in investments in green hydrogen production*
- 75% of the total network will consist of retrofitted infrastructure, representing 50% of the total CAPEX
- OPEX includes maintenance and operations costs for the pipelines and compression stations assuming a load factor of 5000hr/yr and also accounts for electricity costs

1. Low/high ranges are determined based on gas TSO’s experience in investing and maintaining natural gas pipes and extrapolated to hydrogen

Source: Guidehouse EU hydrogen backbone report; Strategy& analysis

For areas that cannot be connected by pipes, other options are available. Transporting compressed hydrogen as a gas could meet the needs of the mobility market. However, only relatively small quantities of energy can be transported this way due to hydrogen's low energy volume density, making it more difficult to meet the large volumes expected across industries.

Liquefied hydrogen is another option for transporting or storing hydrogen over a short period. However, due to high costs and the need to store it at -253°C, it will most likely be used as a fuel in aviation and space applications (such as short to medium haul flights and rocket propulsion).

Liquid organic hydrogen carriers (LOHC) such as methyl cyclohexane or methanol are also a way to transport hydrogen in bulk over long distances. They are fully compatible with existing transportation means, reusable and can be handled at room temperature and atmospheric pressure. Some of the drawbacks are the heat required to separate the hydrogen at the point of consumption and the time it takes to carry out the chemical reaction.

Ammonia is also a convenient way to store hydrogen in large quantities over a long duration. It has a high energy density and can be used without further transformation in a wide range of industrial sectors. It can also be used directly as a fuel source to power gas turbines or ships. Ammonia supply networks and transportation infrastructure are mature. Drawbacks include its high toxicity and the nitrogen oxide emissions during combustion. Today, ammonia seems to benefit from a slight cost advantage compared to LOHC.

Just like transport, hydrogen storage is needed to ensure a continuous supply of large volumes to industrial users. It can be stored as a liquid in the form of ammonia, LOHCs or liquid hydrogen, but this is much more expensive than storing hydrogen as a gas. Salt caverns and depleted gas fields offer the best potential to store large quantities at costs below \$0.30/kg and \$2/kg respectively. The remote geographical location of such storage may not be the most efficient way of matching demand with supply. However, alternatives such as aquifer storage, are still being investigated. Technical and operational challenges have included gas volume losses and chemical and microbiological reactions with bacteria leading to corrosion within the borehole.

EXHIBIT 9

Case study: World's first blue ammonia shipment between Saudi Arabia and Japan happened on September, 20th 2020

Sustainable hydrogen usage with energy carrier and a circular carbon economy

Project name	Saudi-Japan blue ammonia supply demo
Year	Cooperation launched in 2017 1st shipment in 2020
Involved stakeholders	Saudi Aramco; Saudi Arabia; Ministry of Economy, Trade and industry; Institute of Electrical Engineers of Japan; SABIC
Description	40 tons of high-grade blue ammonia dispatched for use in zero carbon power generation
Objective	• Conversion of hydrocarbons to hydrogen then to ammonia • Capture of CO_2 emissions: – 30t CO_2 later used in methanol production at SABIC's Ibn-Sina facility – 20t CO_2 used for Enhanced Oil Recovery Process (EOR) at Aramco's Uthmaniyah field • Use of Ammonia in a zero carbon power generation plant in Japan • Set a successful transnational, multi-industry partnership as part of the circular carbon economy
End use	Energy use

Source: Project website; Strategy& analysis

Enabling regulatory frameworks underpinning the market

While demand, supply and transport/storage are the core pillars of a hydrogen economy, these pillars need to be founded on a robust regulatory framework. Governments have a critical role to play by ensuring there is a hydrogen strategy in place, with clear targets and complemented by strategic investments and fiscal incentives. Once this has been established, this will send the right market signals to encourage private sector participation. This is precisely what happened in the UK to promote the offshore wind industry for example. The UK government has set a clear ambition to become a world leader, defining targets and enabling investment through contracts for difference (CfDs). Having started this journey in the early 2000s, the UK saw offshore wind capacity reach some 10GW in 2020. Now the UK government is seeking to reach 40GW by 2030.

There are similar initiatives across Europe for hydrogen. The EU-wide hydrogen roadmap (*see Exhibit 10, page 21*) and the national hydrogen strategies recently put in place by a number of countries (*see Exhibit 11, page 22*) are important steps towards ensuring the green hydrogen market achieves its full potential. They provide the long-term visibility that allows stakeholders on both the supply and demand side of the equation to undertake the necessary investments. Co-operation and co-ordination between countries will be critical to guaranteeing a level playing field and fair competition both within Europe and at its borders.

Government financial support will also be needed in the nascent green hydrogen market to give producers and consumers the right level of incentives to switch to low carbon hydrogen technologies. This could take various forms: direct CAPEX or OPEX subsidies, or compensation mechanisms. In Europe, the agreement reached in December 2020 to establish a hydrogen Important Project of Common European interest (IPCEI) will be a real accelerator to achieving the ambitious targets for electrolyzer capacity installation set out in the EU Hydrogen Strategy.[4]

At a national level, funds earmarked for post-COVID-19 stimulus packages will be powerful tools to support demonstration projects, development of hydrogen technologies and to encourage supply and demand through financial incentives. This support will be required until green hydrogen becomes cost competitive with other energy sources, which is not expected until 2030, as outlined previously.

Regulation will also be key to driving the transition to green hydrogen. A carbon tax increase, a European border tax or imposing binding targets or mandatory quotas for hydrogen use in industrial processes would all help the EU/European countries achieve their goal to create demand for hydrogen in large volumes and support the market take off.

4 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

EXHIBIT 10

The 2020 EU H_2 Strategy is fostering hydrogen development and co-operation to achieve ambitious objectives by 2050

EU Hydrogen strategic roadmap to 2050

Key objectives

- Reduce greenhouse gas emissions ahead of 2030
- Contribute to the recovery of EU economy by spurring economic growth, funding and job creation
- Achieve climate neutral and zero pollution EU economy by 2050
- Foster research and innovation to maintain EU technological leadership

Key focus areas	Main actions
Developing an investment agenda	• Stimulate the roll out of production and use of H_2 and build a pipeline of projects • Support strategic investment in clean H_2 in the context of the commission's recovery plan
Boosting demand for H_2 and scaling up production	• Propose measures to facilitate the use of H_2 and its derivatives in the transport sector • Explore additional support measures including demand side policies in end-use sectors • Introduce low carbon threshold and criteria for the promotion of H_2 • Develop a carbon contract for difference programme to support low carbon production
Designing an enabling and supportive framework: support schemes, market rules and infrastructure	• Plan H_2 infrastructure networks in EU and the network of fueling stations • Explore additional support measures including demand side policies in end-use sectors • Design enabling market rules to support H_2 deployment and access to an integrated and liquid H_2 gas market
Promoting research and innovation in hydrogen technologies	• Launch 100MW electrolyzer, green airports and ports call for proposals under Horizon 2020 • Establish the Clean H_2 partnership focusing on renewable H_2 production, transport, storage and distribution • Steer development of key pilot projects and facilitate demonstration of H_2 technologies
Strengthening the international dimension and cooperation	• Strengthen EU leadership for technical standards, and regulations definitions on H_2 • Promote cooperation with Southern and Eastern partners and energy communities countries • Set out co-operation process on renewable H_2 with the African Union • Develop a benchmark for Euro denominated transaction by 2021

Source: A hydrogen strategy for a climate-neutral Europe, Strategy& analysis

EXHIBIT 11

European countries' focus on hydrogen is increasing with most of them publishing national H_2 strategies (selection of European countries)

		Germany	UK	Italy	Turkey	France	NL	Spain	Poland	Belgium	Austria	Portugal
Natural gas consumption in TWh, 2018		950	880	769	530	475	399	350	208	193	96	**65**
National focus on H_2		◕	◑	◑	◔	◕	◑	◕	◑	◑	◑	◕
Country pledge in €		€9 Bn by 2030	N/A	N/A	N/A	>€7 Bn by 2030	Qualitative plan by 2050	~€9 Bn[1] by 2030	N/A	N/A	N/A	€7 Bn by 2030
National strategy's year of publication		2020	Upcoming	N/A	N/A	2020	2020	2020	Upcoming	N/A	Upcoming	2020
Key focus areas for decarbonization	Energy				✓				✓			
	Industry	✓			✓	✓	✓	✓	✓		✓	✓
	Buildings		✓									
	Mobility	✓			✓	✓	✓	✓	✓		✓	✓
Main objectives		5 GW Electrolyser capacity by 2030 with plan to increase it to 10 GW by 2035	Launch of a national strategy before COP26 (Nov. 2021). Focus on blue and green H_2	Focus on production, storage, power to gas and regulation. Many H_2 related projects	Focus on producing blue hydrogen as they want to leverage their local coal resources	6,5 GW Electrolyser capacity by 2030	3-4 GW Electrolyser capacity by 2030	4 GW Electrolyser capacity by 2030	2-4 GW Electrolyser capacity by 2030.	Local governments are spearheading hydrogen development while waiting for a comprehensive national strategy	The National hydrogen strategy is expected to be released shortly	At least 1 GW Electrolyser capacity by 2030. 70% of existing pipelines in Portugal are ready to distribute H_2

◕ Strong
◑ Medium
◔ Weak
Developed H_2 national strategy
H_2 national strategy under development

1. Mix of public and private funding with most of the investment borne by the private sector
Sources: Government and local associations' websites; Strategy& analysis

National hydrogen strategies in focus

As countries accelerate the creation of a hydrogen economy, it will be essential for governments to develop detailed national hydrogen strategies. In Europe, France and Germany have already articulated their respective approaches (*see Exhibit 12 and Exhibit 13, next page*). Other governments in the region will need to follow this example and in so doing the regulatory framework to promote hydrogen will be reinforced.

As a word of caution, it is important that these national strategies are aligned and do not promote any anti-competitive practices by adversely favoring one demand sector over another. As illustrated *in Exhibit 10*, the EU is seeking to set some broad objectives and focus areas to coordinate and align efforts across member states.

EXHIBIT 12

The French H_2 strategy focuses on decarbonizing the industry and heavy mobility as well as promoting technical leadership

National green hydrogen strategy in France

Key objectives

- Decarbonise the industry with French electro-lysers clusters
- Focus decarbonising heavy mobility
- Creating jobs and enhancing the technological capabilities

Strategy& perspective on French H_2 strategy
The national plan is very ambitious and will require support on four levels: driving demand to initiate the market, hydrogen production, infrastructure, and technological development

Key levers

Hydrogen decarbonisation	Develop a French electrolysis sector	• The objective is to develop production of carbon-free hydrogen by electrolysis • €1.5bn will be devoted to reach 6.5 GW of electrolysers installed in 2030
	Decarbonize the industry by replacing grey hydrogen by low carbon hydrogen	Especially in the following sectors: • Refining • Chemistry, especially in ammonia and methanol production • Other sectors like electronics or food, which use hydrogen in smaller quan-tities electrolysers installed in 2030
Heavy mobility decarbonisation	Develop a hydrogen heavy mobility offer	Nearly €1bn will be used by 2023 to develop a heavy hydrogen mobility offer, via several calls for projects: • €350 million for demonstrators • €275 million for regional experiments
	Develop large-scale territorial projects by encouraging the pooling of uses	Fostering strong partnerships between communities and industry in order to better synchronize the emergence of the offer and the development of uses
Research support	Support research and development	A priority research program “Hydrogen applications” operated by the ANR will be endowed with €65 million
	Develop skills	Develop training on hydrogen for technicians who will work on vehicles, quality – safety – environment managers, firefighters, engineers and researchers

Expected impact

7 GW	Of electrolysers installed by 2030
21 Mt	Of CO_2 emission reduction by 2030
1,35	Million tons of H_2 locally produced by 2030
0,7	Million tons of green H_2 locally produced by 2030
20%	Of final energy demand by 2050
120K – 250K	Of created direct and indirect jobs by 2050
+	Improved air quality

Sources: www.ecologie.gouv.fr, Strategy& analysis

EXHIBIT 13

The German H_2 strategy puts the stress on infrastructure development, cost competitiveness and imports from partner countries

National hydrogen strategy in Germany

Key objectives

- **Make H_2 cost-competitive**
- **Balance building domestic H_2 production with preparing import paths**
- **Align infrastructure build-up with demand development**

Strategy& perspective on German H_2 strategy
- Holistic cross-value-chain approach applicable to multiple sectors of usage (mobility, steel, etc.)
- Large volume of funding
- Sophisticated governance structure in place (e.g. annual progress reports)

Key levers

Clear but pragmatic type preference	• Promote **primarily green H_2** but also **tolerate less cleaner forms of H_2** in a transition phase
Broad application sectors defined	• Key application fields are **the industry-sector, in particular chemicals, petrochemicals and steel, mobility sector and heat supply**
Re-use existing infrastructure	• Retrofit and re-use natural gas pipelines for H_2 transport • Extend and build dedicated hydrogen pipelines, where necessary
Prepare pathway for imports	• Foster domestic production capacities, but also **create conditions for import via partnerships** with countries with higher exposure to renewable energies
Significant funding volume	• Provide at least € 13.2bn between 2016 and 2026, of which **€ 9bn within its 2020-strategy** • **Direct COVID-19 stimulus package** towards H_2 projects
Openness to concrete and impactful measures	• Consider **implementation of explicit quotas to foster the application** of H_2, e.g. quota for e-fuels in aviation or quota for clean H_2-based steel

Expected impact

90-110 TWh	Expected H_2 demand in 2030
~14 TWh	Expected domestic H_2 production in 2030
2%	Potential regulatory quota for e-fuels in aviation
5 GW	Target volume of electrolysis capacity in 2030
65 TWh	Targeted minimum for hydrogen consumption in the industry by 2030

Until 2030, the strongest demand growth is expected in industry-sector, followed by mobility and heat supply

Sources: German government; World Energy Council; Strategy& analysis

Next steps

As one of our interviewees for this report noted, “it is safe to say that the hydrogen decade has finally begun.” For the market to truly take off in the next ten years, several key actions should be taken.

1. Stimulating the demand through innovation, using low carbon hydrogen as a fuel and a feedstock both within energy generation and industrial process transformation, provided a clear business case is established. Refining and the steel industry will be key target segments and fostering cross-industry collaboration will be important to advance decarbonization.

2. Bridging the cost gap in supply between grey hydrogen (hydrogen from natural gas) and low carbon hydrogen. In terms of OPEX by increasing low carbon electricity supply and reducing its cost. And in terms of CAPEX, by reducing the cost of electrolyzers and other equipment needed in a hydrogen plant. Equally ‘blue’ hydrogen will have an interim role in supplying sufficient quantities of hydrogen until cleaner sources are commercially viable and available.

3. Developing the hydrogen supply chain especially in transport and storage. A developed supply chain is an essential prerequisite to bring together supply and demand for an international trading market to evolve.

4. Promoting a global hydrogen trading market, taking advantage of cheap green electricity in some exporter countries. This will also provide the quantity needed in importer countries to close the cost gap, provided that transportation costs remain competitive.

5. Using regulation, certification and public incentive schemes to help this market to take off. In particular at the EU level, alignment between member states’ strategies will be paramount in order for the nascent low carbon hydrogen market to thrive and to avoid unfair competition both within the EU and at its borders.

It is likely with the right support now, the fledgling low carbon hydrogen market will ramp up and take off by 2030, becoming cost-competitive in this decade. Governments, cities and corporates will all have a part to play, through partnerships, in making a hydrogen economy a reality in Europe.

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