Thematic Research Infrastructure | Green & Sustainable

15.12.2020

Low-carbon hydrogen: sensing the path towards large-scale deployment

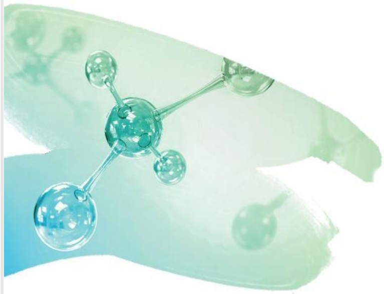
WRITTEN BY

Ivan Pavlovic
ivan.pavlovic@natixis.com

research.natixis.com |

RESEARCH

Based around the world, Natixis CIB Research provides original, fundamental insights and analysis to inform clients' investment and hedging decisions across all asset classes and produce marketing research with an integrated view of markets to better understand economic trends.



GREEN SUSTAINABLE HUB

"The Green & Sustainable Hub is the cross-asset and operational team working alongside Corporate Investment Bank (CIB) business lines. It co-originates and structures green & sustainable financing solutions (through bonds, credit or securitizations), engineers and develops investment products & solutions and provides clients advisory services".

Executive summary (1/5)

Long presented as the ”energy carrier of the future” due to its abundance and absence of CO_2 emissions upon combustion, **hydrogen has apparently entered another era.** While support plans have been multiplying across OECD countries to promote hydrogen-centric mobility, the molecule and its uses has been identified in Europe as a pillar for reviving the economy after the Covid-19 pandemic and achieving neutrality carbon by 2050, an essential condition for the achievement of the Paris Climate Agreement signed in December 2015.

Various energy scenarios developed to model the diffusion of hydrogen in the economy suggest massive growth in the share of the molecule in the satisfaction of final energy demand, from nearly 0 today. **According to the Hydrogen Council's January 2020 report, hydrogen could address 8% of primary global energy demand in 2030 and 15% by 2050**.
With such massive growth, diffusion of hydrogen uses would be instrumental in the world economy progressing towards climate neutrality in the next three decades.

To achieve this, however, it is for a series of changes that the current hydrogen industry and existing economic structures must prepare. In fact, more than 95% of hydrogen is produced today by methane reforming, a technique using natural gas and, to a lesser extent, coal as raw material**. In this form called "grey", hydrogen cannot be considered as a real decarbonization agent insofar as its production is very carbon intensive (world median of 9 kgCO_2 emitted per kg of hydrogen produced). It is only in its "blue"** (reforming methane with CO_2 capture) **and "green"** (electrolysis of water supplied by low-carbon sources of electricity) **forms that the molecule can claim a meaningful role in the decarbonization of the global economy.**

Executive summary (2/5)

In these forms, by replacing fossil fuels which are very largely dominant in existing energy and industrial systems (alone or in addition to other decarbonization agents, in particular low-carbon electricity), **hydrogen can actively contribute to the decarbonization of a series of hard-to-abate sectors:**

1. **Industry using the molecule as energy carrier and / or as feedstock** (chemicals, steel, glass and cement production, refining);
2. **Different segments of land, sea and air mobility** and
3. **Heating and electricity supply for buildings and industry**.

Better still, **produced by the electrolysis of water, hydrogen offers new perspectives to the management of electricity and gas value chains**, mainly because it offers an implicit solution of large-scale storage of low-carbon electricity, whether of renewable or nuclear origin (“**Power-to-Gas paradigm”**). However, **to play this role of "systemic" decarbonization agent, low-carbon hydrogen will have to overcome a number of obstacles** related to:

1. **The high cost of producing the molecule in its blue and green forms** (production costs 2 to 6x higher than for gray hydrogen);
2. **The technical and economic problems associated with the transport and distribution** (hydrogen refueling stations) of the molecule, which almost triple the cost for the end consumer and
3. **The still embryonic nature of hydrogen applications in a number of sectors**, in particular in transport where, in certain segments (trucks, ships, aircrafts), FCEVs (fuel cell electric vehicles) have the potential to respond to some current technical limitations of BEVs (battery electric vehicles) that are probably prohibitive. Thus, in mobility, apart from the case of passenger cars which have just entered the commercial deployment phase, other potential applications of hydrogen are at best in the demonstration phase (trains and buses).

Being still in the structuring phase with very limited uses in volume, **the hydrogen value chain mainly faces scale issues**. These scale issues account not only for the high costs incurred in the production of green and blue hydrogen, but also for the limited deployment thus far of hydrogen-centric applications of the molecule vis-à-vis established, fossil-fuel centric applications, but also emerging low-carbon ones (as currently seen in the passenger vehicle segment).

Executive summary (3/5)

The development of the sector therefore requires an understanding of the challenges of the entire value chain (as in the case of green hydrogen, production of equipment for electrolysis - upstream, production of hydrogen - midstream, production of equipment and services for the end uses of the molecule – downstream) and the various abovementioned technical and economic bottlenecks preventing large-scale diffusion of hydrogen end-uses in the economy.

Observation of these challenges highlights the need for coordinated action along the value chain, this through two main levers:

1. **Lowering the molecule cost through massive investments in electrolyser factories**. If triggered, this cost reduction dynamic is likely to generate a virtuous circle involving the increase in hydrogen demand and investment in the manufacture of all equipment along the value chain (electrolysers and downstream equipment, in particular in mobility), a prerequisite for the industrialization of the sector and the acceleration of the fall in costs;
2. **Getting around the logistical and economic problems linked to the transport and distribution of hydrogen** by concentrating, through "local hubs", the production of the molecule and its various downstream uses, starting with mobility and industrial activities where hydrogen is already used as feedstock (ammonia production).

Somewhat theoretical, **these elements should not obscure the diversity of situations across the globe and the specialization that could take place in the production and use of low-carbon hydrogen**. In certain regions (Australia, North Africa, Latin America, Saudi Arabia, etc.) characterized by a high potential for renewable energy production (in particular wind and solar PV), the production of green hydrogen has a good chance of eventually reaching cost-parity with grey hydrogen. In others (North America, Northern Europe), the production of blue hydrogen has significant potential due to the large presence of raw material (natural gas), sites suitable for CO_2 storage and a diversified industrial sector, allowing a wide distribution of the uses of hydrogen. Finally, other zones not benefiting from these advantages but having substantial industrial production bases (Western Europe, Japan, South Korea) are likely to seek specialization in the manufacture of upstream (electrolysers) and downstream equipment (FCEVs).

Executive summary (4/5)

On the way to achieving potential cost parity with grey hydrogen and then with natural gas, blue and green hydrogens present specific trajectories, the former relying on industrialization / large-scale deployment of CCS, the latter on industrialization of electrolysis and further cost abatement in wind / solar PV. Although the conditions for the success of these two technologies remain largely dependent on local conditions, in view of the recent cost deflation affecting electrolysers (-40% on ALK electrolysers since 2014) and even more renewable energies (levels <$25/MWh for solar PV in certain areas), it is reasonable to anticipate greater cost reductions in the production of green hydrogen than in that of blue hydrogen.

From a strictly temporal point of view, even if the recovery plans announced in Europe could somehow affect the sequencing of investments planned by industrial players before the Pandemic, **sector development will likely be done in various stages**:

1. **By 2030**, as indicated above, **the priority is to massively lower the costs of electrolysis alongside gradual diffusion of downstream uses of hydrogen, particularly in land mobility and industry** where the molecule is already used as feedstock for the production of chemicals**, in order to develop demand and stimulate R&D efforts in other, less-advanced applications**.
2. Once this stage is completed, **perhaps between 2030 and 2040, there will be a phase of gradual deployment of networks dedicated to the transport of hydrogen in pure form, so as to support the dissemination of uses, in particular in industry and mobility**, and foster interconnection between the various local hydrogen hubs having emerged by then;
3. Then, **probably not before from 2040, a last phase of development of the sector would see the large-scale deployment of the molecule in its low-carbon form for <u>specialized</u> uses in industry** (production of methanol, for example), **in parallel with the trivialization of its use in land mobility and its possible development in air and sea transport**.

These elements form the basis of a scenario in which rising demand for hydrogen, upscaling of electrolysis and downstream uses would fuel a virtuous circle making it possible to reach in 2050, <u>in some areas</u>, **levels of production costs for green hydrogen lower than those currently for grey hydrogen (>$1/kg vs. a range of $2.3-$4.6/kg currently).**

Executive summary (5/5)

However, even assuming such a drop in production costs for the molecule in its green form, it is likely that the spread of its uses in a number of industrial activities currently based on fossil fuels will depend on the implementation of carbon pricing systems, a system that exists on a large scale only at the level of the European Union, in the form of a CO_2 emissions cap-and-trade system. The profusion of project launches in blue and green hydrogen reveals the dynamism of a certain number of industrial and energy players and their belief in the potential for the entire sector ultimately achieving commercial viability. **The analysis of these projects and, more generally, the apprehension of the investment needs by 2030 to generate the scale effects necessary to lower costs (some $280bn) reveals the importance of public support in this process.**

In addition to direct aid for pilot projects in the sector, governments will have to provide the regulatory visibility required for risk-taking on the part of industrial players, **but also provide relevant price signals** (role of carbon prices, in particular in hard-to-abate sectors) **to encourage investments in low-carbon technologies being diffused.The deployment of assets along the value chain will most likely require the establishment of innovative financing schemes replicating the infrastructure model** involving a large sample of actors (equipment suppliers, users, public authorities, commercial banks and development banks) and covering the widest possible range of equipments (in particular electrolysers and mobility infrastructure/equipment – hydrogen refueling stations and FCEVs)

In this emerging ecosystem, green finance will have a critical, twofold role to play: mobilize the collective savings available to finance the development of the sector and ensure transparency in the use of private capital and build confidence in the investor base.**The development of low-carbon hydrogen production presents a certain number of issues and potential risks,** for the moment theoretical in view of the state of development of the sector: **extent of water resources required for large-scale deployment of electrolysis and potential damage to biodiversity as far as green hydrogen is concerned as well as safety of carbon transport and final storage, as far as blue hydrogen is concerned.**

These risks and issues must be understood by the various stakeholders (private companies, governments, NGOs, local communities) and integrated into the structuring of financing products / solutions for the sector. **Integrating these issues and risks and, in doing so, promoting best practices in the emerging industry constitute a major challenge for green finance in its support of the world economy's decarbonization.**

CONTENTS

[For all terms followed by an asterisk*, there is a definition in a glossary in the appendix section]

01.

BASICS OF HYDROGEN

Chemistry of hydrogen

In broad terms, **hydrogen** is a colorless, odorless, tastless, non-toxic, nonmetallic highly-combustible **diatomic gas with the molecule formula H_2**

While the molecule is the most abundant chemical substance in the universe, **most of the hydrogen on Earth exists in molecular forms such as water (H_2O) and organic compounds such methane (CH_4) which accounts for hydrogen being manufactured,** not extracted (like fossil fuels – oil, coal and natural gas) to serve human uses

Used as an **energy carrier, hydrogen offers several advantages relative to fossil fuels**

- **It does not emit CO_2 upon combustion, but rather produces steam,** which makes it a climate-friendly energy carrier
- **Even through it has** a **lower energy density per unit of volume**, **it displays a high energy density with respect to weight:** 1 kg of hydrogen has the same energy content as 1 gallon of gasoline
- **It enjoys a wide flammability range:** it can be combusted via a wide range of fuel-air mixtures. In particular, hydrogen can run on a “lean” mixture, which means the amount of fuel is less than the amount needed for combustion with a given amount of air

Manufacturing of hydrogen

There are two main processes for the production of hydrogen:

- **Steam methane reforming (SMR)** using natural gas (80%) or coal (20%) as a feedstock, which accounts for over 95% of present-day hydrogen production
- **Water electrolysis** using water (H_2O) as a feedstock

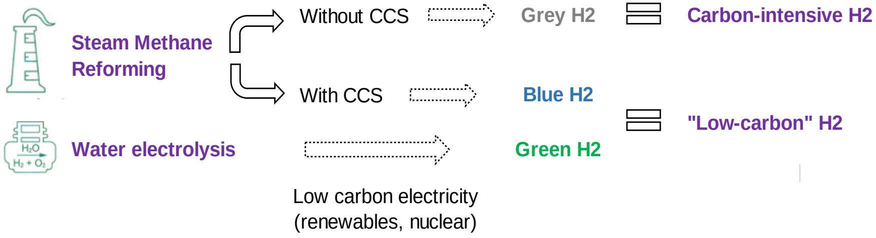
In broad terms, both processes rely on the “cracking” of the molecule used as a feedstock using steam (natural gas or coal for SMR) or electric current (water for electrolysis).

Besides the manufacturing costs involved (see below), **the main difference between the two processes lies in their respective carbon footprint:**

  - **SMR is a carbon intensive technology** (median intensity of 9 kg CO_2 per 1 kg H2) whose CO_2 emissions (circa 830 million tons of CO_2 p.a., i.e. slightly over 2% of annual carbon emissions) can nonetheless be mitigated using carbon capture and storage (CCS) processes.
  - **Water electrolysis is carbon-free provided the electric current used comes from carbon-free sources**, which is the case with renewable/nuclear energy-powered electrolysers

The various processes involved in the manufacturing of the molecule and their respective carbon footprint have led to a distinction between **three forms of hydrogen: “grey”, “blue” and “green”**

MAIN PROCESSES FOR THE MANUFACTURE OF HYDROGEN



Steam Methane Reforming

Without CCS → **Grey H2** = **Carbon-intensive H2**

With CCS → **Blue H2**

Water electrolysis → **Green H2**

Low carbon electricity (renewables, nuclear)

Blue H2, **Green H2** = **"Low-carbon" H2**

Source: Natixis

Present day uses of hydrogen

Today, around 120 million tons of hydrogen are produced each year, of which two-thirds is pure hydrogen and one third in mixture with other gases (IRENA, 2019)

Being predominantly manufactured through SMR (>95%) hydrogen finds its main (>90%) uses in the industry, as a feedstock in the following sectors:

- Chemicals, for the production of ammonia and other products primarily used as fertilizers
- Refining, for the processing of fossil fuels (hydrocracking)
- Steel, when hydrogen is used for iron ore reduction

A key feature of today's hydrogen industry is that **the molecule is used near the site of its production, as part of a captive process**

02.

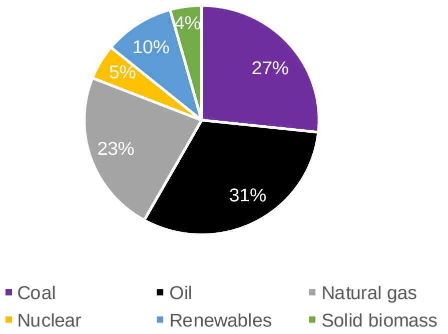
IN ITS LOW-CARBON FORM, HYDROGEN OFFERS NEW AVENUES TO ACCELERATE THE DECARBONIZATION OF THE WORLD ECONOMY

Present-day economic and energy systems remain highly dependent on fossil fuels… and carbon intensive

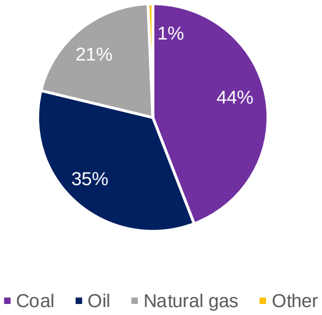
To progress towards climate neutrality by 2050, the world economy must drastically reduce its dependence on fossil fuels (c. 80% share in primary energy demand)

Whilst **decarbonization of electricity & heat production** (41% of total CO_2 emissions) is **achievable through established technologies** (nuclear, wind, solar PV), **that of transport and industry sectors is more challenging, for it implies following more disruptive pathways** to displace the currently predominant use of fossil fuels

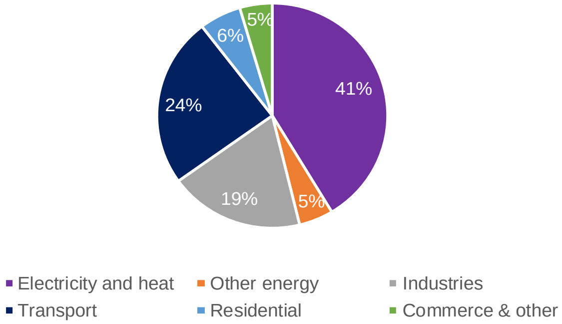
BREAKDOWN OF 2018 WORLD PRIMARY ENERGY DEMAND (14.3 BNTOE) (%)



BREAKDOWN OF 2017 WORLD CO_2 EMISSIONS (32.8 MT) BY FUEL (%)



BREAKDOWN OF 2017 WORLD CO_2 EMISSIONS BY SECTOR (%)



Source: IEA (2019)

Low-carbon hydrogen can help decarbonize hard-to-abate activities / sectors…

With applications as an energy carrier or as a feedstock, **low carbon forms of hydrogen can displace fossil fuels and/or decarbonize large parts of the world economy, in particular hard-to-abate sectors such mobility and industry**

Sector	Application	H2-centric application	Main fossil fuel currently in use	Sector's or application's share (%) in worldwide CO2 emissions
Industry	Production of ammonia	Low carbon H2 as a feedstock	Natural gas and coal (2)	6%
	Production of methanol	Low carbon H2 as a feedstock	Natural gas and coal (2)	
	Steel production	Low carbon H2 as a feedstock (hydrogen-base direct reduced iron - DRI)	Natural gas and coal (2)	
Mobility	Light-duty mobility (passenger cars)	Fuel cell engine	Oil	17%
	Heavy-duty mobility (trucks, buses) + taxi fleets	Fuel cell engine	Oil	
	Trains	Fuel cell engine	Oil (diesel) / coal	
	Ships	Liquified hydrogen or ammonia	Oil (diesel)	
	Large aircrafts	Synthetic kerosene (1) or fuel cell engine	Jet fuel (kerosene)	
	Small aircrafts	Fuel cell engine	Jet fuel (kerosene)	
Power and heating for buildings and industry	Power generation for buildings	Hydrogen-fueled power plants	Coal, natural gas	35% o.w. 19% (buildings) 16% (industry)
	Residential heating	Hydrogen-fueled boilers	Natural gas, oil	
	Industry heating	Hydrogen-fueled furnaces	Coal, natural gas	

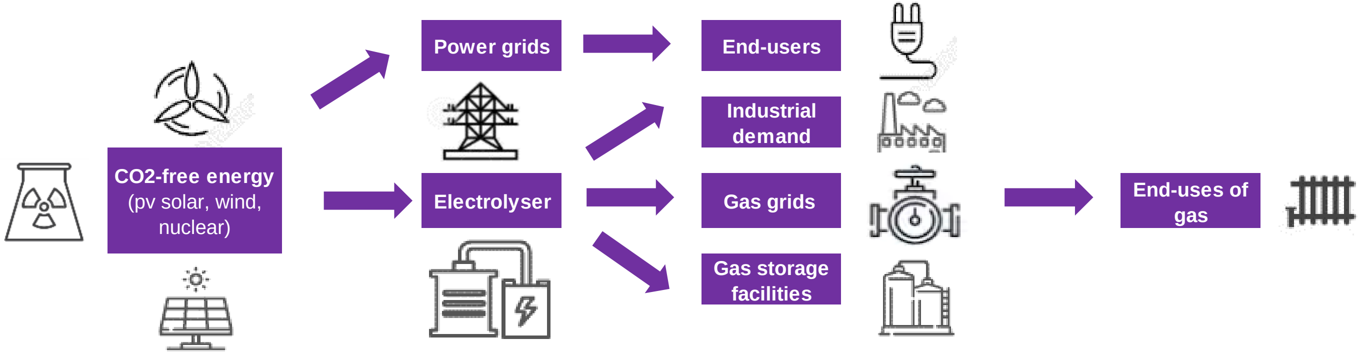
(1) A blend of hydrogen and carbon monoxide manufactured using hydrogen and carbon as feedstock / (2) Used for the production of "grey" H2

Sources: Hydrogen Council, Natixis

… while upscaling of low carbon electolysis can pave the way for new, optimized forms of energy management

Deployed on a large scale, low-carbon electrolysis could offer new perspectives for the management of existing electricity and gas systems, through:

- **Optimized output electricity from nuclear and renewable sources**, electricity being either sold on the wholesale / retail electricity market, or valorized through the electrolysis of water, depending on prevailing conditions on electricity / gas / hydrogen markets
- **Potential storage** (within certain limits - see below) **of excess electricity production ("power-to-gas" paradigm)** by taking advantage of existing gas infrastructures
- **Secured gas supplies and optimized management of gas consumption seasonality**



CO2-free energy (pv solar, wind, nuclear)

Power grids

Electrolyser

End-users

Industrial demand

Gas grids

Gas storage facilities

End-uses of gas

Source: Natixis

Hydrogen competes with other decarbonization solutions (1)

Overview of uses of hydrogen as an energy carrier and competing options

While it is set to remain the unique decarbonization solution of industrial sectors using "grey" hydrogen as a feedstock, **low-carbon hydrogen competes with other decarbonization solutions (low-carbon electricity, CCS, biomethane) in most of its potential applications as an energy carrier**

Sector	Application	H2-centric application	Alternative decarbonization option(s)
Mobility	Light-duty mobility (passenger cars)	Fuel cell engine	BEVs (1)
	Heavy-duty mobility (trucks, buses) + taxi fleets	Fuel cell engine	BEVs
	Trains	Fuel cell engine	Electric catenary
	Ships	Liquified hydrogen or ammonia	None
	Large aircrafts	Synthetic kerosene or fuel cell-engine	Bio-kerosene (2)
	Small aircrafts	Fuel cell engine	Bio-kerosene or BEVs
Power and heating for buildings and industry	Power generation for buildings	Hydrogen-fueled power plants	Low-carbon sources (nuclear, hydro, renewable energies) or CCS
	Residential heating	Hydrogen-fueled boilers	Biomethane
	Industry heating	Hydrogen-fueled furnaces	Low-carbon electricity (heat pumps) or CCS

(1) Battery Electric Vehicles / (2) Bio-jet fuel produced from various plant materials, including oil crops, sugar crops, starchy plants and lignocellulosic biomass

Sources: Hydrogen Council, Airbus, Natixis

Hydrogen competes with other decarbonization solutions (2)

Various uses of hydrogen in mobility but rising interest in fuel cell applications

The transport sector has seen a lot of research and technological developments in recent years aimed at replacing fossil fuels, the applications of hydrogen being in competition with other technologies

Hydrogen applications have so far taken three distinct paths, the molecule being used:

- **To fuel an internal electricity generation unit which itself powers the given vehicle – case of fuel cell electric vehicles – FCEVs* in land mobility**
- **To serve as fuel or as the main raw material for the production of a fuel substituting for fossil fuels and directly decarbonizing the type of mobility concerned** (respective cases of liquefied hydrogen and ammonia as substitutes for diesel and liquefied natural gas in shipping)
- **Serving as a raw material for the manufacture of a fuel** almost similar to that which is widespread today and offering an **indirect climatic benefit** (case of synthetic kerosene in air mobility where hydrogen is blended with sequestrated carbon to produce a nearly-perfect proxy of kerosene)

➡ **Growing interest in trying to extend the use of fuel cell technology to sea and air mobility**

Hydrogen competes with other decarbonization solutions (3)

BEVs better placed than FCEVs in the passenger car segment today…

In land mobility, FCEVs face direct competition from battery electric vehicles* (BEVs) to displace thermal cars (internal combustion engines – ICEs), both technologies having reached commercial deployment phase, albeit to a lesser extent for the former

In the passenger car segment, probably up until 2030, BEVs are better placed than FCEVs to displace ICEs

PROS AND CONS OF BEVS AND FCEVS VS ICES IN LAND MOBILITY (PASSENGER CAR SEGMENT)

	Pros	Cons
BEVs	High CO2 emissions reduction potential vs. ICEs if electricity used is CO2-free	High carbon footprint of battery manufacturing
	Low ongoing costs relative to ICEs (continent on local electricity costs)	Higher upfront cost than ICEs (+30%)
	Relatively easy logistics, electricity being nearly everywhere in developed economies	Relative lack of charging infrastructure in developed economies and high charging time (15'-20' at best)
	High operating performance (short acceleration time)	Limited range / Performance (range) affected by extreme weather conditions
FCEVs	High CO2 emissions reduction (vs. ICEs) if hydrogen used is low-carbon	High carbon footprint of fuel cell manufacturing
		Higher upfront cost than ICEs (+100%) and BEVs (+50%)
	Low charging time relative to BEVs (4'-5')	Complex and costly logistics in the absence of dedicated hydrogen networks adding to the molecule production costs / Lack of refueling stations
	Range: lower than ICEs but higher than BEVs	

Source: Natixis

Hydrogen competes with other decarbonization solutions (4)

… but FCEVs enjoy promising development potential in some specific segments

In land mobility, the comparative analysis of BEVs and FCEVs suggests a potential division of roles between the two technologies to displace ICEs in at least two segments:

- **Some segments of light mobility**, in particular compact urban cars, **are likely to be dominated by BEVs**, such trend being fueled by the accelerated development of home charging appliances
- Relative to BEVs, **FCEVs enjoy high potential development in heavy-duty land mobility** (buses, trucks) **where range is key and where costs incurred in hydrogen distribution can be shared**

For long haul aircrafts and long-distance shipping, electric batteries' specific features in terms of weight and volume constitute significant obstacles to the development of this technology

In contrast, the high energy density of hydrogen relative to its weight (see above) makes the use of fuel cells more plausible to propel planes and boats over long distances. At this stage, this use remains at R&D stage, no commercial application of the technology being planned before 15 years (case of Airbus and the recently-launched development programme for fuel cell aircraft)

However, all of these developments will be contingent on manufacture of low-carbon hydrogen enjoying significant cost reductions (see below) .

03.

THE INDUSTRY NONETHELESS CURRENTLY FACES A SERIES OF KEY LIMITATIONS…

Producing low-carbon hydrogen remains costly (1)

Comparing various types of hydrogen with natural gas and biomethane

Still produced in very limited quantities (> 6 million tons p.a.), **green and blue hydrogen remain much more expensive to manufacture than hydrogen**, with respective cost ranges of \$2.3-\$4.6/kg and \$1.3-\$3.3/kg vs. \$0.7-\$2.3/kg

Expressed in €/MWh, while grey hydrogen can in some cases approach cost-parity with natural gas, **green and blue hydrogen remain far from cost parity** vis-à-vis the latter

In most instances, **green hydrogen remains more costly to manufacture than biomethane**, another low-carbon gas with indirect climate benefit and a direct competitor when it comes to decarbonizing the residential uses of natural gas (see above)

COST COMPARAISON OF THE VARIOUS SOURCES OF HYDROGEN VS. TTF (€/MWH)

(€/MWh)	Biomethane (upgraded gas)	Grey hydrogen	Blue hydrogen	Green hydrogen	TTF (1)
BNEF	N/C	19-61	35-90	67-123	15 (2)
Gas4climate	70-90	28	37-41	70-100	
IEA	c.60	N/C	37-61	76-198	

(1) Natural gas price quotation in the Netherlands / (2) Public price quotation at 27/11/20

Sources: Gas4climate, IEA, BNEF, Natixis

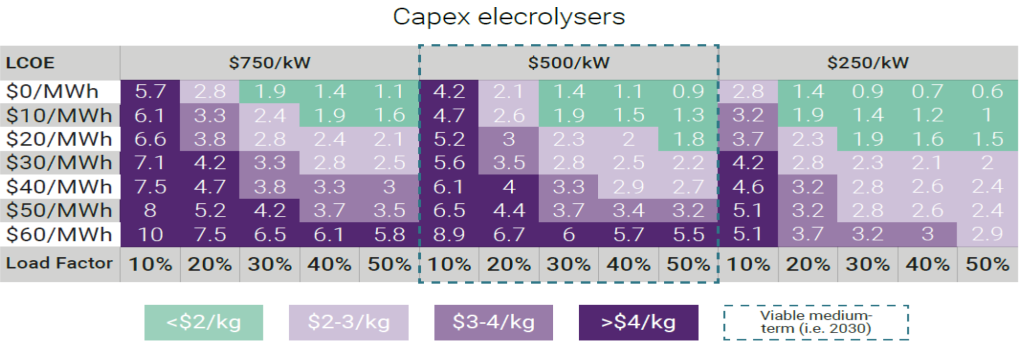
Producing low-carbon hydrogen remains costly (2)

Production of green and blue hydrogen currently suffers from a lack of scale (a)

Production of green hydrogen faces a twofold challenge:

- **High capex** (electrolysers – see appendix #1 for a detailed presentation of various electrolysers)
  - ALK electrolysers remain costly, with $750/KW…
  - … due to their small size (a majority < 100 MW) & inefficient manufacturing processes (no assembly lines in place)

- **High opex** in relation to the amount and price of low-carbon electricity needed to power electrolysers
  - **Electrolysis is energy-intensive**, with ALK electrolysers typically displaying efficiency rates of 50-70%...
  - … which makes the economics of the process highly sensitive to power prices. G**reen hydrogen today approaches cost parity with grey hydrogen only when electricity prices are very low** (≤ $20/MWh) (see table below)



Capex elecrolysers

LCOE	$750/kW					$500/kW					$250/kW				
$0/MWh	5.7	2.8	1.9	1.4	1.1	4.2	2.1	1.4	1.1	0.9	2.8	1.4	0.9	0.7	0.6
$10/MWh	6.1	3.3	2.4	1.9	1.6	4.7	2.6	1.9	1.5	1.3	3.2	1.9	1.4	1.2	1
$20/MWh	6.6	3.8	2.8	2.4	2.1	5.2	3	2.3	2	1.8	3.7	2.3	1.9	1.6	1.5
$30/MWh	7.1	4.2	3.3	2.8	2.5	5.6	3.5	2.8	2.5	2.2	4.2	2.8	2.3	2.1	2
$40/MWh	7.5	4.7	3.8	3.3	3	6.1	4	3.3	2.9	2.7	4.6	3.2	2.8	2.6	2.4
$50/MWh	8	5.2	4.2	3.7	3.5	6.5	4.4	3.7	3.4	3.2	5.1	3.2	2.8	2.6	2.4
$60/MWh	10	7.5	6.5	6.1	5.8	8.9	6.7	6	5.7	5.5	5.1	3.7	3.2	3	2.9
Load Factor	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%

<$2/kg
$2-3/kg
$3-4/kg
>$4/kg
Viable medium-term (i.e. 2030)

Source: Hydrogen Council

Producing low-carbon hydrogen remains costly (3)

Production of green and blue hydrogen currently suffers from a lack of scale (b)

Upscaling of blue hydrogen remains hampered by the technical and economic/regulatory challenges raised by the wide deployment of CCS:

- **Processes currently developed "only" reach a 90% efficiency rate (1)**, which entails specific treatment costs for the remaining 10%
- **Deployment of CCS implies**
  - **Tailor-made work** to adapt the process to the specific features of concerned industrial facilities. For this reason, **CCS remains hard to industrialize at this stage of technology development** and its deployment has been limited thus far to a limited number of pilot projects
  - **Availability of large storage sites** (depleted gas fields, suitable rock formations)
- In the absence of carbon allowance systems throughout the world, there is currently **little financial incentive for the most CO_2-intensive sectors (refining, steel and cement making) to undertake massive capex / R&D effort to scale up the process**
- In the hydrogen industry, according to various estimates (Bloomberg NEF, Hydrogen Council), **it currently takes a carbon price of $50-$70/ton for blue hydrogen to reach cost parity with grey hydrogen**

---

(1) From a technical standpoint, it is possible to capture 100% of carbon emissions. However, CCS allows CO_2 capture for around 90% of emissions in economically-acceptable conditions. For the remaining 10%, CO_2 capture induces prohibitive costs (CO_2 >> $100/t)

Distributing hydrogen involves high costs / complex logistics (1)

Cost-wise, **use of existing gas networks offers the most efficient solution** to transport hydrogen (cost as low as $0.1/kg for transport using high pressure pipelines with daily quantities > 100 tons over 100 km) but faces **two main constraints**:

- **Hydrogen can be blended with natural gas into existing infrastructures but up to certain limits** (10% in transmission networks / 20% in distribution networks)
- **In most of its applications** (mobility as an energy carrier, industry as a feedstock) **hydrogen can only be used in a pure form**: pipeline transport therefore requires dedicated infrastructures, either new ones or existing ones upon repurposing

In comparison, transport by truck and ship offers the possibility to transport pure streams of hydrogen but is much more expensive and involves complex logistics

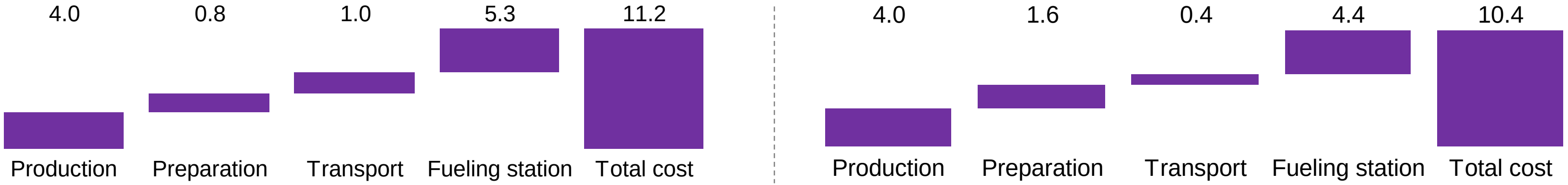
- **Costs of hydrogen trucking range from $1.8/kg** (gaseous trucking involving $0.8/kg of compression cost) **to $2.0/kg** (liquid trucking involving $1.6/kg of liquefaction)
- **Shipping of hydrogen** involves either liquefying the molecule (LH2 shipping) or turning it into ammonia before reconversion to H_2 is carried at destination point. It is estimated that the **cost of LH2 shipping from Saudi Arabia to Japan currently amounts to $15/kg** (source: Hydrogen Council)

Distributing hydrogen involves high costs / complex logistics (2)

Distribution of hydrogen for mobility purposes also face major cost challenges reflecting the "chicken and egg dilemma“ in the light mobility segment:

- Due to low utilization rates, **refueling stations' (HRS) cost remain very high** (average level of around $5/kg, including an investment cost/kg of hydrogen distributed of $6,000)
- As a result, **the cost of hydrogen at distribution points borne by the end user remains very high,** which weighs in the cost equation of the sector compared to its competitors ICEs (internal combustion engines) and BEVs and **in turn slows down the penetration of FCEVs in the light mobility segment**
- **HRS enjoying low utilization rates in turn constrains the deployment of new units, which in turn creates another obstacle to the adoption of FCEVs in the light mobility segment**

COST OF HYDROGEN (USD/KG DISPENSED): GAZEOUS TRUCKING (LHS) / LIQUID TRUCKING (RHS)



Source: Hydrogen Council

Cost issues in relation to downstream equipment (1)

In mobility, which represents the bulk of hydrogen-centric applications open to the general public, **the use if the molecule remains marginal**

Despite numerous announcements in the past 6-12 months, **save for the passenger vehicles (FCVs) segment, applications have not yet reached the commercial development phase**

H2-CENTRIC MOBILITY APPLICATIONS: COMPARATIVE STAGES OF DEVELOPMENT

R&D	Pilot project	Demonstration/niche market	Commercial development	Commercial viability
Long distance aircrafts	**Small ships**	**Buses / Trucks**	**Passenger vehicles**	
N/D	N/D	4.4 k buses (97% in China) 1.8 k trucks (98% in China) 3 trains (+14 in 2021)	18 k worldwide	

Sources: IEA, Natixis

Cost issues in relation to downstream equipment (2)

In the light mobility segment, FCEVs remain marginal relative to BEVs (18k vs. 4,500k)

FCEVs still enjoying very low penetration rates relative to BEVs is attributable to a set of various factors:

- **Higher equipment cost:** +50% (Toyota Mirai vs. Tesla 3)
- **Higher charging cost :** +125% (Toyota Mirai vs. Tesla 3 in Germany: per 100,000 km in Germany)
- **Lack of refueling stations:** 470 stations for FCVs vs. 7,200 k charging points for BEVs worldwide at end-2019

As seen for the production of blue and green hydrogen, the currently prohibitive cost of FCEV equipment is mainly attributable to scale issues:

- **Limited market size provides no incentive to develop automated assembly lines**, resulting in FCEVs being mostly assembled by hand
- **High procurement costs due to lack of investments from suppliers of equipment** (fuel cell membrane electrode assemblies - MEAs*- and ionomers*)

04.

… WHICH HAVE TO BE OVERCOME TO ENSURE A COST-EFFECTIVE DIFFUSION OF HYDROGEN USES IN THE ECONOMY

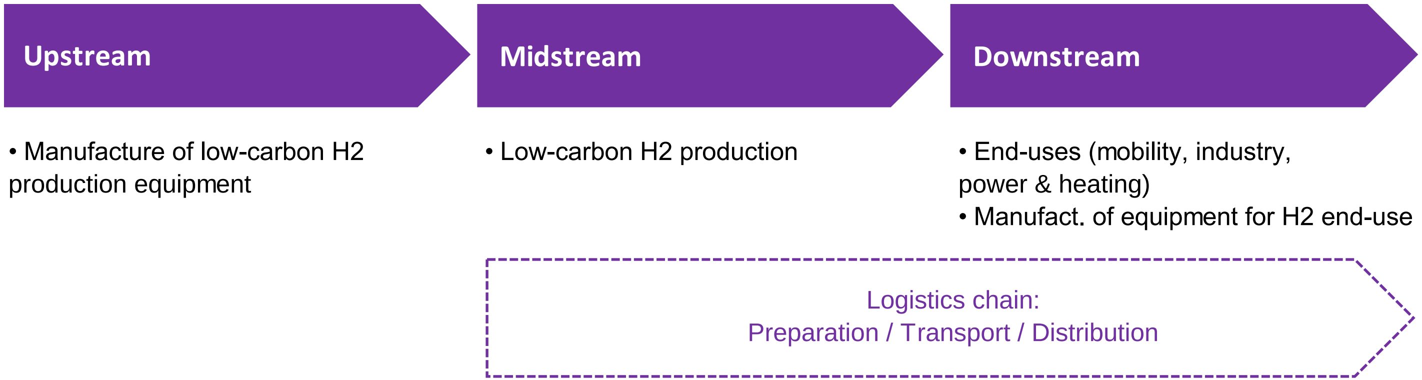
Need for coordinated action along the value chain (1)

The hydrogen value chain is at the cross-roads of industry, mobility and energy sectors

Present day sectoral challenges must be addressed in a “systemic” perspective capturing:

- The interdependence between the "upstream", "midstream" and "downstream" parts of the value chain
- The current barriers to the diffusion of various hydrogen-centric end-uses arising from technical and economic problems in relation to the transport and distribution of the molecule

LOW-CARBON HYDROGEN SECTORAL VALUE CHAIN



Upstream

- Manufacture of low-carbon H2 production equipment

Midstream

- Low-carbon H2 production

Downstream

- End-uses (mobility, industry, power & heating)
- Manufact. of equipment for H2 end-use

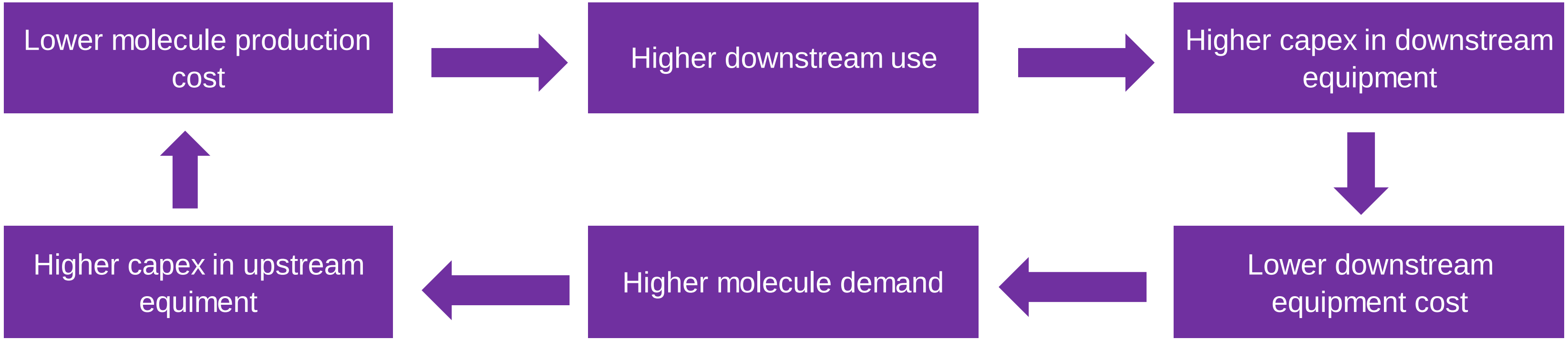
Logistics chain:
Preparation / Transport / Distribution

Source: Natixis

Need for coordinated action along the value chain (2)

Generate simultaneous upstream and downstream scale effects to lower costs

Sector take-off requires generation of simultaneous scale effects in the production of the molecule and the various end-use equipment so as to bring down costs at both ends of the value chain



Lower molecule production cost

Higher downstream use

Higher capex in downstream equipment

Lower downstream equipment cost

Higher molecule demand

Higher capex in upstream equiment

Source: Natixis

Need for coordinated action along the value chain (3)

Sources of cost reduction are everywhere across the industry

In mass of potential cost savings, **generation of scale effects and series effects** constitute the two primary sources of competitiveness improvement for the sector.

SOURCES OF COST REDUCTIONS ALONG THE HYDROGEN VALUE CHAIN

	Upstream	Midstream	Downstream	Transport	Comments
Scale economies	+++	+++	+++	+	**Absorption of high fixed costs (capex and R&D) through bigger equipments**: Bigger electrolysers factories ≥ 1GW ("giga factories") Bigger electrolysers Bigger downstream equipment factories
Series effects	+++	+++	+++	N/A	**Industrialization of equipment manufacturing**: moving from hand manufacturing of equipment & components to automated assembly lines
Cost mutualization	+	+	+	+++	Until market reaches size commensurate with large-scale pipeline deployment, cost mutualization through **bundling of H2 end-uses close to molecule production or large delivery sites** will be key to reducing delivery costs
Technology improvements	++	+++	+++	+	**Higher equipment efficiency:** Midstream equipment: electrolysers' effciency rates Dowstream: FCVs' range, H2-fueled turbines' efficiency, etc.

Source: Natixis

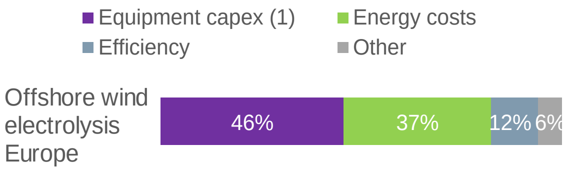
Need for coordinated action along the value chain (4)

Reaching tipping points simultaneously

Investment in capex equipment both upstream (electrolysers) and downstream (FCV assembly lines) alongside development of final demand (mobility & industry) is key to achieving significant cost reductions in the next 10 years

Midstream

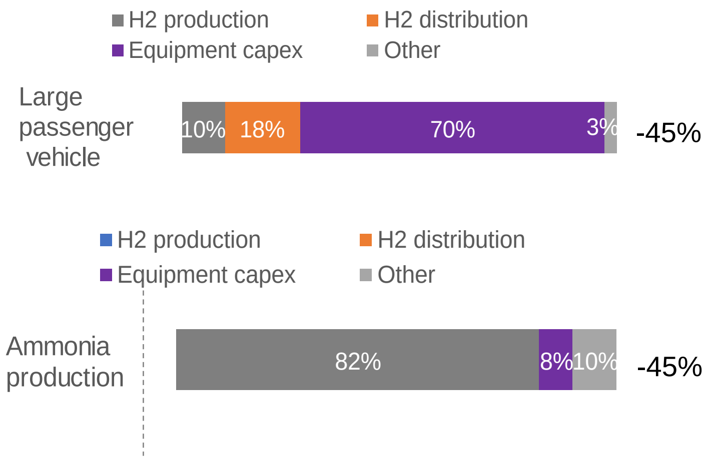
Sources of a potential 60% cost abatement in offshore wind electrolysis in Europe by 2030 (%)



(1) Cost abatement achieved with the deployment of 90 GW electrolysis capacity in Europe

Downstream

Sources of potential cost abatement of H2 applications by 2030 (%)



Industrialization of FC and H2 tank manufacturing with annual prod. going up to 200 k, then to 700 k, with respective cost reduction of -18% and -11%

Scale up of system size and manufacturing of electrolysers for green H2 production

Source: Hydrogen Council

Overcoming the various challenges raised by hydrogen logistics (1)

Duplicating / repurposing existing gas networks not yet the option

Given the complex and costly logistics transport of hydrogen implies, this is no surprise that **most present-day uses of the molecule occur near the site of its production** as part of captive processes in some industrial sectors (see above).

From a pure cost perspective, **duplicating or repurposing existing networks to accommodate pure streams of hydrogen alongside deployment of HRS offers the best option to bring down transport costs** in the sector

Some estimates (Bloomberg NEF) put the **cost of hydrogen pipeline as low as $0.05/kg** for transport using high pressure networks with daily quantities > 1,000 tons for distances below 10 km, such cost going up to a range of 0.1-0.58 for longer distances (range of 100-1,000 km)

However, **optimizing such investments implies reaching certain volume thresholds**, which at this stage entails a bet on the diffusion of hydrogen-centric application across the various sectors of the economy

Overcoming the various challenges raised by hydrogen logistics (2)

In the short run, local hubs are best suited to accompany sector development

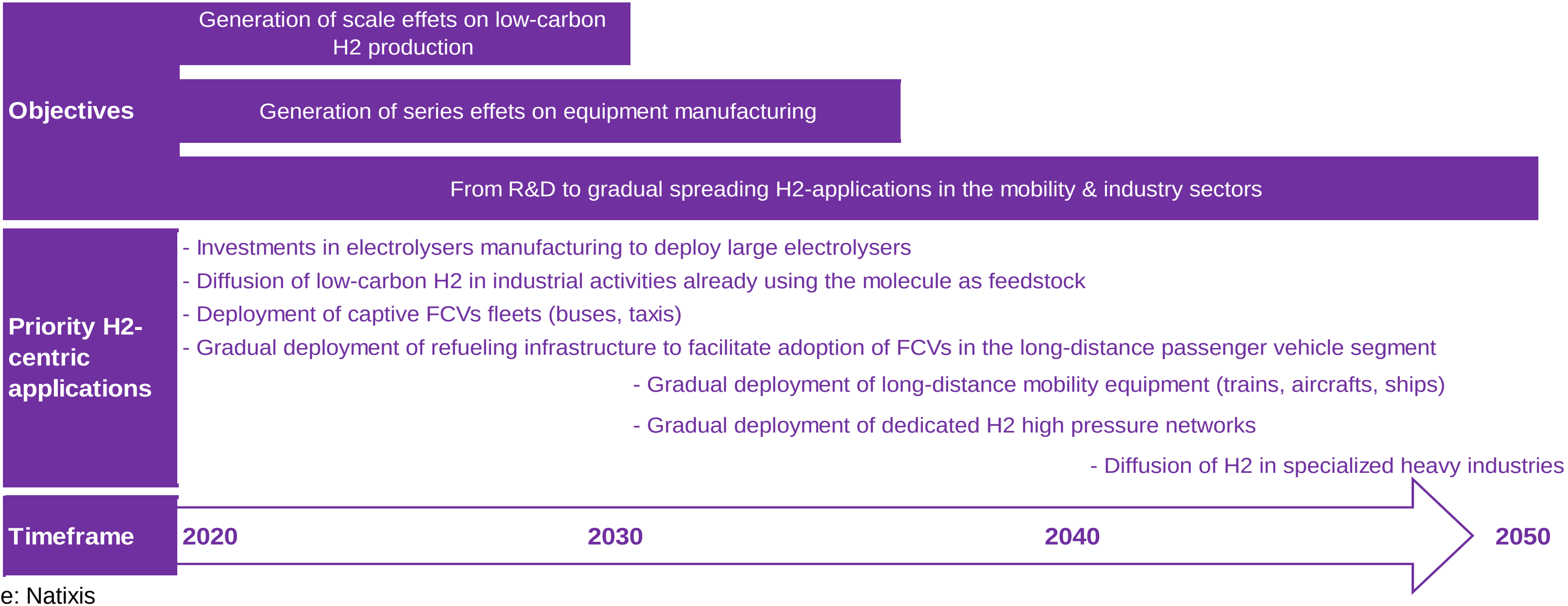
At this stage of sector development, some recently announced landmark **low-carbon hydrogen-centric industrial projects** (Iberdrola-Fertilaria / Zero-carbon Humber / NEOM – see below) suggest the **replication of closed-loop systems to avoid transportation costs**

However, the various **national government support plans (targeted "Territorial hubs" in France) / projects supported by local authorities announced to date (see below) suggest another, more inclusive approach**. Under this scheme, new low-carbon hydrogen production capacities would be dedicated to a specific use (mobility), with the possibility of modulating upwards low-carbon hydrogen production capacity according to the development of downstream uses (other types of mobility, industry, residential heating)

Time and geography will be key (1)

Sector upscaling requires a step-by-step approach

Sector development is likely to go through an iterative approach focused on cost abatement in the midstream segment (low carbon production) which is the prerequisite for the gradual diffusion of end-uses, depending on their current degree of commercial maturity



Objectives

Generation of scale effets on low-carbon H2 production

Generation of series effets on equipment manufacturing

From R&D to gradual spreading H2-applications in the mobility & industry sectors

Priority H2-centric applications

- Investments in electrolysers manufacturing to deploy large electrolysers
- Diffusion of low-carbon H2 in industrial activities already using the molecule as feedstock
- Deployment of captive FCVs fleets (buses, taxis)
- Gradual deployment of refueling infrastructure to facilitate adoption of FCVs in the long-distance passenger vehicle segment
- Gradual deployment of long-distance mobility equipment (trains, aircrafts, ships)
- Gradual deployment of dedicated H2 high pressure networks
- Diffusion of H2 in specialized heavy industries

Timeframe

Source: Natixis

Time and geography will be key (2)

Geography matters / Towards regional specializations?

Given the currently challenging economics of low-carbon hydrogen production, geography is likely to play a key role in the upscaling of the sector. **Green hydrogen production is likely to take off in areas where renewable energies** (solar PV, onshore and offshore and wind, hydro) **already enjoy low LCOEs** with further cost abatement potential (notable cases of solar PV and offshore wind)

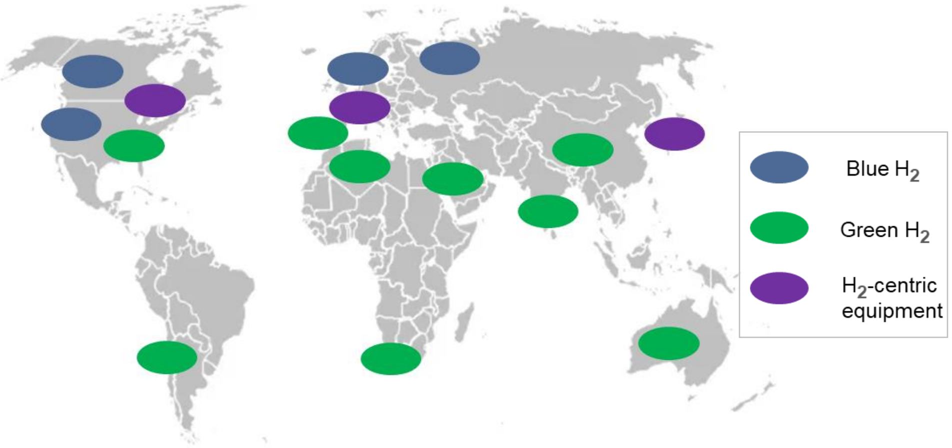
Blue hydrogen also enjoys some development potential in areas combining:

- Availability of large quantities of **cheap feedstock** (**natural gas**)
- **Presence of suitable CO_2 storage sites** (see above) and/or
- **Commercial outlet for carbon** as a feedstock for industrial processes (refining, steel making, etc.)

Some regions lacking key natural resources or large-scale renewable development potential but enjoying advanced industrial infrastructures are likely to **specialize in midstream (electrolysers) / downstream (FCEVs) equipment manufacturing** typical **case of Japan, South Korea and, to a lesser extent, Western Europe**

High green hydrogen production potential in Saudi Arabia, Australia, North Africa, Southern Europe and South America / Blue hydrogen production potential especially high in Northern Europe, USA .

REGIONS WITH HIGH POTENTIAL DEVELOPMENT OF HYDROGEN PRODUCTION & RELATED EQUIPMENT



Sources: Various, Natixis

Hydrogen sector take-off implies strong and continuous support from public authorities (1)

Massive public intervention will be key to generating scale effects, this through subsidies in the upstream segment of the value chain to lower the molecule cost as well as through direct or indirect support in the downstream segment (mobility)

TYPES OF EXISTING OR FRESHLY-ANNOUNCED H2-CENTRIC PUBLIC SUPPORT SCHEMES

Type of public support	Relevant link in the value chain	Illustrations	Nature of public support
Electrolysers deployment targets	Upstream	**EU:** electrolysers capacity of 40 GW by 2030 **France:** electrolysers capacity of 6.5 GW by 2030	Direct subsidies to build upstream equipment ("Giga factories")
FCEVs deployment targets	Downstream (mobility)	**China:** FCEVs ≥ 1 million by 2030	Central and local financial subsidies
HRS deployment targets	Downstream (mobility)	**China:** HRS >1,000 by 2030	Hydrogen refueling station incentive through central government subsidies to local authorities (29 cities part of a pilot programme
PPPs at local level for green H2 mobility	Downstream (mobility)	**France** (métropole de Dijon): development of green H2-centric mobility ecosystem	Take-or-pay contractual arrangement between an H2 producer and a municipality deploying an H2-fueled fleet of buses, garbage trucks, etc.

Sources: Various, Natixis

Hydrogen sector take-off implies strong and continuous support from public authorities (2)

At international level, recent institutional developments suggest **increased focus from governments** as well **increased competition** among countries and the **start of specialization** at the level of countries / regional geographical blocs

Recent announcement in **Europe** suggest **mounting ambition** from the EU but also from prominent Member States (France, Germany, Spain and Italy) **to build competitive advantage** in some key segments of the value chain, through the recovery plans announced

EUROPE: OVERVIEW OF RECOVERY PLANS AND THEIR HYDROGEN COMPONENT

	Overall recovery package	H2 support plan	Main H2 development objective
EU-28	€750bn	N/D	Electrolysis capacity of 40 GW by 2030
France	€100bn	€7.2bn	Electrolysis capacity of 6.5 GW by 2030
Germany	€130bn	€9bn	Electrolysis capacity of 5 GW by 2030
Italy	€209bn indirectly (1)	€10bn	Electrolysis capacity of 5 GW by 2030
Spain	€140bn indirectly (1)	€9bn	Electrolysis capacity of 4 GW by 2030

(1) Italy and Spain have been allotted €209bn and €140bn, respectively of the EU's €750bn Recovery Fund

The magnitude of **investments and public subsidies needed to scale up the sector by 2030 is very significant**

According to estimates made by the Hydrogen Council and Bloomberg NEF, **investments needed by 2030 in the entire value chain to generate the scale effects necessary to lower costs would amount to some $280bn, which includes**

- **$70bn of subsidies needed to bridge the cost gap between the hydrogen technologies and the cheapest low-carbon alternative** (Hydrogen Council)
- **$150bn of subsidies needed to bridge the cost gap between hydrogen technologies and the cheapest fossil-fuel based alternative option**, of which over $100bn to deploy 3.7 million of FCEVs (Bloomberg NEF)

Sources: Various, Natixis

Carbon price floors will most likely be needed in 2050 to support a number of hydrogen end-uses

All in all, **thanks to large scale deployment of electrolysis, continuous fall in renewable energies LCOEs and rising demand** (from currently 120 MMt to nearly 700 MMt in BNEF's strong policy scenario)…

… various estimates point to the potential landing of green hydrogen production below $1/kg by 2050 in a series of key countries (USA, Canada, China, Germany, India, Saudi Arabia), which is the key factor underpinning the deployment of hydrogen-centric applications across the economy

ESTIMATED COST TRAJECTORY OF BLUE AND GREEN HYDROGEN (2019-2050)

$/kg	2019	2030	2050	Δ 2019-2050
Grey H2	0.71-2.29	N/D	N/D	N/A
Blue H2 (gas feedstock)	1.34-3.34	1.34-2.91	1.25-2.82	-13% (2)
Green H2	**2.53-4.57**	**1.14-2.71**	**0.73-1.64**	**-67% (2)**
Natural gas (1)	0.17-1.39	N/A	N/A	N/A

(1) $/kg H2 equivalent ($/MMBtu) / (2) Trend in cost based on the average of range values

Source: BNEF

Source: BNEF

Carbon price floors will most likely be needed in 2050 to support a number of hydrogen end-uses

Even in this price scenario, it is likely that a number of **hydrogen-centric applications will not achieve cost parity with the cheapest fossil fuel-based technologies by 2050**

Unlike what is expected in the transport sector most hydrogen-centric applications in the industry (molecule used as an energy carrier to fuel industrial furnaces or as a feedstock) **are likely to remain dependent on high carbon floor prices** to displace cheapest fossil fuel alternatives

LEVEL OF CO2 PRICE NEEDED TO ENSURE COST PARITY OF H2 (1) WITH CHEAPEST FOSSIL FUEL ALTERNATIVES

Sector	Application	Carbon price required for H2 to complete with cheapest fossil fuel in 2050 ($/tCO2)
Industry	Refining	16
	Cement	50
	Steel	60
	Ammonia	78
	Methanol	139
Transport	Cars	0
	Buses	0
	Light trucks - Heavy trucks	0
	Ships	145
Building	Gas network blending	160

(1) Assuming H2 prices of $1/kg for large customers / H2 pump prices of $4/kg

Source: BNEF

05.

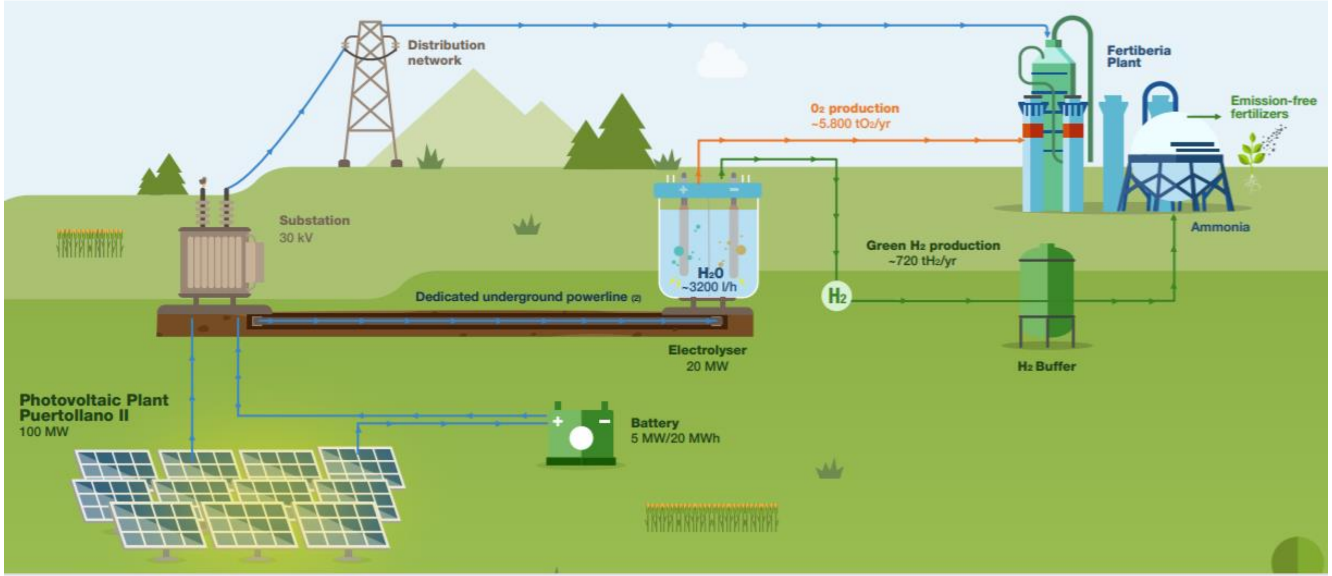
RECENT HYDROGEN-CENTRIC INITIATIVES SUGGEST VARIOUS POTENTIAL PATHWAYS TO DEVELOP AND FINANCE THE SECTOR

An illustration of emerging green H2-centric industrial clusters

The Iberdrola-Fertiberia partnership (Puertollano, Spain) (1)

In July 2020, Spanish utility Iberdrola and Spanish chemical group Fertiberia announced an agreement for the first-of-a-kind, **€150m project in Europe for the production of green hydrogen for industrial use** (more specifically chemical manufacturing)

OVERVIEW OF THE IBERDROLA-FERTIBERIA GREEN H2 PARTNERSHIP



Source: Iberdrola

An illustration of emerging green H2-centric industrial clusters

The Iberdrola-Fertiberia partnership (Puertollano, Spain) (2)

Looked at in detail, the project introduces innovations on both sides:

- **Iberdrola will be responsible for the production of green hydrogen from 100% renewable sources**. The solution will consist of a 100 MW photovoltaic solar plant, a lithium-ion battery system with a storage capacity of 20 MWh and one of the largest electrolytic hydrogen production systems in the world (20 MW)
- **The green hydrogen produced will be used at Fertiberia's state-of-the-art ammonia plant in Puertollano**, with a production capacity of more than 200,000 t/year. **Fertiberia will update and modify the plant** to be able to use the green hydrogen produced to manufacture green fertilizers

All in all, this green hydrogen project due to be completed in 2021 positions itself as the first developed for exclusively industrial use in a closed-circuit logic. For its different components, **the project draws upon the geographical proximity of cost competitive energy (1) and industrial assets to create a complete value-added chain in green hydrogen**, from generation of renewable energy to industrial use of green hydrogen produced by electrolysis

(1) Iberdrola did not provide cost details for the solar PV plant under construction. However, based on local climate conditions, we would expect its LCOE to stand below €35/MWh (see above for electrolysis' sensitivity to power prices)

An illustration of potential blue H2-centric industrial clusters:

the Humber project (North-East England, UK) (1)

UK power producer Drax group, UK energy networks operator National Grid and Norvegian Oil & Gas group Equinor signed a Memorandum of Understanding in May 2019 for the launch of a project in the Humber region, North-East England, UK. This project is likely to be a **landmark in the development of blue hydrogen-centric industrial clusters**

This project is still in the exploratory phase, **with final investment decision expected in 2021** and potential full completion in 2040

Consortium members recently (7 October) submitted a £75m bid for phase two funding from the UK Government's Industrial Strategy Challenge Fund (£800m), which builds on a successful application for phase one funding that was announced back in April.

Chances of successful bidding are high in view of the Humber region being today UK's largest industrial cluster by CO_2 emissions (12.4 million tons p.a., representing over 3% of country's overall carbon emissions in 2019)

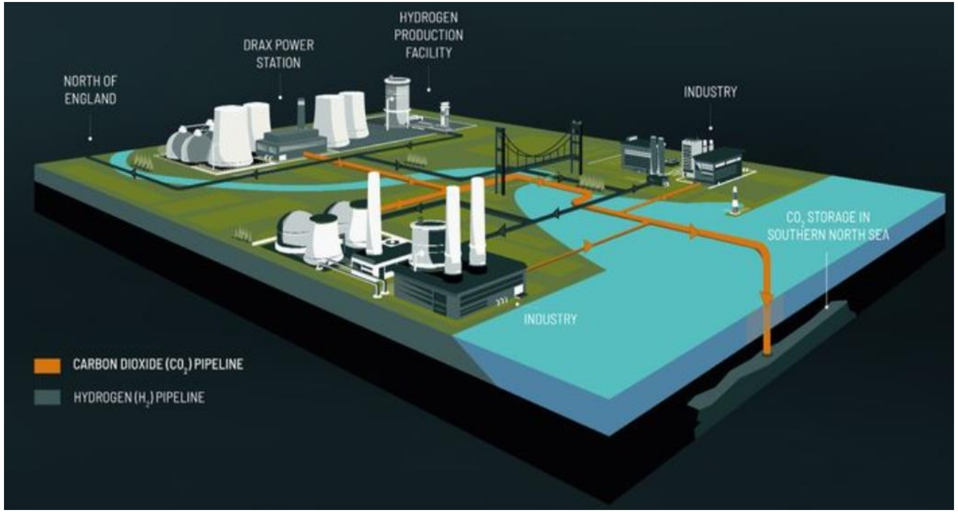
An illustration of potential blue H2-centric industrial clusters:

the Humber project (North-East England, UK) (2)

Consortium members' ambition is to bring out a **low-carbon hydrogen-centric industrial ecosystem**, with a value chain involving:

- **Blue hydrogen production** by Equinor within the Saltend chemical park
- **Gradual conversion of surrounding chemical plants** to use 100% hydrogen
- **Transport of hydrogen** by National Grid for use in **nearby industrial sites** (refineries, steelworks)
- **Transport of captured carbon** by National Grid to BP-operated Endurance storage site (naturally occurring aquifer)
- Development by Drax of the **BECCs* process at its neighboring power plant** with **use of the carbon infrastructure** (transport and storage)

SIMPLIFIED OVERVIEW OF THE HUMBER PROJECT



Source: Zerocarbonhumber

An illustration of potential blue H2-centric industrial clusters:
the Humber project (North-East England, UK) (3)

With an estimated cost not yet disclosed, **this project is particularly ambitious insofar as it aims to decarbonize a set of hard-to-abate activities** (refining, chemicals, steel production).

In its envisaged configuration, it can nonetheless rely on the abovementioned **key success factors of blue hydrogen production upscaling**:

- **Availability of feedstock (natural gas)** with the nearby Easington gas terminal
- **Availability of suitable CO_2 storage site** (naturally occurring aquifer)
- **Potential use of existing natural gas networks to transport CO_2**
- **Very high concentration of diversified industrial activities** in a limited area (refineries, chemical plants, steelworks, power plants) offering a **high potential for pooling the costs** incurred in the deployment of a dedicated hydrogen network
- **Supportive policy framework in the UK for investments in low-carbon technologies**
  - Potential direct financial support from the UK government
  - Stringent carbon emissions emissions in the form of carbon taxation for power generation and energy-intensive industries (current carbon tax set at £18/ton of CO_2) which gives industries concerned direct incentive to invest in low-carbon technologies

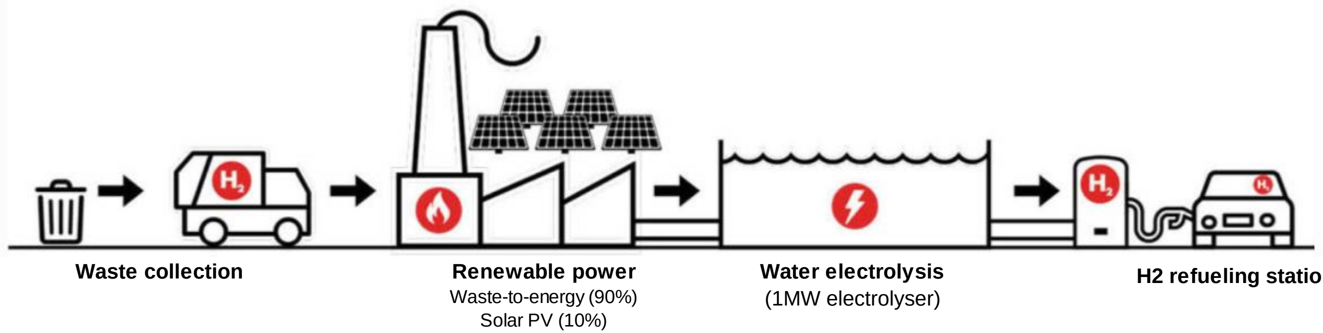
The Dijon Métropole (France) Smart EnergHy project (1)

A local green H2-centric mobility ecosystem

The recently (July 2020) launched Smart EnergHy project in Dijon Métropole (France) offers an interesting example of **value chain built at local level** around the application of hydrogen in different means of transport, with **an autonomous ecosystem involving**:

- **Renewable power generation** (waste-to-energy / solar PV)
- **Water electrolysis** (1MW electrolyser to be supplied by McPhy)
- **A captive fleet of FCEVs** (set of 22 buses, 9 waste collection trucks, 15 light-duty vehicles upon project completion, to be later expanded)
- **One Hydrogen refueling station** (HRS)

SIMPLIFIED OVERVIEW OF THE SMART ENERGY PROJECT



Source: MacPhy

The Dijon Métropole (France) Smart EnergHy project (2)

A local green H2-centric mobility ecosystem

In its structuring & financing, **the €6.5m phase 1 of the project relies a great deal on public support/intervention**, with:

- **For the electrolysis part, the creation of an ad hoc company jointly owned by Dijon Metropole (**Greater Dijon municipality) **and Rougeot Energy** (McPhy's contractor for the deployment of the electrolyser)
- **The setting of a take-or-pay contract with local authorities / public transport company Keolis** (70% owned by the SNCF, France's State-owned railways operator) for the local green hydrogen production
- **Direct public financing from the French government in the form of grants totaling €3.4m** from ADEME (France's environment agency):
  - €1.8m for the hydrogen production and distribution infrastructure
  - €1.6m for the captive fleet of vehicles to be purchased by Dijon Metropole

NEOM: towards large-scale production of green hydrogen in Saudi Arabia (1)

Through the NEOM initiative (“new future”), a smart city project, Saudi Arabia seeks to diversify its economy which is still largely dependent on oil revenues (90% of country’s exports earnings)

In a post-oil perspective, **Saudi Arabia increasingly views production and export of green H2 in the form of ammonia as a way to leverage:**

- **Existing/expanding local infrastructures (desalination)**
- **Alternative natural resources** (wind, solar energy) **used for the production of green power at potentially very competitive costs** (current LCOE of solar PV probably ≤ $25/MWh in the country)

Last July, **NEOM signed a $5bn deal with Air Products**, a US industrial gas and chemical company, and Acwa Power, a 40% State-owned Saudi Arabian power and desalination utility, **to build the world’s largest green hydrogen project** (capacity of 650 tons of green hydrogen p.d.). **Conversion of hydrogen in ammonia is expected to start in 2025** for the molecule be shipped to end markets globally before it is converted back to hydrogen

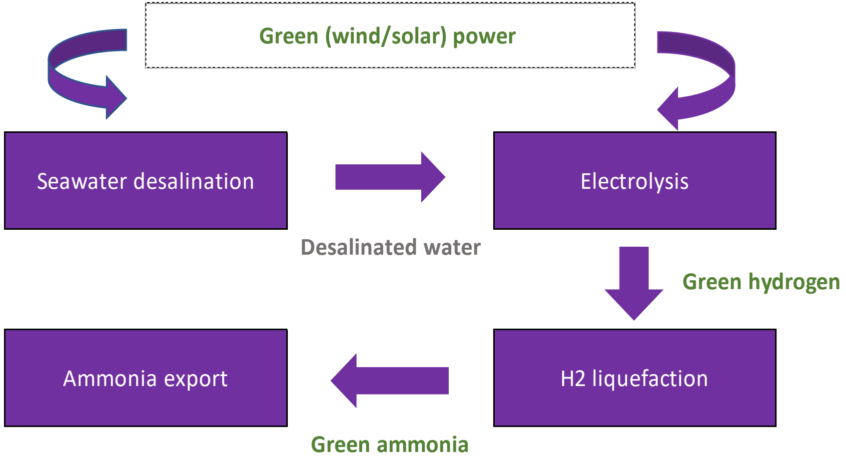
Source: Natixis

NEOM: towards large-scale production of green hydrogen in Saudi Arabia (2)

This **project** is quite **representative of the value chain likely to emerge in Saudi Arabia** for the production and marketing of green hydrogen, with:

- **Supply of water for electrolysis through** continuously expanding **desalination capacities**
- **Electricity supply of the electrolyser by wind and solar PV capacities** (> 4 GW planned under the project)
- **Transformation** of a major part of **green hydrogen into ammonia for export**

OVERVIEW OF SAUDI ARABIA’S EMERGING GREEN H2 VALUE CHAIN



Green (wind/solar) power

Seawater desalination

Desalinated water

Electrolysis

Green hydrogen

H2 liquefaction

Green ammonia

Ammonia export

Source: Natixis

Financial structures for the development of the sector still to be defined

The analysis of the four projects presented in this section allows to draw early lessons on the economics/financing of the nascent hydrogen economy:

The projects' economics are all directly or indirectly highly dependent on public support, through:

- **Direct financing (subsidies):**
  - Key in the development of the Dijon Smart EnergHy project
  - Expected by project sponsors in the case of the Iberdrola-Fertiberia (EU grants) and Humber (UK grant) projects
- **PPP schemes implying off-take agreements of green hydrogen production with public authorities** (Dijon Smart EnergHy project)
- **Involvement of companies with significant capital ties with the host country's government**: case of ACWA's involvement in the NEOM project, which suggests potential preferential pricing for the supply of green energy and desalinated water
- **Existence of a carbon quota system** giving a price per ton of CO_2 emitted and therefore per ton of CO_2 avoided for hard-to-abate sectors investing in low-carbon technologies (Iberdrola-Fertiberia and Humber projects)

Going forward, sector development is likely to be fueled by two, complementary types of projects:

- **Large-scale industrial projects involving large, international groups**
- **Local projects, involving municipalities and local private players in particular for the provision of collective transport services**

In terms of financing, regardless of the share of direct public funding obtained, such development could entail two specific types of structuring / arrangement:

- **Large projects being first funded by project sponsor from their own financial resources** before growing public support for the sector and/or the improvement of cost competitiveness allow feed-in tariff* / contract-for-difference mechanisms* / off-take agreements of low-carbon hydrogen and in turn make possible non-recourse financing schemes which are commonplace in the renewable energy sector
- **Local projects involving PPP schemes similar to those in place in the water and waste industry in Europe**

06.

CONCLUDING REMARKS

Emergence of two complementary models for the development of the sector

In its nascent phase, the low-carbon hydrogen economy is likely to rely on two, complementary forms of project development:

- **“Large projects”** involving international groups **either set to generate scale effects** in the sector (underlying logic of "giga-factories" for the production of electrolysers) **or to benefit from scale effects** (expected impact of projects involving giant electrolysers > 1 GW)
- **“Local low-carbon hydrogen hubs”** underpinning spreading of hydrogen uses across the entire economy, starting with transport infrastructure and some industrial activities where use of hydrogen is already established and with green or blue hydrogen displacing grey hydrogen

In parallel, improvement of sector economics are also likely to stem from:

- **Optimized project subcontracting, through the emergence of an integrated industrial supply chain likely to be a key source of series effects** in the deployment of equipment, as seen in France with the nuclear program spanning from 1975 to 2000, these series effects having, according to EDF allowed a 30% drop in constant terms in the cost of reactor build between 1980 and 2000
- **The constant search for technological improvement** likely to improve the performance of all equipments involved along the value chain, as seen in the solar PV sector over the past 10 years

Technological options for the decarbonization of the world economy still very open

Although at this stage benefiting from less favorable cost reduction prospects than green hydrogen, blue hydrogen may be a relevant option in certain areas combining natural resources and an industrial ecosystem. For policy makers, sector upscaling involves the support / use of technologies and infrastructure necessary for the production / distribution in the economy of low-carbon H2

- **Parallel support** (where and when needed) **for the technologies necessary for the production of the molecule:**
  - **For green hydrogen: competitive low-carbon electricity production/supply** through policies supporting the deployment of new capacities or subsidies / support for low-carbon electricity used for the electrolysis of water
  - **For blue hydrogen: improvement/industrialization of CCS**
- **Use** (in keeping with technical limitations) **of existing gas networks to generate scale effects in the production of low-carbon hydrogen, the molecule automatically finding a commercial outlet**

Correlatively, the decarbonization of the economy will imply hydrogen being used in addition to other decarbonization agents, when and where the molecule is best placed compared to other existing solutions from a technical and economic perspective

In some already identified end-uses, hydrogen is unlikely to be successfully compete with other decarbonization solutions:

- **Case of the transport sector** where FCVEs are better positioned than BEVs in long distance, heavy-duty mobility, but unlikely to reach cost competitiveness vis-à-vis the latter in the compact urban car segment
- **Case of residential heating** where upscaling of biomethane offers the prospect of displacing natural gas while preserving the value of existing gas infrastructure

Manufacture of low-carbon hydrogen has potential externalities/risks that need to be sensed and addressed

While the development of low-carbon hydrogen offers promising prospects for the decarbonization of hard-to-abate sectors such as mobility and manufacturing, the deployment of associated processes / infrastructures is not without inducing externalities/risks:

- **Electrolysis' high-water intensity (9 liters of water / kgH2) raises the question of water resources' availability in the long term:**
  - **Manufacture of 700 MMt of potential hydrogen demand by 2050** (see above) 100% through electrolysis would **require 6.3 bcm of water resources**, e.g. 114% of France's annual water consumption
  - **Such water-intensivity is both a challenge and an opportunity**: deployment of electrolysers could induce trade-offs among various uses of hydric resources but also underpin the development of solar PV-powered desalination units coupled with electrolysers in arid areas (typical case of Saudi Arabia – see above), hereby offering a catalyst for the greening of the desalination sector
- **Deployment of solar PV and wind energy to power electrolysers raises a biodiversity issues in particular for the former technology,** given its high footprint relative
- **Risks in relation to relation to large-scale use of CCS for the manufacture of blue hydrogen** (risk of carbon leakage throughout the process from capture to transport and final storage)

Importance of continued public support and innovative financial schemes (1)

The scale of investments needed to bring the entire sector to commercial scale requires sustained mobilization of governments and the financial sector

Governments must put in place **supportive policies combining:**

- **Direct subsidies to bridge the cost competitiveness gap** of the sector with currently prevailing fossil fuel-based technological solutions
- **Supportive regulatory frameworks offering visibility to private actors**, whether in the form of feed-in tariffs for the production of low-carbon hydrogen or in the form of PPPs in the deployment of downstream uses of the molecule, etc.
- **Price signals,** through the setting of carbon price floors, **favoring investment in low-carbon technologies**, in particular in certain hard-to-abate industrial activities (cement, steel, glass, refining, etc.)

Importance of continued public support and innovative financial schemes (2)

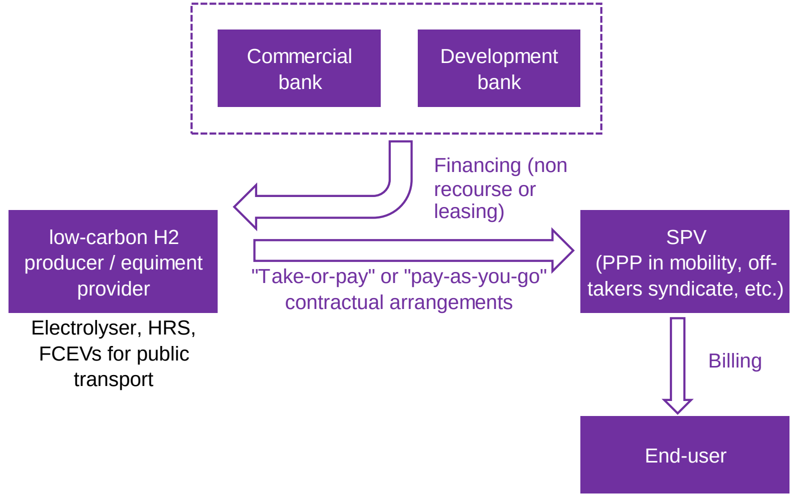
The deployment of assets along the value chain will require **the establishment of innovative financing schemes**

Such scheme could replicate the infrastructure model involving a large sample of actors…

- Equipment suppliers
- End-users
- Public authorities
- Commercial banks
- Development banks

… **covering the widest possible range of equipment** (in particular electrolysers & mobility infrastructure/equipment - HRS and FCEVs)

POTENTIAL H2-CENTRIC INFRASTRUCTURE MODEL



Source: Natixis

Importance of continued public support and innovative financial schemes (3)

For its part, **green finance, has a twofold role** to play at this early stage of the low-carbon hydrogen economy:

- **Mobilize the collective savings available** to finance the development of the sector
- **Ensure transparency** in the use of private capital and build confidence in the investor base

It be ensured through the **development of impact-based financing products** (green bonds & loans) **based on rigorous environmental taxonomies**, promoting the deployment of technologies, both the most relevant (from a climate standpoint and the most virtuous (from a broader environmental standpoint – preservation of biodiversity and natural resources, including water, used for other types of human activities)

07.

APPENDICES

- TYPES OF ELECTROLYSERS
- GLOSSARY
- BIBLIOGRAPHY

Types of electrolysers: no clear leading technology. Trade off based on the intermittence of the power (load factor) and the Capex

	1 Alkaline electrolysis			2 PEM electrolyser			3 SOEC *(solid oxide electrolysis cells)*		
	2019	2030	Long term	2019	2030	Long term	2019	2030	Long term
Electrical Efficiency *(%, LHV(1))*	63-70	65-71	70-80	56-60	63-68	67-74	74-81	77-84	77-90
Operating pressure *(bar)*	1-30			30-80			1		
Operating temperature *(°C)*	60-80			50-80			650-1,000		
Stack lifetime *(operating hours)*	60,000-90,000	90,000-100,000	100,000-150,000	30,000-90,000	60,000-90,000	100,000-150,000	10,000-30,000	40,000-60,000	75,000-100,000
Load range *(% of nominal load)*	10-110			0-160			20-100		
Footprint *(m2 /MWe)*	95			48					
CAPEX *(USDm/kWe)*	0.5-1.4	0.4-0.85	0.2-0.7	1.1-1.8	0.65-1.5	0.2-0.9	2.8-5.6	0.8-2.8	0.5-1.0
description	Mature and commercial technology. Several alkaline electrolysers with a capacity of up to 165MW were built in countries with large hydropower resources. Almost all of them were decommissioned when natural gas and steam methane reforming for hydrogen production took off in the 1970s.			First introduced in the 1960s by General Electric. They are able to produce highly compressed hydrogen for decentralised production and storage at refuelling stations and offer flexible operation, including the capability to provide frequency reserve and other grid services.			Least developed electrolysis technology. They have not yet been commercialised, although individual companies are now aiming to bring them to market. They operate at high temperatures and with a high degree of electrical efficiency. Because they use steam for electrolysis, they need a heat source.		
Benefit	**Low Capex** (avoidance of precious materials) **Well know technology**			**Use pure water** for electrolyte solution: no need for potassium hydroxide solution Limited footprint **Can operate from 0 to 160%** of design capacity			**Low material costs**: use ceramics as the electrolyte Can **cogenerate heat** Can be **reversed as a fuel cell**		
Drawback	Still more expensive than SMR/ATR Need to **recycle the potassium hydroxide** electrolyte solution			**Expensive electrode catalysts** (platinum, iridium) and membrane materials. **Shorter lifespan** than Alkaline			**Least developed technology** for now Need hot source that put stress on the materials integrity		

Sources: IEA, Natixis Energy Transition Advisory Solutions
Note: (1) LHV = lower heating value

Glossary (1)

Battery electric vehicle (BEV)	**Type of electric vehicle (EV) that exclusively uses chemical energy stored in rechargeable battery packs, with no secondary source of propulsion (e.g. hydrogen fuel cell, internal combustion engine, etc.).** BEVs use electric motors and motor controllers instead of internal combustion engines (ICEs) for propulsion. They derive all power from battery packs and thus have no internal combustion engine, fuel cell, or fuel tank. BEVs include – but are not limited to – motorcycles, bicycles, scooters, skateboards, railcars, watercraft, forklifts, buses, trucks, and cars
Bio-energy with carbon capture and storage (BECCS)	**Process of extracting bioenergy from biomass and capturing and storing the carbon, thereby removing it from the atmosphere.** The carbon in the biomass comes from the greenhouse gas carbon dioxide (CO_2) which is extracted from the atmosphere by the biomass when it grows. Energy is extracted in useful forms (electricity, heat, biofuels, etc.) as the biomass is utilized through combustion, fermentation, pyrolysis or other conversion methods. Some of the carbon in the biomass is converted to CO_2 or biochar which can then be stored by geologic sequestration or land application, respectively, enabling carbon dioxide removal and making BECCS a negative emissions technology.
Contract for difference (CfD)	**Contract between two parties**, typically described as "buyer" and "seller", **stipulating that the buyer will pay to the seller the difference between the current value of an asset and its value at contract time (if the difference is negative, then the seller pays instead to the buyer**. **In the electricity generation business, CfDs have recently been recently developed in the UK as a system of reverse auctions intended to give investors the confidence and certainty they need to invest in low-carbon generation assets**. CfDs have also been agreed on a bilateral basis, such as the agreement struck for the Hinkley Point C nuclear plant in the UK between the British government and EDF, the main project sponsor. **CfDs work by fixing the prices received by low carbon generation, reducing the risks they face, and ensuring that eligible technology receives a price for generated power that supports investment**. CfDs also reduce costs by fixing the price consumers pay for low carbon electricity. This requires generators to pay money back when wholesale electricity prices are higher than the strike price and provides financial support when the wholesale electricity prices are lower. The costs of the CfD scheme are funded by a statutory levy on all UK-based licensed electricity suppliers (known as the ‘Supplier Obligation’), which is passed on to consumers.
Feed-in Tariff (FIT)	**Policy mechanism designed in the electricity sector to accelerate investment in renewable energy technologies by offering long-term contracts to renewable energy producers**. Their goal is to offer cost-based compensation to renewable energy producers, providing price certainty and long-term contracts that help finance renewable energy investments. Typically, FITs award different prices to different sources of renewable energy in order to encourage development of one technology over another. For example, technologies such as wind power and solar PV are awarded a higher price/kWh than conventional power.

Glossary (2)

Fuel cell electric vehicle (FCEV)	**Electric vehicle that uses a fuel cell, sometimes in combination with a small battery or supercapacitor, to power its onboard electric motor. Fuel cells in vehicles generate electricity generally using oxygen from the air and compressed hydrogen. Most fuel cell vehicles are classified as zero-emissions vehicles that emit only water and heat.**
Internal combustion engine (ICE)	**Heat engine in which the combustion of a fuel occurs with an oxidizer (usually air) in a combustion chamber that is an integral part of the working fluid flow circuit. In an internal combustion engine, the expansion of the high-temperature and high-pressure gases produced by combustion applies direct force to some component of the engine.** **ICEs are usually powered by energy-dense fuels such as gasoline or diesel fuel, liquids derived from fossil fuels.** While there are many stationary applications, most ICEs are used in mobile applications and are the dominant power supply for vehicles such as cars, aircraft and boats
Ionomer	**Polymer** (substance or material consisting of very large molecules, or macromolecules, composed of many repeating subunits) **composed of repeat units of both electrically neutral repeating units and ionized units covalently bonded to the polymer backbone as pendant group moieties.** **Ionomers have unique physical properties including electrical conductivity and viscosity. This is the reason why some more recent applications for ionomers include being used as ion-selective membranes in a variety of electrical and energy applications**. Examples include the cation exchange membrane for fuel cells, which allow only protons or specific ions to cross the membrane.
Levelized Cost of Energy (LCOE)	**Concept developed to measure the average net present cost (expressed in $/MWh) of electricity generation for a generating plant over its lifetime**. The costs taken into account include initial capex, operation & maintenance costs (O&M) as well as the cost of capital used as a discounting factor. The LCOE is calculated as the ratio between all the discounted costs over the lifetime of an electricity generating plant divided by a discounted sum of the actual energy amounts delivered. The LCOE is used to compare different methods of electricity generation on a consistent basis.
Membrane electrode assemblies (MEAs)	**The Membrane Electrode Assembly (MEA) is the core component of a fuel cell that helps produce the electrochemical reaction needed to separate electrons.** On the anode side of the MEA, a fuel (hydrogen, methanol etc.) diffuses through the membrane and is met on the cathode end by an oxidant (oxygen or air) which bonds with the fuel and receives the electrons that were separated from the fuel. Catalysts on each side enable reactions and the membrane allows protons to pass through while keeping the gases separate. In this way cell potential is maintained and current is drawn from the cell producing electricity.

Bibliography

Airbus, https://www.airbus.com/newsroom/stories/hydrogen-combustion-explained.html, November 2020

Ballard, https://www.ballard.com/about-ballard/newsroom/news-releases/2020/09/21/ballard-comments-on-china-s-new-policy-to-support-adoption-of-fuel-cell-electric-vehicles, September 2020

BNEF, Hydrogen Economy Outlook, March 2020

https://www.cleantech.com/chinas-hydrogen-society-beginning-to-take-shape/#:~:text=New%20Energy%20Vehicles%20still%20a,hydrogen%20refueling%20stations%20(HRSs), October 2020

Gas4climate, https://gasforclimate2050.eu/wp-content/uploads/2020/03/Navigant-Gas-for-Climate-The-optimal-role-for-gas-in-a-net-zero-emissions-energy-system-March-2019.pdf, March 2019

FuelCell Store, https://www.fuelcellstore.com/fuel-cell-components/membrane-electrode-assembly

ICCT, https://theicct.org/blog/staff/china-sketching-roadmap-hydrogen-vehicles-aug2020, August 2020

IEA, World Energy Outlook 2019, October 2019

IEA, World Energy Outlook 2020, October 2020

IEA, https://www.iea.org/reports/hydrogen, June 2020

IEA, https://www.iea.org/reports/global-ev-outlook-2020, June 2020

Humber Project, https://www.zerocarbonhumber.co.uk/wp-content/uploads/2019/11/Capture-for-Growth-Zero-Carbon-Humber-V4.9-Digital.pdf, July 2019

Hydrogen council, https://hydrogencouncil.com/en/path-to-hydrogen-competitiveness-a-cost-perspective/, January 2020

DISCLAIMER

Reference prices are based on closing prices.

The information contained in these publications is exclusively intended for a client base consisting of professionals or qualified investors. It is sent to you by way of information and cannot be divulged to a third party without the prior consent of Natixis. It cannot be considered under any circumstances as an offer to sell, or a solicitation of any offer to buy financial instruments. While all reasonable effort has been made to ensure that the information contained is not untrue or misleading at the time of publication, no representation is made as to its accuracy or completeness and it should not be relied upon as such. Past and simulated performances offer no guarantee as to future performances. Any opinions offered herein reflect our current judgement and may change without notice. Natixis cannot be held responsible for the consequences of any decision made with regard to the information contained in those documents. Natixis has set up due procedures for the separation of activities, notably in order to prevent conflicts of interest between the research activities and its other activities. Details of these 'information barriers' are available on request from the head of compliance. On the date of those reports, Natixis and/or one of its subsidiaries may be in a conflict of interest with the issuer mentioned herein. In particular, it may be that Natixis or any person or company linked thereto, their respective directors and/or representatives and/or employees, have invested on their own account in, or act or intend to act, in the next twelve months, as an advisor, provider of liquidity, market maker, or corporate banker (and notably for underwriting transactions, placements or connected transactions), for a company discussed in this report.

Natixis is authorised in France by the Autorité de Contrôle Prudentiel et de Résolution (ACPR) as a Bank – Investment Services Provider and subject to its supervision. Natixis is regulated by the AMF in respect of its investment services activities.

This document can be distribute in the UK. Natixis is authorised by the Autorité de Contrôle Prudentiel et de Résolution (ACPR) and subject to limited regulation by the Financial Conduct Authority and Prudential Regulation Authority. Details about the extent of our regulation by the Financial Conduct Authority and Prudential Regulation Authority are available on request from London office.

This document can be distribute in Germany. Natixis is authorised by the ACPR and regulated by the BaFin (Bundesanstalt für Finanzdienstleistungsaufsicht) for the conduct of its business under the right of establishment in Germany.

Natixis is authorised by the ACPR and regulated by Bank of Spain and the CNMV for the conduct of its business under the right of establishment in Spain.

Natixis is authorised by the ACPR and regulated by Bank of Italy and the CONSOB (Commissione Nazionale per le Società e la Borsa) for the conduct of its business under the right of establishment in Italy.

Natixis is authorised by the ACPR and regulated by the Dubai Financial Services Authority (DFSA) for the conduct of its business in and from the Dubai International Financial Centre (DIFC). The document is being made available to the recipient with the understanding that it meets the DFSA definition of a Professional Client; the recipient is otherwise required to inform Natixis if this is not the case and return the document. The recipient also acknowledges and understands that neither the document nor its contents have been approved, licensed by or registered with any regulatory body or governmental agency in the GCC or Lebanon.

Natixis, a foreign bank and broker-dealer, makes this research report available solely for distribution in the United States to major U.S. institutional investors as defined in Rule 15a-6 under the U.S. Securities Act of 1934. This document shall not be distributed to any other persons in the United States. All major U.S. institutional investors receiving this document shall not distribute the original nor a copy thereof to any other person in the United States. Natixis Securities Americas LLC a U.S. registered broker-dealer and member of FINRA is a subsidiary of Natixis. Natixis Securities Americas LLC did not participate in the preparation of this research report and as such assumes no responsibility for its content. This research report has been prepared and reviewed by research analysts employed by Natixis, who are not associated persons of Natixis Securities Americas LLC and are not registered or qualified as research analysts with FINRA , and are not subject to the rules of the FINRA.

I(WE), ANALYST(S), WHO WROTE THIS REPORT HEREBY CERTIFY THAT THE VIEWS EXPRESSED IN THIS REPORT ACCURATELY REFLECT OUR(MY) PERSONAL VIEWS ABOUT THE SUBJECT COMPANY OR COMPANIES AND ITS OR THEIR SECURITIES, AND THAT NO PART OF OUR COMPENSATION WAS, IS OR WILL BE, DIRECTLY OR INDIRECTLY, RELATED TO THE SPECIFIC RECOMMENDATIONS OR VIEWS EXPRESSED IN THIS REPORT.

The personal views of analysts may differ from one another. Natixis, its subsidiaries and affiliates may have issued or may issue reports that are inconsistent with, and/or reach different conclusions from, the information presented herein.

The stocks mentioned might be subject to specific disclaimers. Please click on the following link to consult them

https://www.research.natixis.com/GlobalResearchWeb/main/globalresearch/DisclaimersSpecifiques

NATIXIS
BEYOND BANKING

47, quai d'Austerlitz
75013 Paris
Tél. : +33 1 58 32 30 00

research.natixis.com

GROUPE BPCE