



# Understanding the Hydrogen Market and its opportunities for Cogeneration

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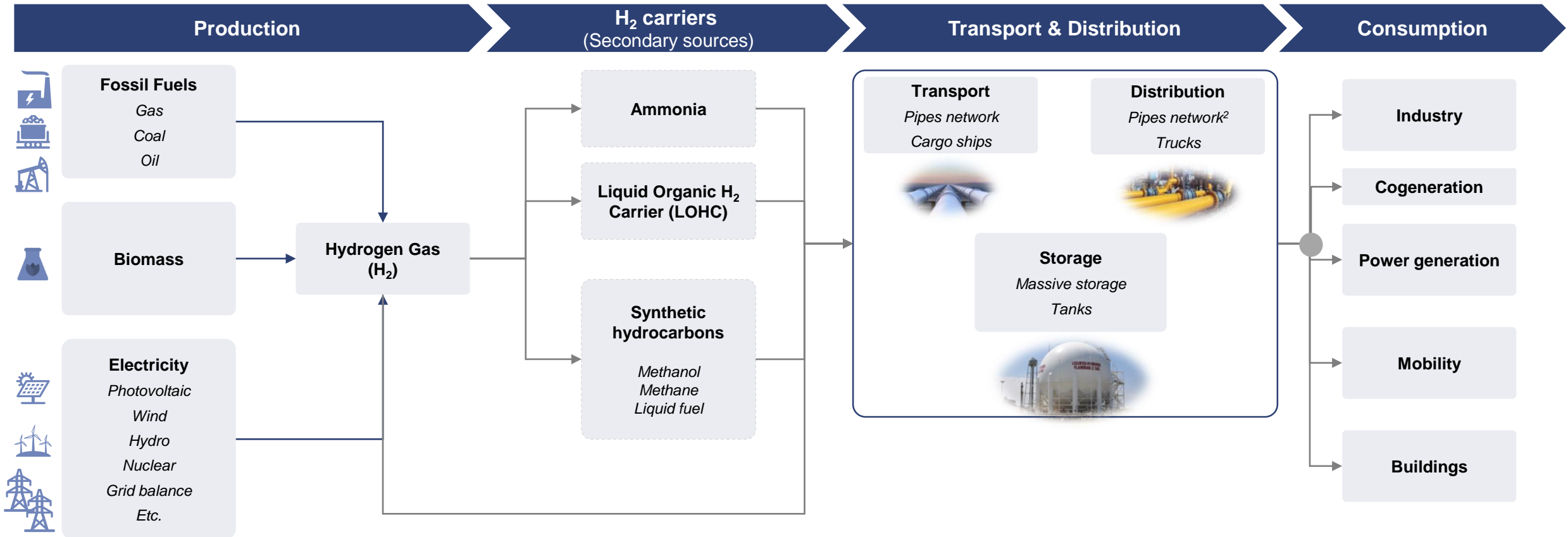
# 01.

## Current context for hydrogen in Spain

- H<sub>2</sub> Value chain
- Spanish H<sub>2</sub> market
- Hydrogen opportunities in Spain
- Hydrogen Roadmap
- Fundable hydrogen projects
- Context of hydrogen in Cogeneration

## H<sub>2</sub> Value Chain

Hydrogen Value Chain covers all processes that occur from production (generation) to consumption, including their different forms of transport/transmission and distribution.



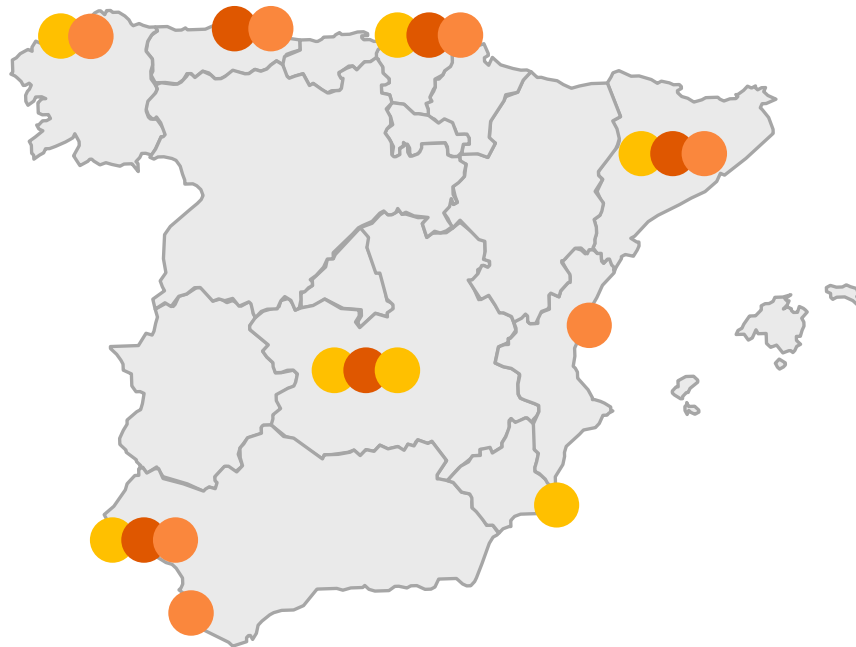
Almost 98% of hydrogen is produced from fossil raw materials (natural gas and coal). The need to decarbonize the industry is driving the combination of CCUS<sup>1</sup> with fossil hydrogen generation or its complete replacement by green hydrogen.

## H<sub>2</sub> market in Spain – General overview

Nationally, some 500,000 tons of hydrogen are consumed today (5<sup>th</sup> Country in the EU), of which 81% are destined for the oil refining industry, and 95% are fossil in origin (grey hydrogen)

### Hydrogen Production Plants<sup>1</sup>

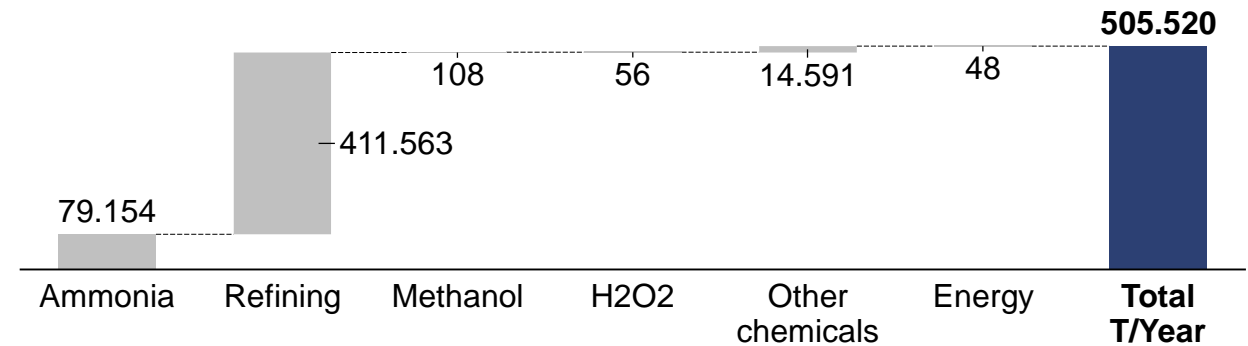
There are currently 31 plants operating throughout the national territory



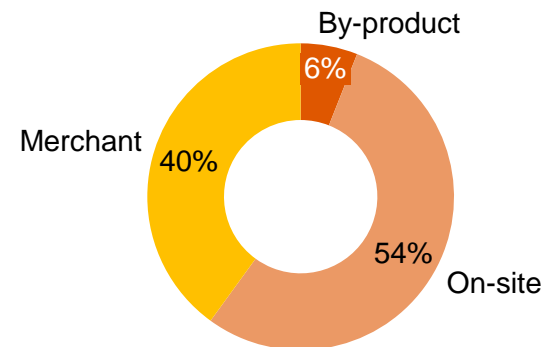
- Merchant: Direct sale to market
- By-product: Indirect production
- On-site: Consumption at same location as production

### Hydrogen Consumption<sup>2</sup>

Annual hydrogen consumption is around 500,000 Tons per year, with the refining sector demanding the most.



### Hydrogen Production<sup>2</sup>

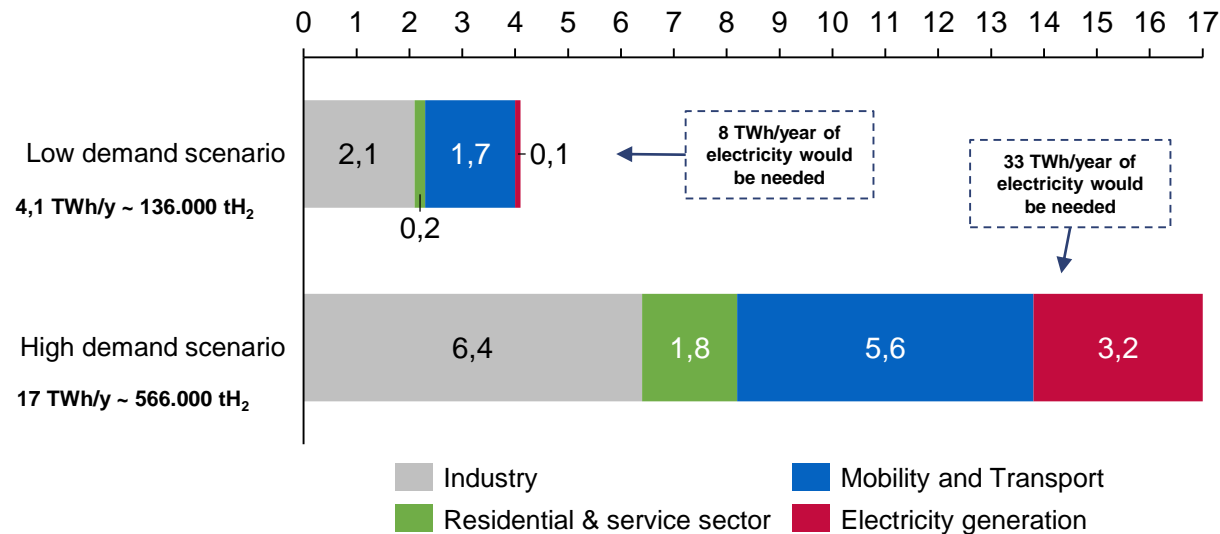


- About 95%<sup>3</sup> of the hydrogen consumed in Spain is within the environmental category of hydrogen "grey".
- More than 50% of hydrogen is produced and consumed at the facility.
- The current turnover of hydrogen technologies in Spain is approximately 594 M€<sup>3</sup> per year.

## H<sub>2</sub> market in Spain – Renewable H<sub>2</sub> demand evolution in Spain for 2030

During next decade, demand for green hydrogen in Spain is expected to be 13% higher than current demand for Hydrogen.

Estimated demand for renewable H<sub>2</sub> in Spain by 2030 (TWh/year)<sup>2</sup>



Currently, in Spain conventional hydrogen used mainly in the industry is produced from fossil fuels (e.g., by steamed methane reform) or is a by-product of other chemical processes.

*Fuel Cells and Hydrogen Joint Undertaking<sup>2</sup>* estimates two renewable hydrogen demand scenarios by 2030:

- **Low scenario:** Renewable hydrogen accounts for 0.5% of final total energy demand (i.e., 4.1 TWh/y of 868 TWh/y) or 3.4% of final gas demand (120 TWh/y), according to EUCO3232.5<sup>3</sup>.
- **High scenario:** Renewable hydrogen accounts for 1.9% of final total energy demand (i.e., 16.9 out of 868 TWh/y) or 14.0% of final gas demand (120 TWh/y) according to EUCO3232.5<sup>3</sup>.

Both scenarios assume that renewable hydrogen would partially replace current conventional production and additional demand (e.g., in the transport sector) by 2030. Specifically:

- By volume, the main uses to which the H<sub>2</sub> produced would be the industry (oil refining and production of ammonia) and mobility/transport.
- **Cogeneration could be added to the consumption of this hydrogen by providing heat and surplus electricity to the industrial, residential and tertiary sector.**

**To produce the current demand Spain (500,000 t/year), about 29 TWh/year of electricity is required**

**To produce the hydrogen indicated in the high-demand scenario (566,000 t/year), about 33 TWh/year of electricity is required**

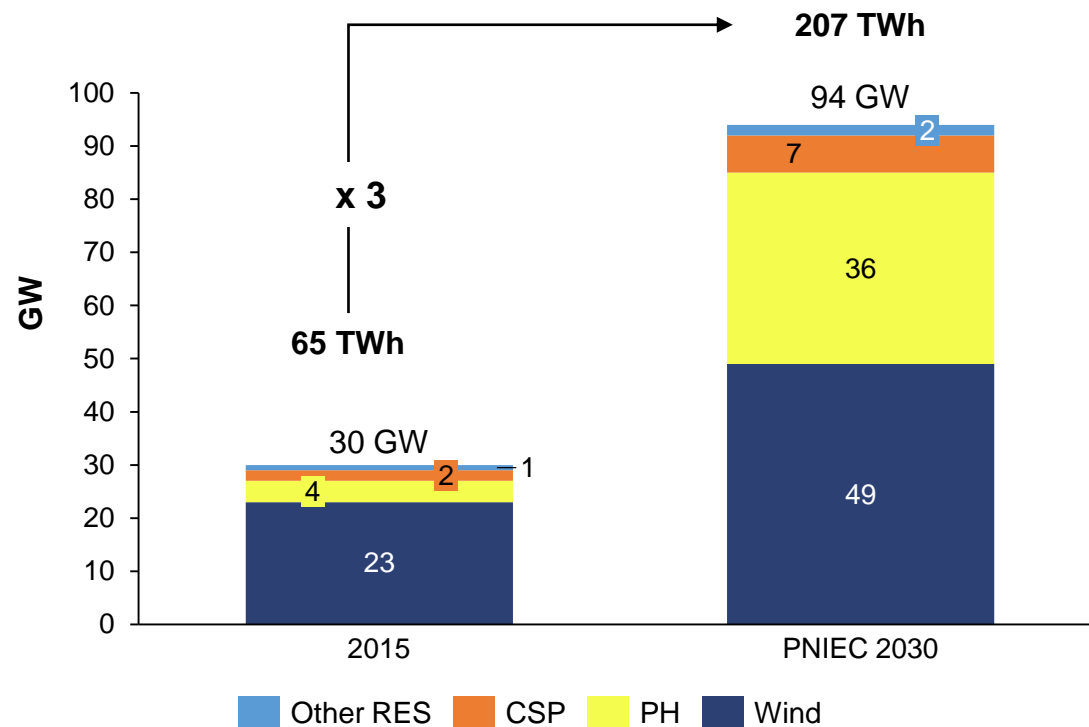
**Sources:** <sup>1</sup>(2019-Endesa): El papel del almacenamiento en la transición energética hacia un sistema descarbonizado. Jornada sobre almacenamiento con energías renovables. <sup>2</sup>Fuel Cells and Hydrogen Joint Undertaking (FCH) 2020: Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans.

**Notes:** 1 kg of H<sub>2</sub> equals 33.3 kWh of energy; 58 kWh of electricity is needed to produce 1 kg of H<sub>2</sub>. <sup>3</sup>The EUCO3232.5 scenario is part of a group of EUCO scenarios used in the development of EU energy and climate policy.

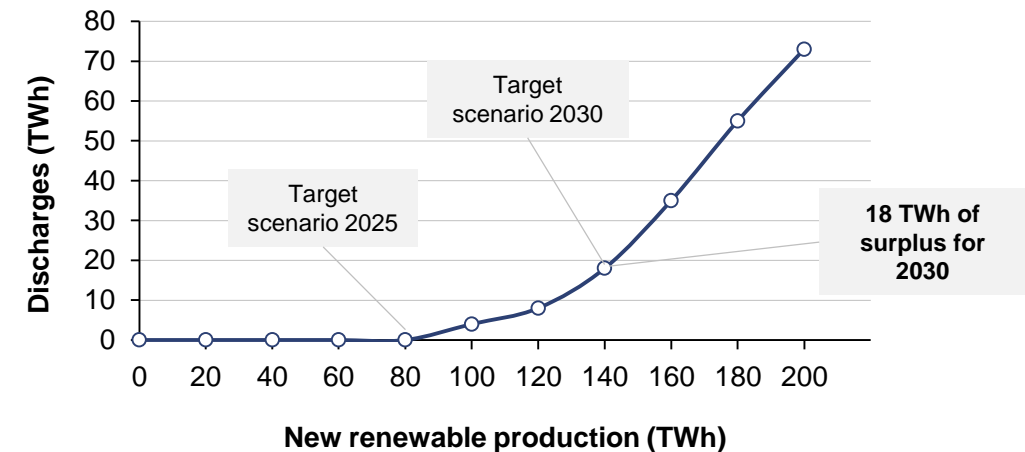
## H<sub>2</sub> market in Spain – Renewable surplus impact in the growth predictions

Based on the increase in installed RES capacity established in the PNIEC by 2030, both the use of discharges into the grid from the seasonal surplus of electricity production, and the development of off-grid plants dedicated to its production, will ensure the production of green hydrogen in Spain.

NEW RENEWABLE POWER PNIEC 2030



ESTIMATED SURPLUS DISCHARGES TO THE NETWORK<sup>1</sup>

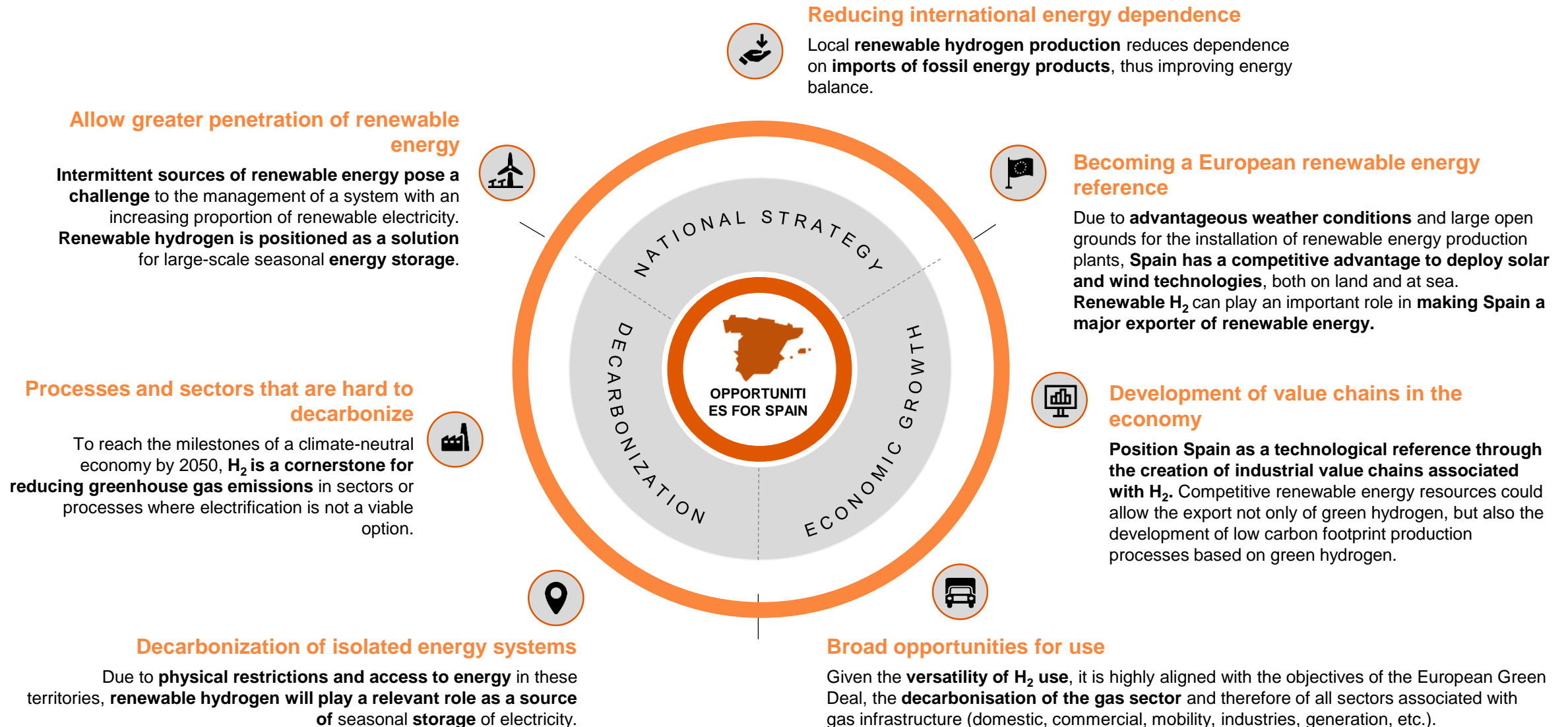


- If the target set in the PNIEC for renewable boost (RES) is met, the installed capacity and electricity generation planned for 2030 will triple in the system.
- From 120 TWh (68% RES-E) the system will have a risk of saturation, increasing spills. This surplus can be used for H<sub>2</sub> production.
- In addition, part of this new renewable project portfolio, which is expected to be installed in Spain, will be dedicated exclusively to the production of green hydrogen.
- There will be a need for flexibility and manageability in the system, something to which cogeneration will contribute.



## Hydrogen opportunities in Spain

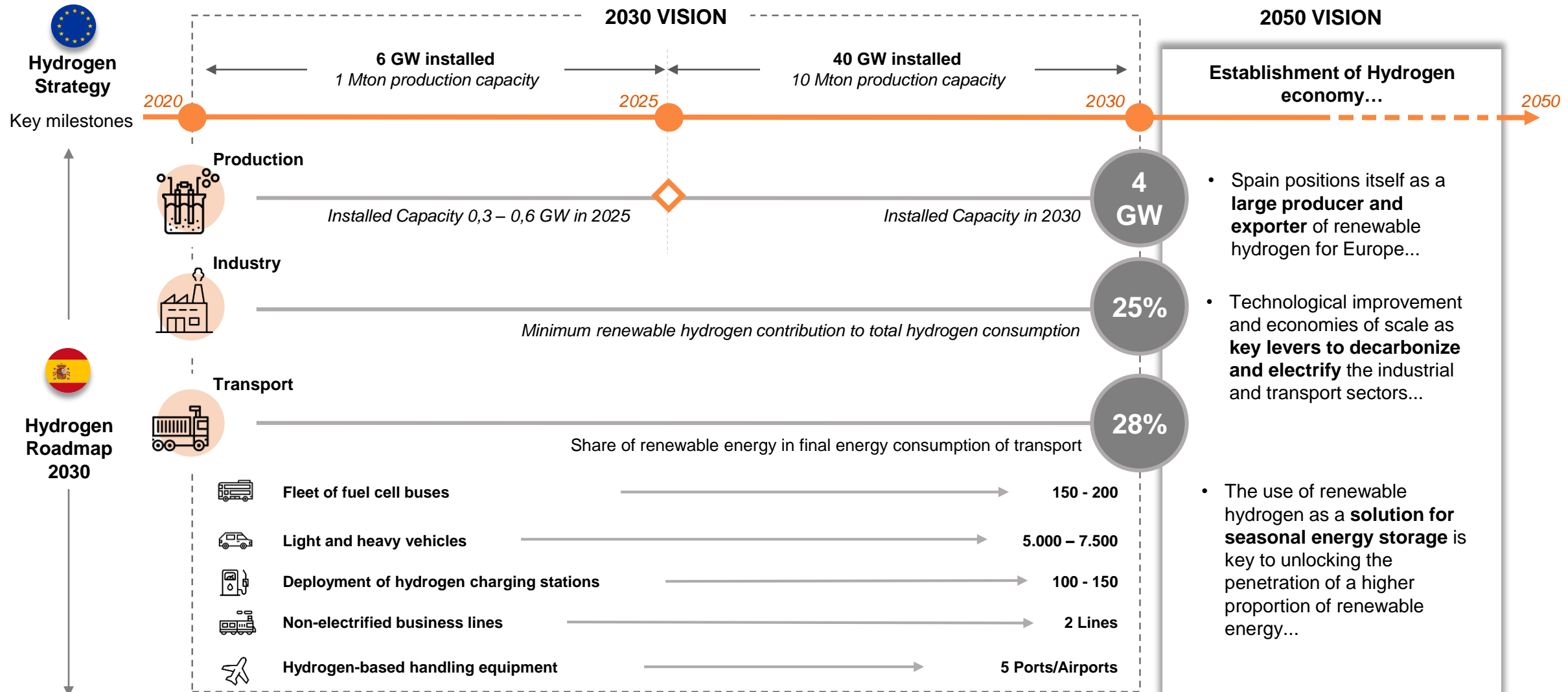
Spain's large capacity to produce renewable energy makes it a leading European potential in the production and export of green hydrogen.





## Hydrogen Roadmap

Spain proposes the Hydrogen Roadmap which will mobilize 8.900 million euros in investments to meet the 2030 objectives.



## Fundable hydrogen projects

The Government will allocate more than 1.5 billion to boost renewable hydrogen by 2023 through the European Recovery Fund.<sup>(1)</sup>

### Hydrogen Projects that will be financed in Spain:

#### 1. Innovative value chain and knowledge, including R&D activities and early deployments

- Improvement of productive capacities, prototyping, application deployment, distribution and refueling infrastructure, etc..

#### 2. Cluster projects with the collaboration of different actors in development and execution

- Large-scale production, processing and consumption of renewable hydrogen in a unique place. (It should be located in areas that absorb more than 10k tons per year).

#### 3. Pioneering sectoral integration projects

- Hydrogen production and use, allowing a first-of-a-kind demonstration in the final phase of a first industrial/commercial deployment in an enterprise environment (You must consume approx. 1k tons per year).

A consortium covering the entire hydrogen value chain will have greater potential to be a tractor project



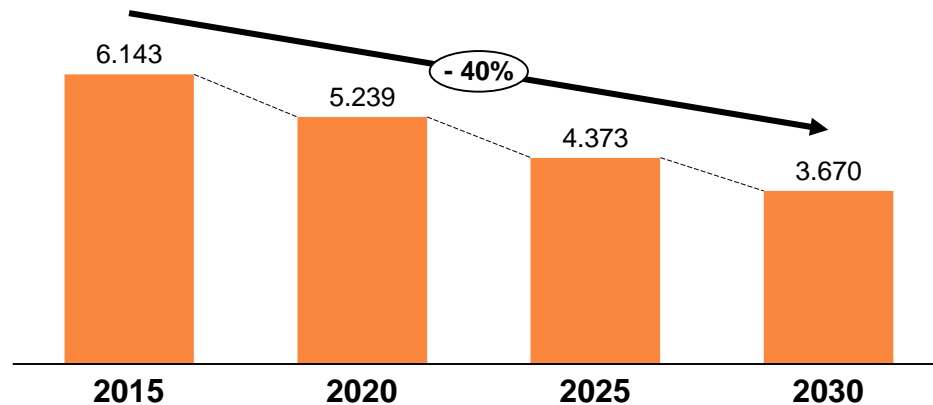
<sup>(1)</sup> The government launched in December 2020 a "Manifesto of Interest" to know tractor projects and relevant actors in renewable hydrogen, obtaining the knowledge associated with the entire renewable hydrogen value chain.

## Context of hydrogen in Cogeneration

In this context, while Spain's energy transition situation does not support the development of cogeneration, **renewable hydrogen could boost the renewal of cogeneration plants and boost the sector.**

### Situation of Cogeneration within the PNIEC

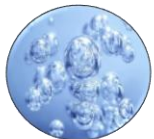
Evolution of installed cogeneration power by fuel type(MW)<sup>(1)</sup>



It creates some uncertainty around the future of cogeneration

- At the national level, the cogeneration facility park **should adapt its technology and efficiency**, with a clear short-term renovation framework.
- The **regulations must provide legal certainty and stability**, in order to undertake the necessary investments to adapt the cogeneration park and maintain competitiveness.
- **There is still no clear commitment of the PNIEC to cogeneration**, despite being more efficient than gas thermal groups, for which the PNIEC has maintained the installed generating capacity.

### Opportunities for Cogeneration with the boost of renewable hydrogen



**Regulatory changes**, such as the inclusion of programs for equipment to admit a certain % of H<sub>2</sub>, certificates of origin, ad hoc auctions, etc., **would help to address the investment needed to adapt technology and renew plants for hydrogen consumption**, just as European and national subsidies can play a key role in this.



The use of **renewable hydrogen as a natural gas substitute fuel** helps reduce the carbon footprint and allows **cogeneration to play its part in decarbonization targets**.



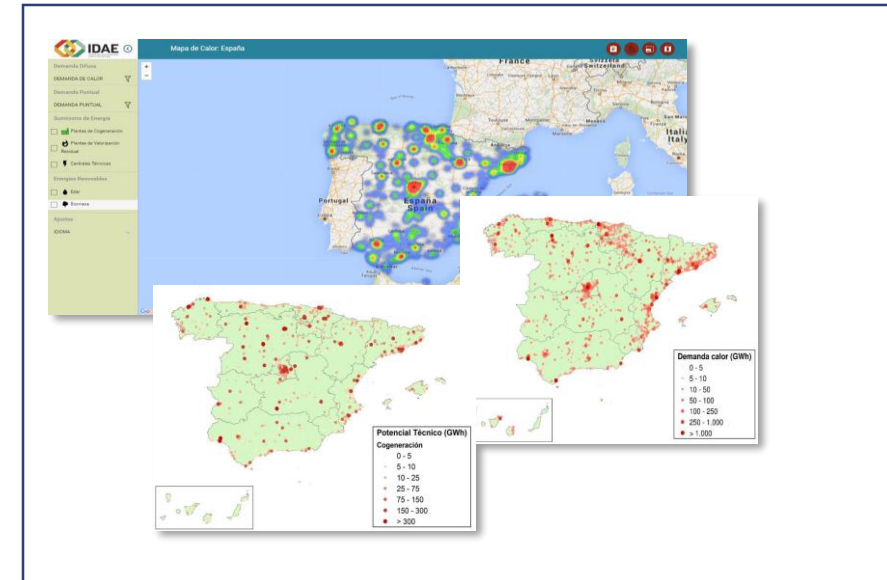
The **use of renewable hydrogen not consumed** in the cogeneration plant can be used as a **long-term renewable energy storage system** (Power-to-power), **providing flexibility to the grid** in the face of the forecast of increased seasonal renewable energies.

<sup>(1)</sup> Based on data published by PNIEC 2021 – 2030 (Plan Nacional Integrado de Energía y Clima)

## Context of hydrogen in Cogeneration – Alternative for decarbonization

Considering the scenario of national heat demand and the difficulty of electrifying certain segments of it (high heat consuming industries), the use of H<sub>2</sub> for technologies such as cogeneration, are presented as a solution to reduce emissions in these segments.<sup>1</sup>

- Total national **thermal demand** is estimated to be **460,000 GWh<sup>1</sup>**, including the Residential, Tertiary and Industrial sectors.
- This demand can be covered by high efficiency cogeneration providing **added value** compared to other technologies such as combined cycles:
  - ✓ **Flexibility** for high, medium and low temperature heat input, supported with heat storage systems.
  - ✓ **Very high efficiency**, providing significant savings in primary energy.
- By replacing its current energy sources with **green hydrogen**, the role of cogeneration will be strengthened, being able to add to the **process of decarbonization** of its activity and therefore to that of the national system.



NG consumption in 2017 in the industry sector by applied heat temperature range (TWh/year)<sup>2</sup>

<100 °C (low)	100-500 °C (medium)	>500 °C (high)	Total
32 (36%)	23 (26%)	33 (38%)	88 (100%)

**Cogeneration using renewable hydrogen could cover an important part of the national energy demand from the thermal point of view, as its technical potential currently amounts to 10,137 GWh, contributing to the decarbonisation of the system.**

# 02.

## Potential uses of hydrogen adapted to cogeneration

- Potential uses of H<sub>2</sub>
- Cogeneration by industry and synergies with H<sub>2</sub>
- Cogeneration value levers in the energy transition

## Hydrogen uses with great potential – H<sub>2</sub>-to-X

Hydrogen can play an important role as a renewable energy storage vector, allowing its distribution in different sectors and regions, benefiting from existing infrastructures and technologies.



### H<sub>2</sub>-to-Power

Hydrogen can be used in different power generation applications acting as a renewable energy storage solution for long-term seasonal storage.

- Hydrogen can be re-electrified directly through fuel cells and gas turbines (CCGT).
- Hydrogen-derived ammonia can be burned at existing (developing) coal-fired power plants.

It is estimated that H<sub>2</sub>-to-Power applications will gain importance in 2030



### H<sub>2</sub>-to-Gas

Green hydrogen has the potential to link electricity and natural gas networks allowing the reduction of the CO<sub>2</sub> intensity of the gas network with small modifications to existing infrastructure.

- Hydrogen can be injected directly into existing natural gas networks (mixing limitations) or distributed through dedicated hydrogen networks.
- Synthetic methane can be produced from hydrogen and CO<sub>2</sub> by methanization and injected without any restrictions into gas networks. Energy efficiencies lead to very high costs, preventing large-scale deployment.

H<sub>2</sub>-to-Gas applications could play a relevant role in the 2030 horizon



### H<sub>2</sub>-to-Liquid


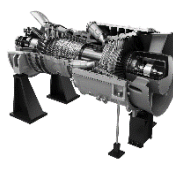
Hydrogen can be converted to low-carbon synthetic liquid fuels that are easy to handle and with higher energy densities than gaseous hydrogen. These fuels take advantage of the infrastructures and uses of fossil fuels that exist today.

In addition, technological advancement is enabling the development of new forms of low-emission transport – ground vehicles, ships and aircraft – powered by hydrogen fuel cells, which can be a paradigm shift in the transport sector.

Models as H<sub>2</sub>-to-Fuel could compete with biofuels from 2035

## Hydrogen uses with great potential – H<sub>2</sub>-to-Power

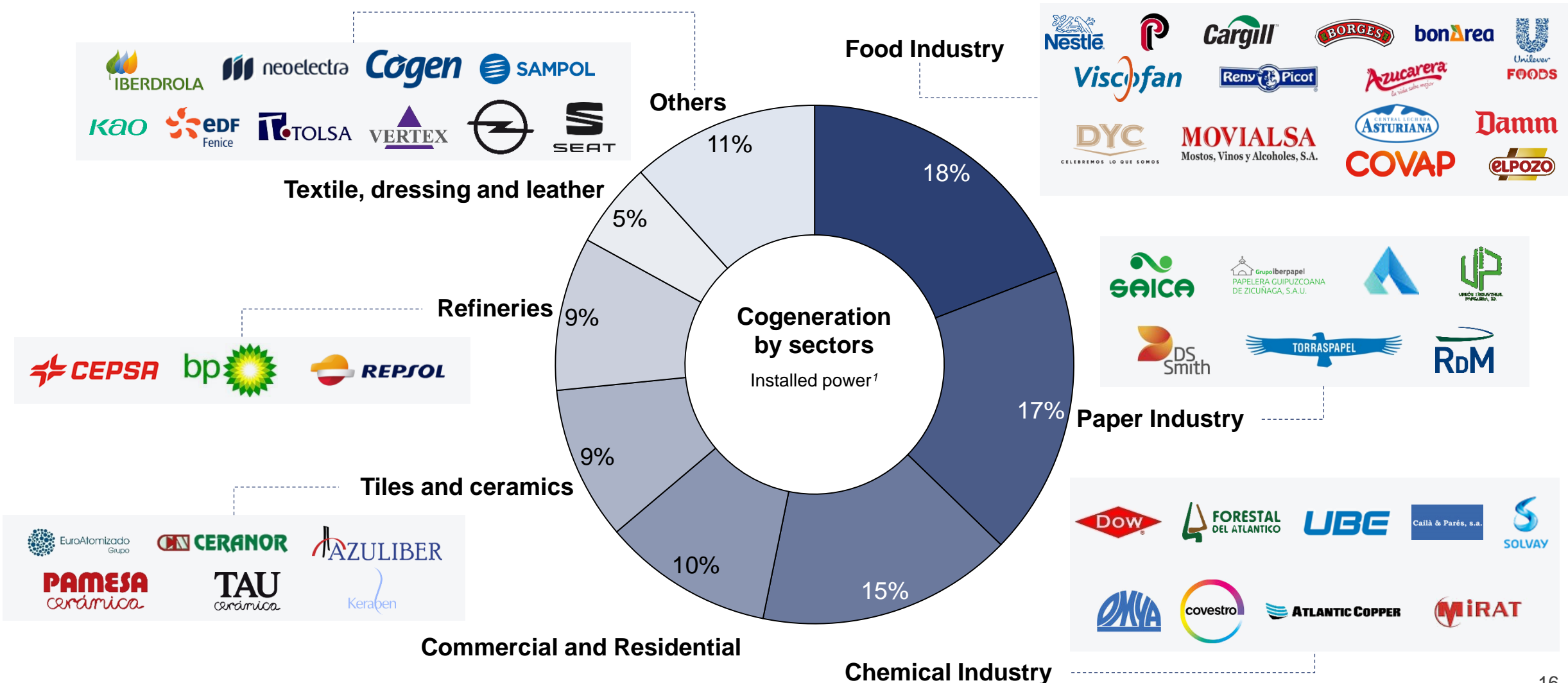
Of the three main uses described, H<sub>2</sub> to Power is the one that would correspond to turbines and cogeneration engines, in addition to other technologies such as those described below:

TECHNOLOGY	 <h3>Stationary Fuel Cells</h3>	 <h3>Power Gas Turbines, engines and CCGTs</h3>
DESCRIPTION AND HIGHLIGHTS	<p>FCs are typically used for <b>distributed generation, back-up and off-grid power substituting diesel generation</b>.</p> <p>Fuel cells (FCs) oxidize hydrogen <b>without combustion</b> producing <b>power and heat</b> with 50%-60% (LHV) electric efficiency. FCs are classified based on the electrolyte and operation temperature:</p> <ul style="list-style-type: none"> <li>• <b>Low temperature FCs:</b> PEM FCs is the most used low temperature FC and runs on pure hydrogen or carbon fuels (if coupled with a reformer).</li> <li>• <b>High temperature FCs:</b> molten carbonate FCs or Solid Oxide FCs (SOFC) are the main high temperature FCs. They run with hydrogen and unreformed carbon fuels. High temperature FCs generate high temperature heat which can be used for CHP and drive overall energy efficiency up to 80% in the case of SOFC.</li> </ul> <p>FCs typically exist in <b>Low-Mid power scales</b> (&lt;50MW).</p>	<p>Hydrogen can be used as fuel in gas turbines and CCGTs.</p> <ul style="list-style-type: none"> <li>• <b>Existing turbines can handle a H<sub>2</sub> share between 2%-5% without relevant modifications although most restrictive guidelines set a 1% limit.</b> Some state of the art gas turbines can handle variable shares of hydrogen reaching up to 90%. The industry estimates to supply turbines capable of running 100% H<sub>2</sub> by 2030.</li> <li>• <b>In micro-gas turbines the direct use of ammonia as fuel has been successfully demonstrated (&gt;2MW).</b> Larger turbines are facing several technical issues regarding NO<sub>x</sub> emissions and flame stability. In this cases previous cracking of ammonia into hydrogen and nitrogen would be needed slightly lowering the total efficiency.</li> <li>• Green hydrogen in power generation has very low efficiencies. Hydrogen produced from electricity at 25 €/MWh would generate power between 84 €/MWh (CCGT at 60% utilization) or 168 €/MWh (simple cycle 25% utilization)<sup>3</sup>.</li> </ul>
PROS AND CONS	<ul style="list-style-type: none"> <li>✓ High operational flexibility</li> <li>✓ Allows distributed generation</li> <li>✗ Limited life-cycle (~40.000 h)</li> <li>✗ High CAPEX (3.000-6.000 €/kW)</li> </ul>	<ul style="list-style-type: none"> <li>✓ Low H<sub>2</sub> feed possible in existing gas turbines</li> <li>✓ Synergies with gas T&amp;D infrastructure</li> <li>✗ A combination of low H<sub>2</sub> prices (~1,5 €/kgH<sub>2</sub>) and high CO<sub>2</sub> costs are required to compete with natural gas</li> </ul>



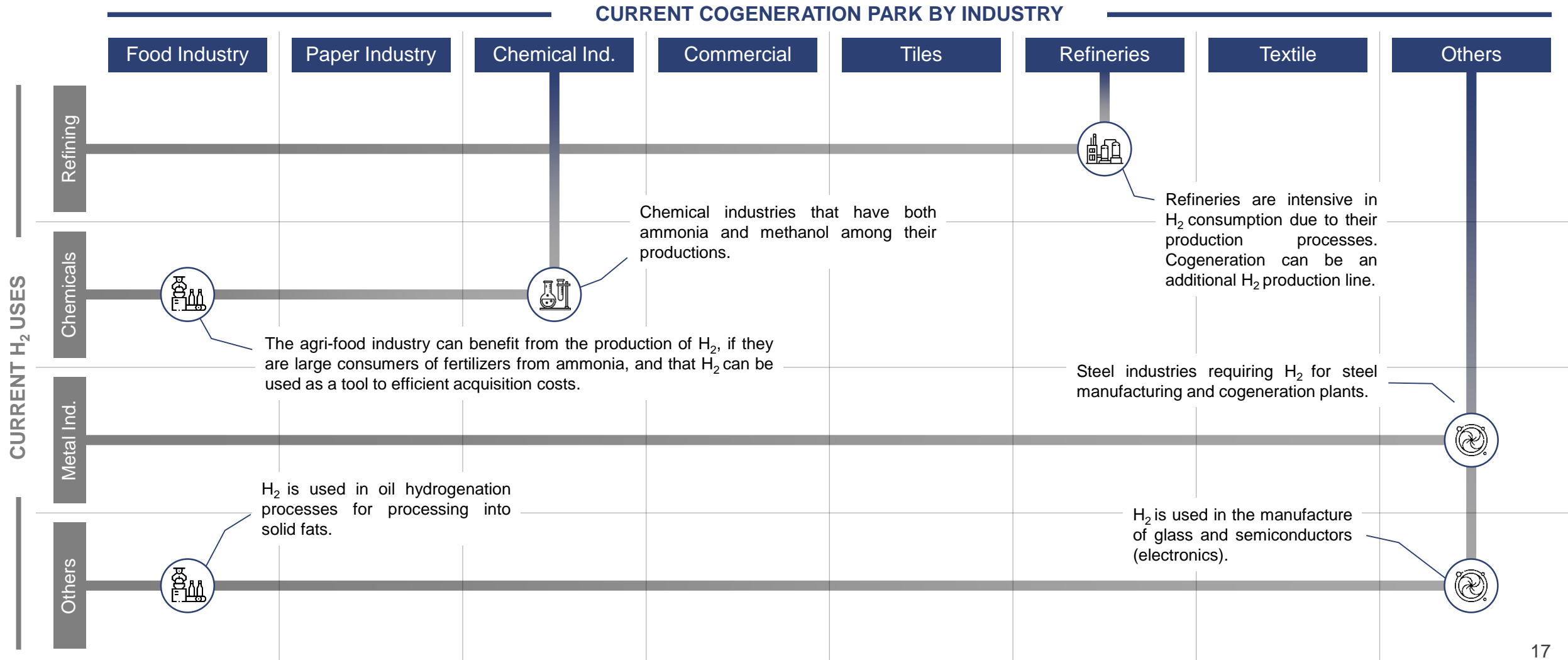
## Current cogeneration park by industry

The cogeneration park in Spain is spread across different industrial sectors. However, the food industry, paper and chemical industry have a great weight in this mix, as they account for approximately 50% of the total installed power.



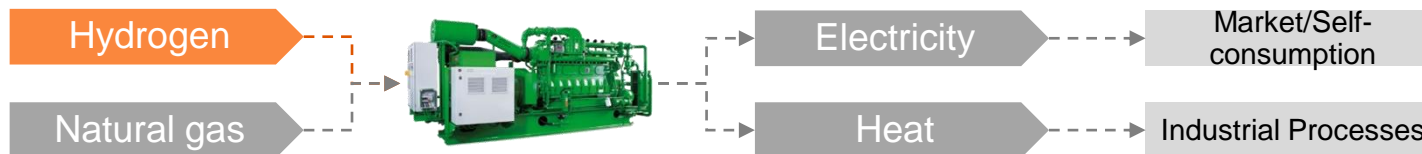
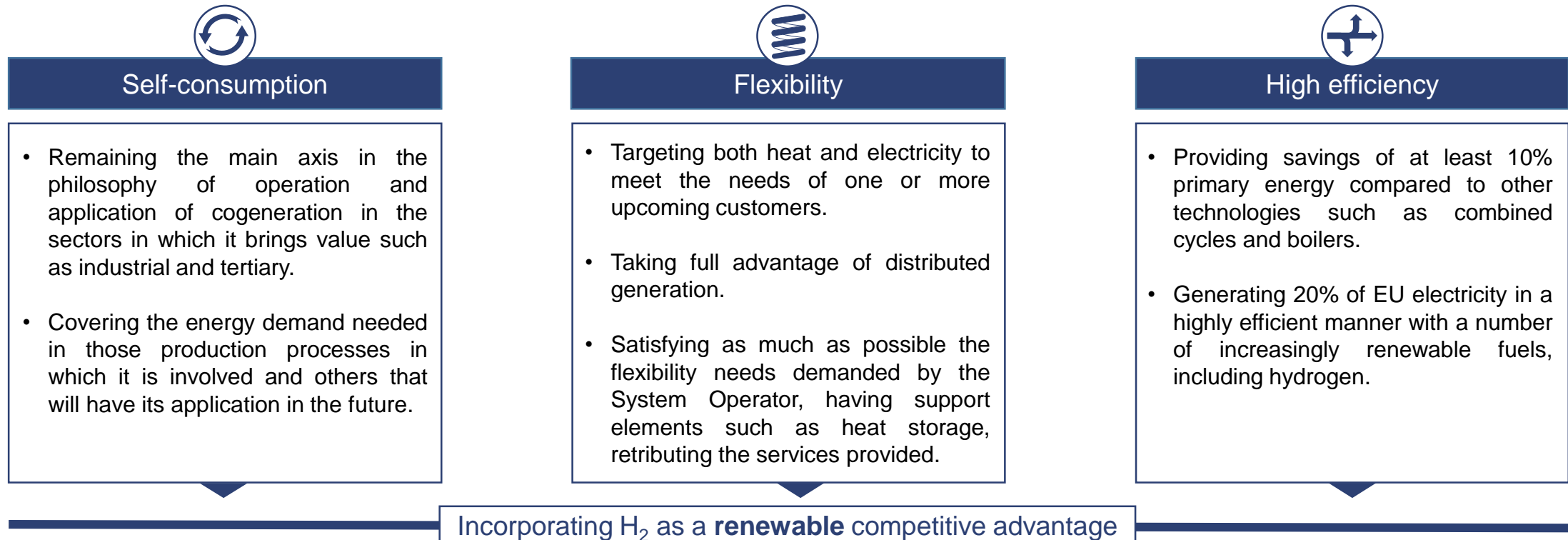
## H<sub>2</sub> synergies in industries that currently cogenerate

Traditional cogenerating sectors that currently consume H<sub>2</sub> can take advantage of synergies between cogeneration and intensive H<sub>2</sub> use, allowing for more aggressive transformation scenarios for their plants.



## Cogeneration value levers – The role of cogeneration in energy transition

In those industrial areas where cogeneration exists, the incorporation of hydrogen as a primary source of energy will provide an advantage that adds to those it already has over other technologies.

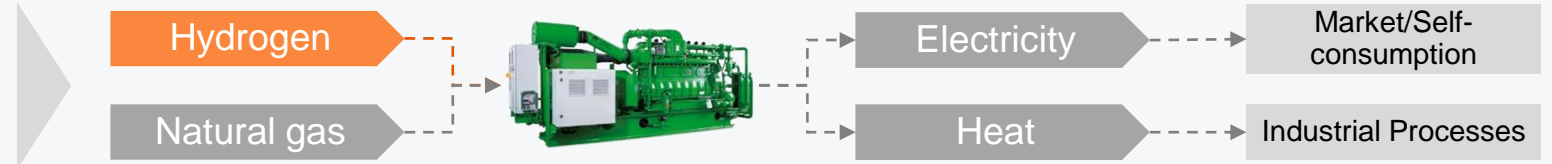


Hydrogen can be used as a substitute fuel for natural gas for heat and electricity production, completely eliminating emissions associated with current cogeneration

## Cogeneration value levers – Renewable H<sub>2</sub> use as fuel

One scenario that can be well received within the cogeneration industry is hybridization in the consumption of natural gas and hydrogen.

Hydrogen can be used as a substitute fuel for natural gas for heat and electricity production



To do this, cogeneration plants must invest in the adaptation or renovation of their plants:

### Necessary Infrastructure

#### 1. Complete renewal

→ Cogeneration plant

Renovating the cogeneration plant, installing an engine/turbine that allows the burning of NG and/or H<sub>2</sub>. **It is currently technologically possible<sup>1</sup>.**

#### 2. Equipment adaption

→ Entry components (valves, pipes, etc.)

→ Turbine/Engine

Adaptation of the current plant to allow cogeneration with natural gas and hydrogen, modifying the main components to enable the burning of both fuels. **It is currently technologically possible<sup>1</sup>.**

On the other hand, the pros and cons identified with respect to this scenario are as follows:

### Pros & Cons

- P** Reducing the carbon footprint of the cogeneration plant, putting the role of cogeneration as a necessary element within the energy mix.
- P** H<sub>2</sub> is seen as a key vector in the energy transition, so there will be subsidies to amortize some of the investment.
- P** Developing a renewable self-consumption facility would mitigate the risk of price exposure in the energy market.
- C** Significant upfront investment
- C** In the current scenario, renewable hydrogen is in an initial deployment phase in which the technology still needs to be developed, and therefore, boosting plans, such as the Recovery, Transformation and Resilience Plan, would be needed.

<sup>1</sup>Explained in detail in part 5: Technologies; <sup>2</sup>IEA (2019): The Future of Hydrogen.

## Main conclusions of the section – H<sub>2</sub> use in the cogeneration setting

H<sub>2</sub> can play a key role in the energy transition, and cogeneration can take advantage of it, thus bringing its competitive advantages to the energy system: self-consumption, flexibility and high efficiency

### H<sub>2</sub> MAY PLAY A RELEVANT ROLE IN THE ENERGY TRANSITION

The different applications of H<sub>2</sub> – industry, mobility, electricity and heat generation, etc. – make this raw material an energy vector that can play a relevant role in the energy transition, because it can be a substitute for both oil and natural gas..

Therefore, the co-generating industry should consider this energy source within its plans for the future, as it would allow it to adapt the design of its plants to the objectives set out in the PNIEC.

### SYNERGIES OF THE H<sub>2</sub> INDUSTRY WITH THE COGENERATIVE PARK

Industries that currently co-generate and are additionally H<sub>2</sub>-intensive (refineries, chemical, food, etc.) can be the key to the development, in the short and medium term, of cogeneration business models that view H<sub>2</sub> as a real alternative.

The success or failure of these business models will determine the feasibility of using H<sub>2</sub> as fuel for cogeneration, thereby enabling the development of high-efficiency renewable cogeneration.

### SCENARIO FOR RENEWABLE COGENERATION TAKING ADVANTAGE OF ITS COMPETITIVE LEVERS

The development of renewable H<sub>2</sub> can be the definitive boost to make the leap to renewable cogeneration, and thus take advantage of all the benefits that this technology brings to the energy system:

- Energy self-consumption for heat generation.
- Providing flexibility at the point of consumption, as well as to the electricity grid.
- High-efficiency technology, helping to meet European energy efficiency targets.



# 03.

## Hydrogen production and logistics models to supply cogeneration plants







Future perspectives for H<sub>2</sub> logistics

Future impact of H<sub>2</sub> logistics on cogeneration

## H<sub>2</sub> logistics – Future perspectives

In the short and medium term, new development and technological improvement fronts are opening up around hydrogen logistics and distribution<sup>(1)(2)</sup>.

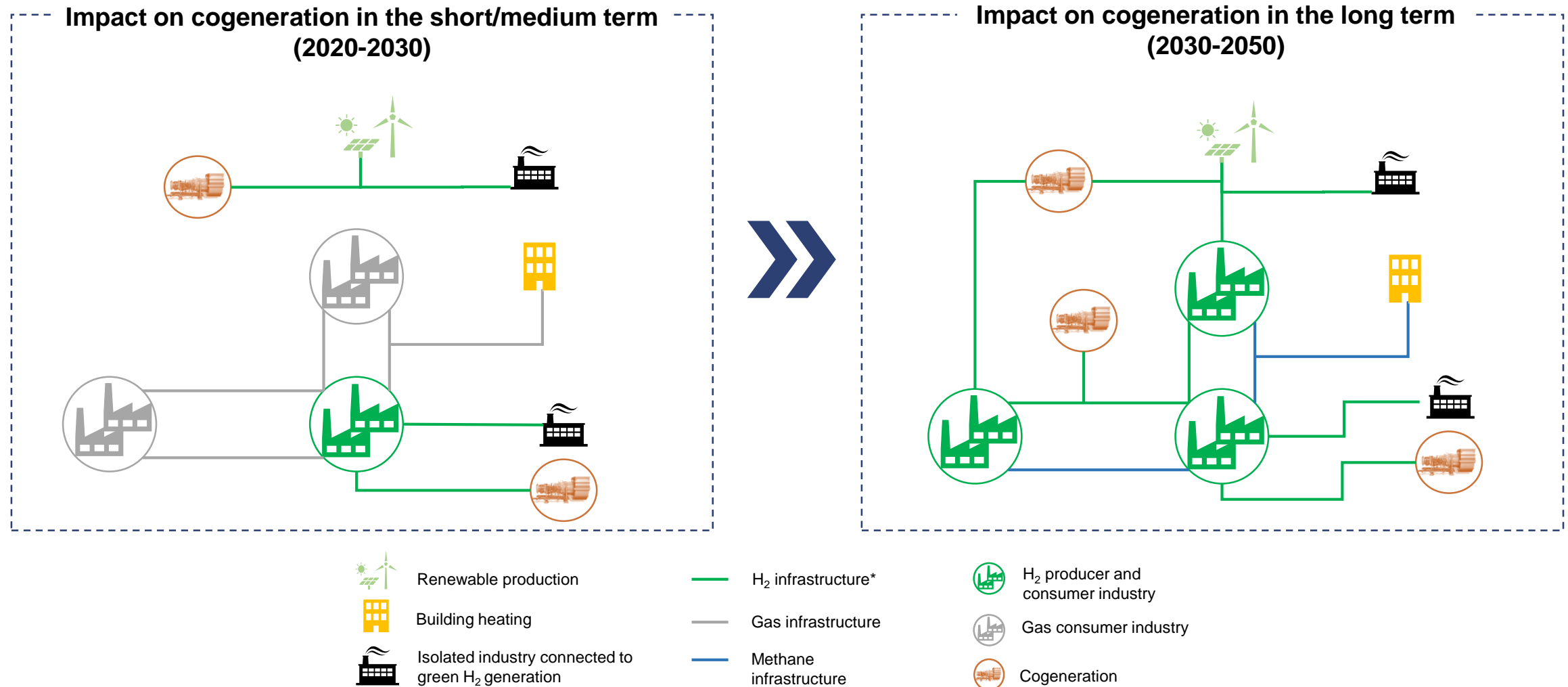
	2025	2030
 <b>Transmission/Transport</b>	<ul style="list-style-type: none"> <li>R&amp;D projects for the development of mixed <b>hydrogen</b> transport in the current <b>network</b> of NG<sup>2</sup>.</li> <li><b>Technological improvement</b> of <b>liquefaction</b> and <b>exhaust losses</b>.</li> </ul>	<ul style="list-style-type: none"> <li><b>Expansion</b> of the hydrogen <b>transport network</b> to meet the <b>demand</b> for <b>new typologies</b> of hydrogen service points (<b>cogenerations</b>, local industries, etc.)</li> </ul>
 <b>Distribution</b>	<ul style="list-style-type: none"> <li><b>Improving compressor efficiency</b> (&gt;88%).</li> <li><b>Feasible conversion</b> of <b>low-pressure natural gas pipelines</b> to run on hydrogen (H<sub>2</sub>).</li> </ul>	<ul style="list-style-type: none"> <li><b>New generation</b> of road transport with liquid H<sub>2</sub>.</li> <li><b>Improvements</b> in the <b>capacity</b> of tubular trailers (1,500 kg) and <b>pressure</b> (700 bar) with CAPEX optimization.</li> </ul>
 <b>Storage</b>	<ul style="list-style-type: none"> <li><b>Research</b> projects to <b>couple large-scale storage</b> with energy applications such as <b>seasonal storage</b>.</li> </ul>	<ul style="list-style-type: none"> <li>First large-scale storage caverns in operation for cost-cutting energy storage applications (about one-third).</li> </ul>
 <b>Hydrogen carriers</b>	<ul style="list-style-type: none"> <li>Liquefaction improvements that allow the transport of cryogenic containers.</li> <li><b>Technical-economic research</b> on different hydrogen <b>carriers</b> and how they affect distance scales.</li> </ul>	<ul style="list-style-type: none"> <li>First commercial liquid hydrogen projects (shipping).</li> <li><b>Improvements</b> in carrier <b>conversion/reconversion efficiency</b> (&gt;90%), and <b>cost reduction</b> (0,82 €/kgH<sub>2</sub>)</li> </ul>

**Hydrogen management and logistics technologies are not yet mature enough in terms of efficiency and costs. Large-scale storage, shipping or long-distance pipeline transmission are expected to reach commercial viability by 2030.**



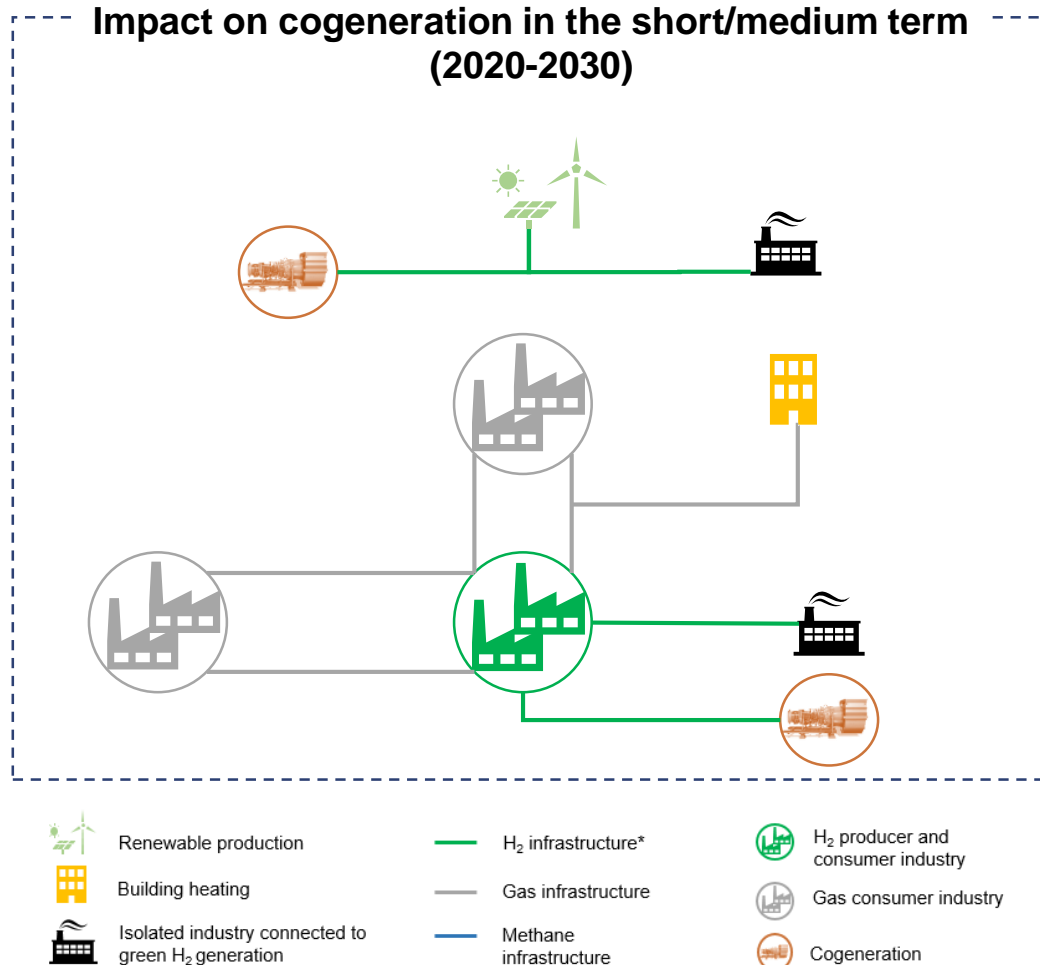
## H<sub>2</sub> logistics – H<sub>2</sub> logistics impact on cogeneration

The roadmap established at European level for the transformation of current gas logistics into new alternative fuels such as H<sub>2</sub> or biomethane, allows the presence and activity of cogeneration.



## H<sub>2</sub> logistics – H<sub>2</sub> logistics impact on cogeneration

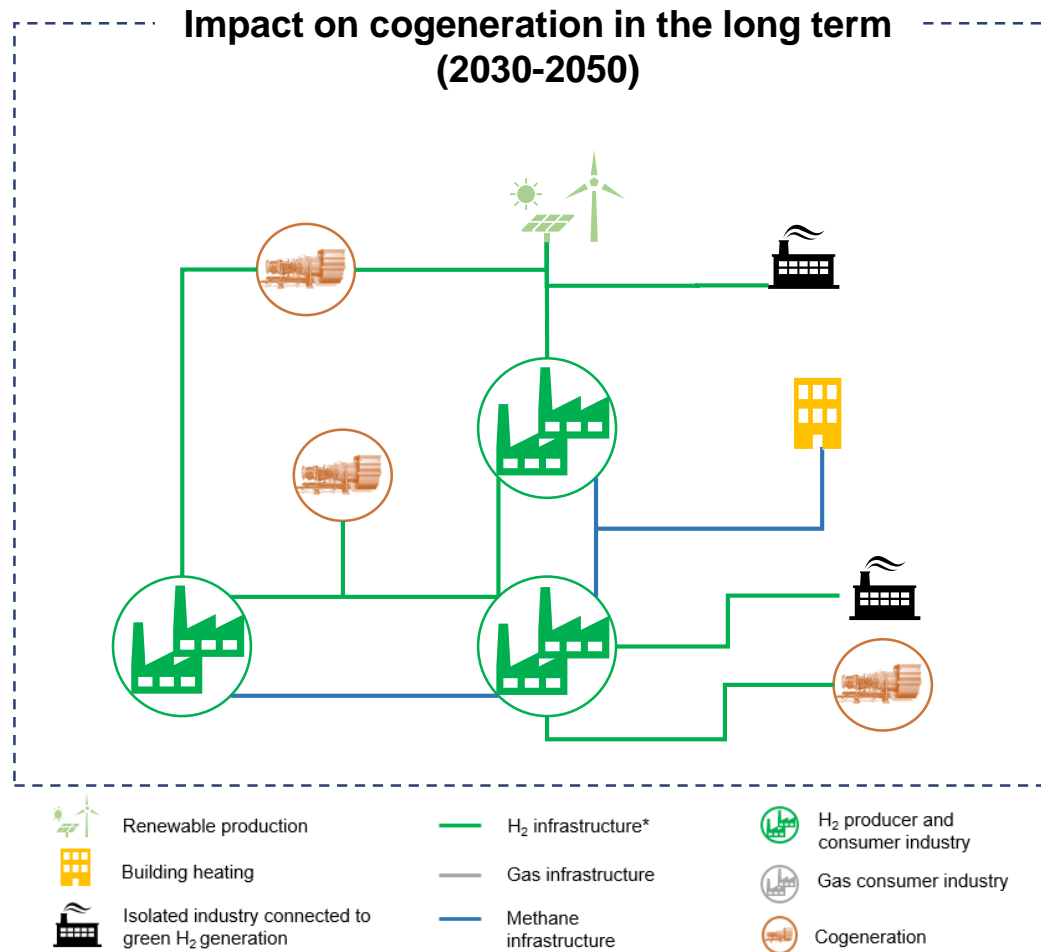
A short-term scenario proposes a hybrid model with a predominant presence of natural gas, albeit with an increasing presence of renewable hydrogen



- 1 A fledgling green hydrogen scenario in which local point industries consume H<sub>2</sub> in place of Gas, **including those linked to cogeneration**. Need to connect industrial cores with new hydrogen production points (wind farms and photovoltaic farms).  
  
Predominant natural gas distribution network but with local developments dedicated to H<sub>2</sub>.
- 2 By 2030 **hydrogen infrastructure** is expected to begin to **develop at regional and/or national levels**, possibly first in north-western Europe and then elsewhere in Europe (central and southern). Planning for these infrastructures should begin during the early years of the decade (2020-2030).
- 3 Production of **cogeneration and hydrogen projects** (mixed with natural gas) using existing, and some (local) dedicated networks that could have been developed.  
  
By 2030, cogeneration will be able to cost-effectively generate 20% of EU electricity with renewable fuels such as H<sub>2</sub>, resulting in additional savings of 78 million tons of primary energy and an additional reduction of 350 million tons of CO<sub>2</sub><sup>2</sup>.

## H<sub>2</sub> logistics – H<sub>2</sub> logistics impact on cogeneration

At a medium- and long-term horizon, European gas TSOs estimate that hydrogen networks will be much more mature allowing access to them to industry and other sectors such as tertiary and residential<sup>1</sup>



- 1 By **2050**, it is estimated that just over **1,700 TWh** of renewable **hydrogen** will circulate through **Europe's transport and distribution networks**. Currently about 5,000 TWh of natural gas flow. **Industrial cores** will be **more connected** to each other through dedicated local and national **hydrogen networks**. There will therefore be greater access to hydrogen by **cogeneration**, as well as the industry that uses it, the tertiary and residential sector.
- 2 **Increased share of renewable electricity** generation for green **hydrogen** production. Which can be transported more easily due to the increased maturity of the adaptive state of European gas networks.
- 3 **Transporting** this entire amount of hydrogen will **require more pipe capacity** per unit of energy compared to natural gas, as a hydrogen energy unit has approximately 3 times more volume than methane.
- 4 **High-efficiency cogeneration** can **generate** between **13 and 16% of electricity** and between **19 and 27% of the total heat** demanded in the US as part of an efficient, integrated and cost-effective zero net energy system. This would ensure **energy savings of between 170 and 220 TWh**, **supporting power grids and ensuring intelligent integration of heat, electricity and gas networks**. This would save between 4 and 8 billion euros in system energy costs across the EU<sup>2</sup>.

**Large quantities of natural gas will continue to be transported through European gas networks in the short term, but from 2030 their prominence will decline rapidly and progressively to the detriment of other renewable gases such as H<sub>2</sub> or biomethane. This will facilitate access to it for technologies such as cogeneration.**

## Main conclusions of the section – H<sub>2</sub> Production and logistics for cogeneration

H<sub>2</sub> can play a key role in the energy transition, and cogeneration can take advantage of this by contributing its competitive levers to the energy mix: self-consumption, flexibility and high efficiency.

### SCENARIOS FOR RENEWABLE COGENERATION FUELLED BY A CHANGING LOGISTICS MODEL

In the short term, the proposed European logistics model will allow certain volumes of renewable hydrogen to be injected and transported through existing natural gas networks. This will allow cogeneration to progressively replace its current main fuel (natural gas), thereby contributing to the EU's objective of decarbonizing industry.

In the long term, it is expected that European and national development policies will allow developments and reforms to be undertaken that will enable an increasingly exclusive network of H<sub>2</sub> and other renewable gases (biomethane) to be established.



# 04.

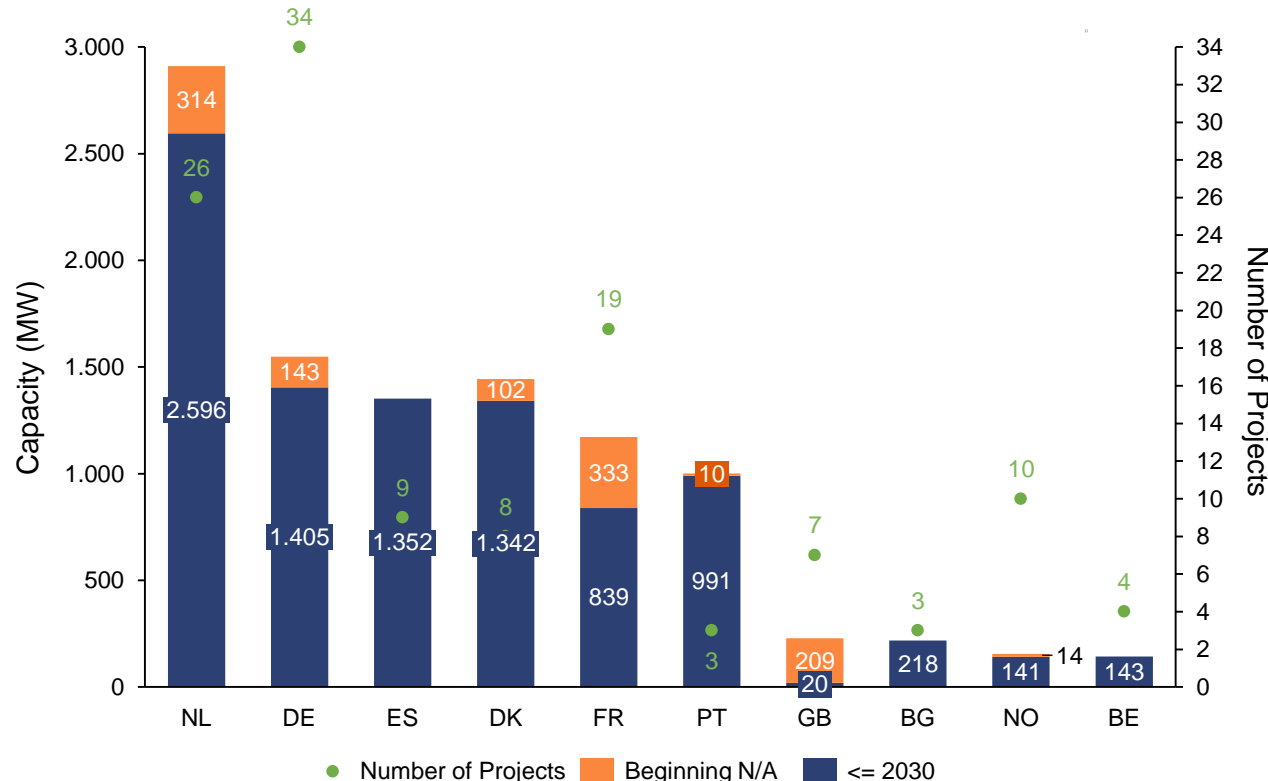
## Analysis of currently available technologies

- Major European H<sub>2</sub> projects in cogeneration and other parts of the value chain
- Technologies available for cogeneration with H<sub>2</sub>

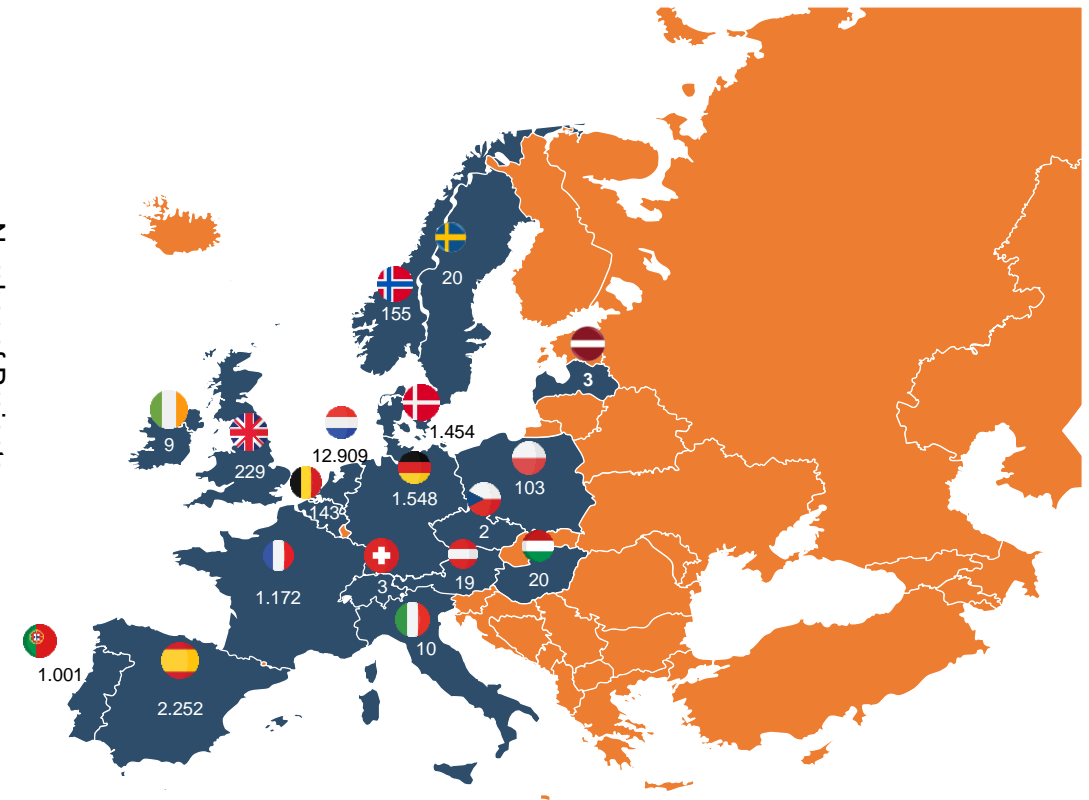
## European hydrogen projects for the 2020 - 2040 horizon<sup>1</sup>

At European level, there is significant momentum on the part of most countries to develop new renewable hydrogen production initiatives. Spain is among the most committed.

"Power to Hydrogen" projects planned for 10 countries in Europe on the horizon 2020-2030



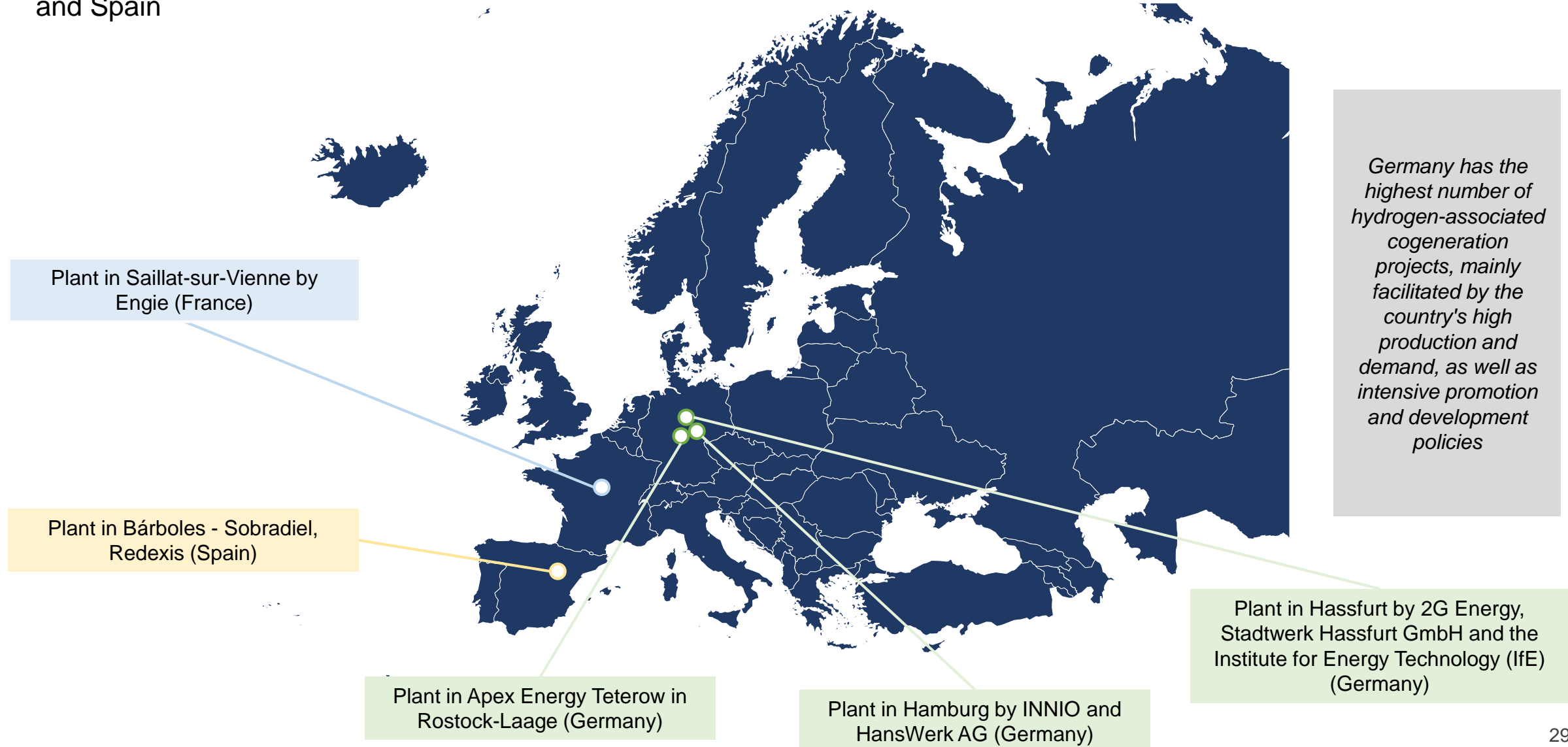
Map of new projects to produce green hydrogen by country (MW) (2020-2040)



**Six countries plan to install more than 1 GW of hydrogen production by 2030, among them Spain**

## European cogeneration projects with H<sub>2</sub>



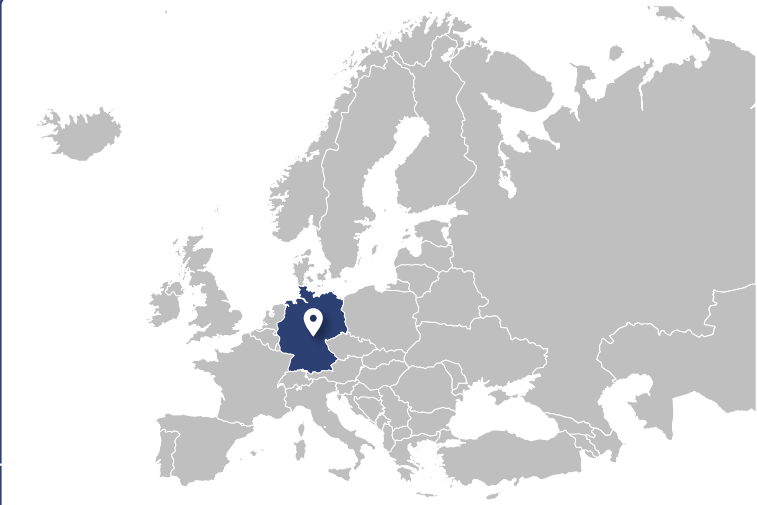
Regarding the use of hydrogen in cogeneration, the most relevant projects at European level are in Germany, France and Spain








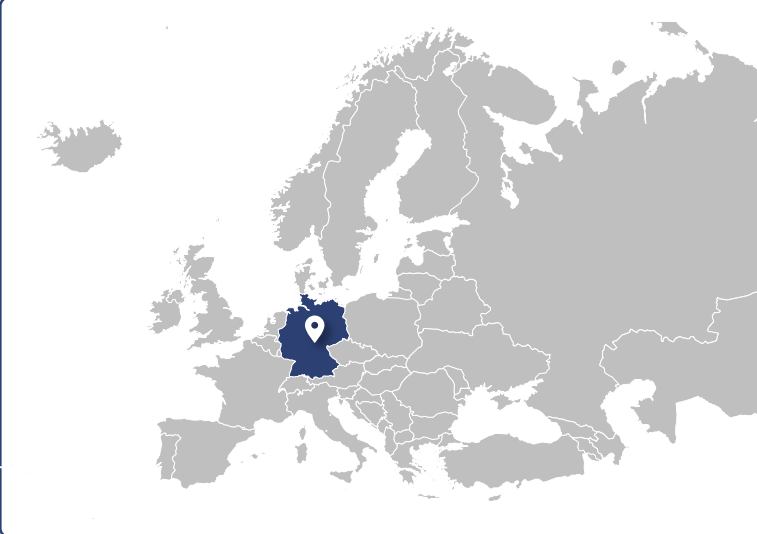


## European cogeneration projects with H<sub>2</sub> – Germany (1/3)

Today there are numerous hydrogen cogeneration projects and for the rest of the value chain. Here are some examples of the highlights.

Project	Technology	Partner entities
Plant in Rostock-Laage, Germany	Hydrogen cogeneration	 
Project Description		Project Location
<ul style="list-style-type: none"> <li>Electricity and heat production plant from renewable hydrogen. It consists of a 2 MW fuel cell, a storage tank, a combined heat and electricity production plant and a stabilizing battery.</li> <li>2G Energy supplies innovative hydrogen cogeneration unit to Apex Energy Teterow in Rostock-Laage, Germany.</li> <li>The highlight of this hydrogen cogeneration plant is that it can run on pure hydrogen without any fossil fuel. However, 2G Energy states that it can also work with a mixture of hydrogen and natural gas, as well as pure natural gas. This increases the operational flexibility of cogeneration.</li> <li>Project cost of €2 million.</li> </ul>		
Financing sources		Other relevant information
<div>Own financing on behalf of both companies</div>		<ul style="list-style-type: none"> <li>Production: <ul style="list-style-type: none"> <li>115 kWh of electricity</li> <li>129 kWh of thermal energy</li> </ul> </li> </ul>



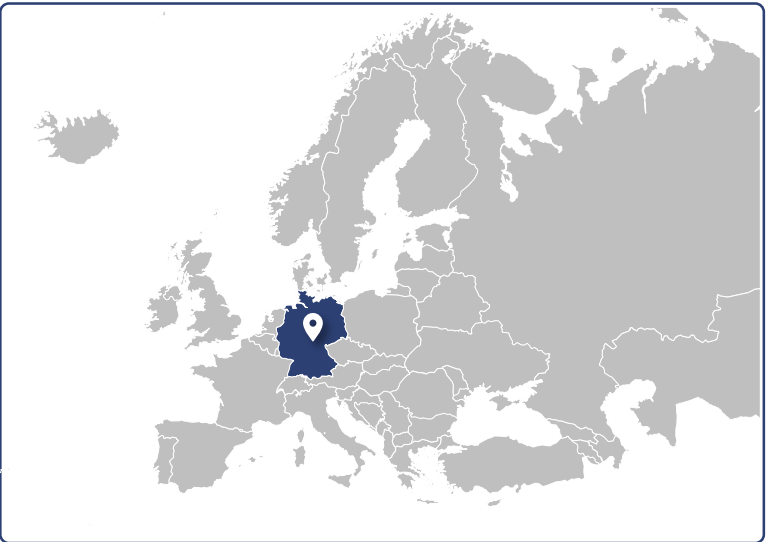
## European cogeneration projects with H<sub>2</sub> – Germany (2/3)

Today there are numerous hydrogen cogeneration projects and for the rest of the value chain. Here are some examples of the highlights. (Cont.)

Project	Technology	Partner entities	
Plant in Hassfurt, Germany	Hydrogen cogeneration		 
Project Description		Project Location	
<ul style="list-style-type: none"> <li>Stadtwerk Hassfurt GmbH project with funding from the Bavarian Ministry of Economic Affairs, Regional Development and Energy (StMWi).</li> <li>The existing gas energy conversion plant in Hassfurt was expanded to include a highly innovative block-type hydrogen thermal power plant (H<sub>2</sub>-BHKW). The module has already been successfully launched.</li> <li>The new cogeneration plant <b>allows to operate with pure hydrogen without fossil fuel components</b>, in contrast to the previous practice of adding hydrogen to the natural gas network with reverse power generation through conventional cogeneration units.</li> </ul>			
Financing sources		Other relevant information	
 Bundesministerium für Wirtschaft und Energie  Bavarian Ministry of Economic Affairs, Regional Development and Energy		<ul style="list-style-type: none"> <li>Production: 200 kW<sub>e</sub></li> </ul>	











## European cogeneration projects with H<sub>2</sub> – Germany (3/3)

Today there are numerous hydrogen cogeneration projects and for the rest of the value chain. Here are some examples of the highlights. (Cont.)

Project	Technology	Partner entities	
Plant in Hamburg, Germany	Hydrogen and gas cogeneration (can work at 100% with both)	 	
Project Description		Project Location	
<ul style="list-style-type: none"> <li>INNIO, an Austrian-based energy solutions provider, has partnered with HanseWerk AG, a German energy service provider, to deliver a <b>1 MW hydrogen-powered electricity and heat cogeneration</b> pilot plant in central Hamburg, Germany.</li> <li>The pilot began operating with natural gas during the spring of 2020 and then, throughout the summer, switch to using a green gas network operating the cogeneration plant with increasing hydrogen levels up to 100%, thus testing its operational flexibility.</li> <li>The converted cogeneration plant provides 30 residential buildings, a sports center, a nursery and a leisure complex (Othmarschen Park) with a reliable supply of heating equivalent to 13,000 MWh each year. Some of the electricity generated is supplied to the electric vehicle charging points in the leisure complex car park, as well as to the local electricity grid.</li> </ul>			
Financing sources		Other relevant information	
<div>Own financing on behalf of both companies</div>		<ul style="list-style-type: none"> <li>Installed power: 1 MW</li> </ul>	






## European cogeneration projects with H<sub>2</sub> – France

Today there are numerous hydrogen cogeneration projects and for the rest of the value chain. Here are some examples of the highlights. (Cont.)

Project	Technology	Partner entities
Plant in Saillat-sur-Vienne, France	Hydrogen and Gas Cogeneration	     
Project Description		Project Location
<ul style="list-style-type: none"> <li>European HYFLEXPOWER project. Consortium consisting of ENGIE Solutions, Siemens Gas and Power, Centrax, Arttic, the German Aerospace Centre (DLR) and four European universities. Siemens is the entity responsible for coordinating the project.</li> <li>It aims to demonstrate that hydrogen can be produced and stored from renewable electricity, and then added up to 100% to the natural gas currently used with combined heat and energy (CHP) plants. This also saves 65,000 t of CO<sub>2</sub> per year emitted into the atmosphere.</li> <li>The installed demonstrator will be used to store excess renewable electricity in the form of green hydrogen. To do this, an existing Siemens SGT-400 industrial gas turbine will be upgraded to convert stored hydrogen into electricity and thermal energy.</li> </ul>		
Financing sources		Other relevant information
<p>The total budget of the project is around EUR 15.2 million, of which EUR 10.5 million will be contributed entirely by the European Union under the Horizon 2020 programme:</p>   		<ul style="list-style-type: none"> <li>Installed power: 12 MWe</li> </ul>

## European cogeneration projects with H<sub>2</sub> – Spain

Today there are numerous hydrogen cogeneration projects and for the rest of the value chain. Here are some examples of the highlights. (Cont.)

Project	Technology	Partner entities
Plant in Bárboles-Sobradriel, Spain	Hydrogen cogeneration at small scale	 
Project Description		Project Location
<ul style="list-style-type: none"> <li>Pioneering project installing a hydrogen fuel cell, supplied by Viessmann, for the generation of electricity and heat in a Regulation and Measurement Station (ERM) of the pipeline network, in this case in the Bárboles-Sobradriel pipeline (Zaragoza).</li> <li>The objective of the project is to analyze the feasibility of a technology based on the use of hydrogen for the generation of electricity and thermal energy, as a step prior to its overall implementation in Theexis gas transport and distribution facilities, with the ultimate aim of reducing the environmental impact of the company's activities and its carbon footprint.</li> <li>In addition, it also seeks to test this technology under variable conditions of use, simulating its operation under the energy conditions and needs that could be given in domestic and tertiary uses.</li> </ul>		
Financing sources		Other relevant information
Research & Development Project (PID in Spanish) financed by:   Centro para el Desarrollo Tecnológico Industrial		<ul style="list-style-type: none"> <li>Installed power: n/d</li> </ul>

## Technologies available for cogeneration with H<sub>2</sub>

Currently, there are practically no limitations to H<sub>2</sub> consumption in cogeneration turbines, apart from those already mentioned, unlike transport and distribution, which do constitute a major barrier to the sector's evolution towards H<sub>2</sub>.

### Mixed combustion solutions (turbines) (1/2)



- GE's current turbine portfolio offers different capacities in terms of percentages of hydrogen volume mixed with natural gas.
- Air turbines** with SAC combustor can **burn up to 95% hydrogen, class B/E** depending on technology, up to **100%**.



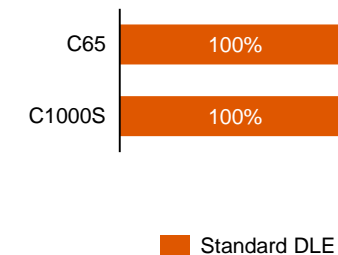
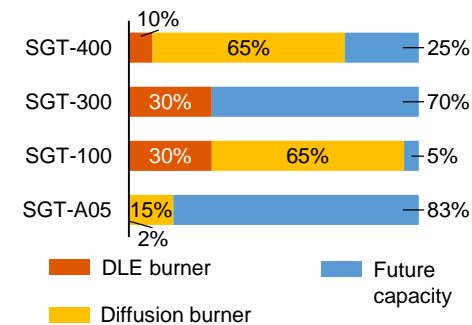
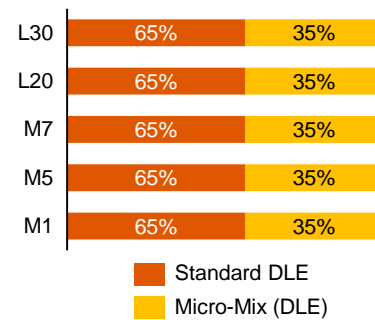
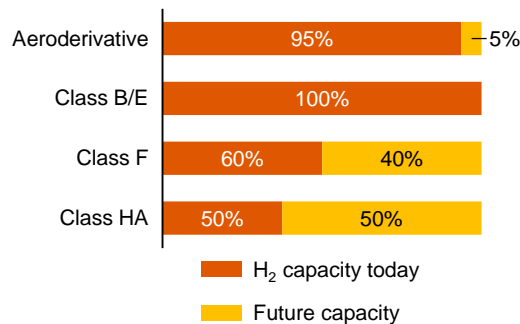
- Currently** offers turbines capable of consuming H<sub>2</sub> mixed with NG at **up to 65% volume using standard DLE burners**.
- The same turbines, on the other hand, have the **capacity** to consume **up to 100% H<sub>2</sub> volume using Micro-Mix burner technology (DLE)**.



- Turbines **capable of operating with mixture of hydrogen and other gases** up to the proportion of **10%** volume for hydrogen (with DLE burners), or up to 65% with diffusion burners.
- Great operational flexibility** as they allows **automatic switching from primary to secondary fuel** on any load.



- Offers **hydrogen microturbines** as a more cost-competitive hydrogen solution, **performing as well as or better** than other traditional fuels.
- The combined heat and power (CHP) capability offers further advantages compared to fuel cells.



**Turbine technology is currently not a barrier for cogeneration to use hydrogen in its processes.**



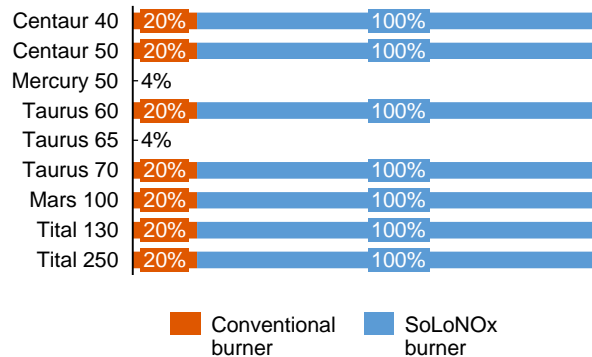
## Technologies available for cogeneration with H<sub>2</sub>

Currently, there are practically no limitations to H<sub>2</sub> consumption in cogeneration turbines, apart from those already mentioned, unlike transport and distribution, which do constitute a major barrier to the sector's evolution towards H<sub>2</sub>.

### Mixed combustion solutions (turbines) (2/2)

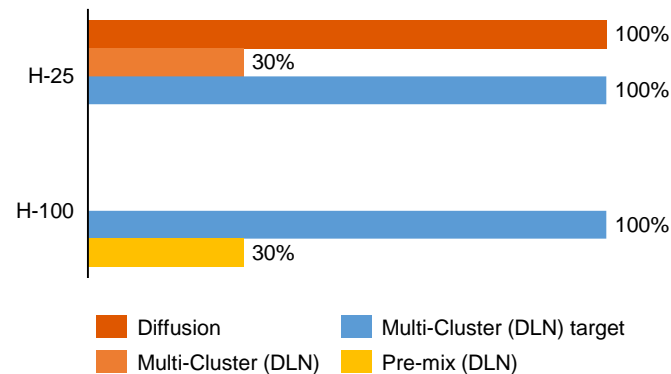
#### Solar Turbines A Caterpillar Company

- Feature **turbines** tested for **20% H<sub>2</sub> mix** for low-emission equipment (DLE or SoLoNOx).
- For projects requiring **100% H<sub>2</sub>**, this would be covered by **conventional combustion equipment (Diffusion combustion)**.



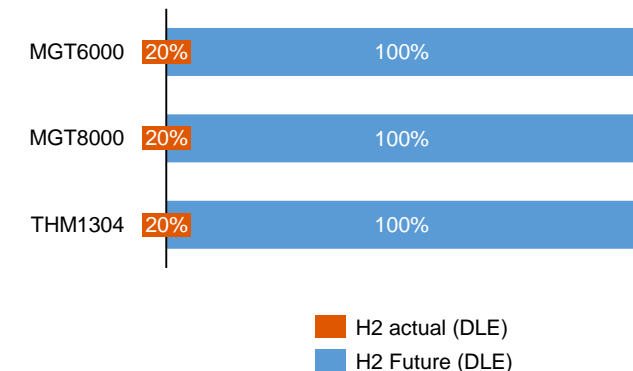
#### MITSUBISHI POWER

- Mitsubishi Power's gas **turbines** can now **accept** different ratios of **H<sub>2</sub> as fuel**.
- Depending on the **type of combustion chamber**, the **mixing volumes** of **H<sub>2</sub> and NG** vary between **30% and 100%**.



#### MAN Energy Solutions

- Features **turbines ready** to run at **20% H<sub>2</sub> by volume** without modifications, maintaining power, efficiency and **ultra-low emissions** (NOx < 9 ppm / CO<sub>2</sub> < 16 ppm). Higher hydrogen percentages are possible with minor modifications.
- In the near future it is expected to achieve **100% H<sub>2</sub> by volume** without modifying the turbine body.











**Turbine technology is currently not a barrier for cogeneration to use hydrogen in its processes.**



**Technologies available for cogeneration with H<sub>2</sub>**

Cogeneration engines also currently have no limitations on H<sub>2</sub> consumption in different volumes. The status and availability of the technology associated with the main national suppliers is shown below:

**Mixed combustion solutions (motors)**

Manufacturer	Pure H <sub>2</sub>	H <sub>2</sub> and NG mix			
		< 10%	< 25%	< 40%	< 60%
	✗		✓		
	✗				✓
	✓				✓
	✗		✓		
	✓		✓		
	✗			✓	
	✓	✓	✓	✓	✓
		✓	✗		

✓ Available  
✗ In Development

**Engine technology today does not constitute a barrier to cogeneration being able to use hydrogen in its processes.**

## Main conclusions of the section – Projects and current state of the cogeneration with H<sub>2</sub>

At European level and at national level through each of its member countries, a significant number of hydrogen projects are being promoted, also applied to cogeneration and its possibilities for future use

### HYDROGEN PROJECTS' DRIVING HORIZON

Motivated by the development of various strategic plans established at European and national level, over the next three decades it is intended to carry out a significant number of projects related to renewable H<sub>2</sub>, spread across all links in its value chain.

In the field of cogeneration, its planning is more discreet, although there are also projects to this day, especially in Central Europe (Germany), which will motivate the design and implementation of new initiatives across the continent (including Spain) for the future.

### CURRENT TECHNOLOGY AVAILABLE TO COGENERATION IS NOT A BARRIER TO H<sub>2</sub>

A wide variety of suppliers of technology associated with cogeneration, engines and turbines mainly present today technological solutions that are compatible to a greater or lesser extent with hydrogen.

In this sense there is also a significant room for improvement that will undoubtedly further facilitate access to and widespread use of this renewable gas by cogeneration in the future.



# 05.

## Main barriers and benefits in the hydrogen market for cogeneration

- Identification of potential barriers to the development of cogeneration in the hydrogen context (economic, technological and regulatory).
- Main benefits of cogeneration using renewable hydrogen

## Existing barriers in the H<sub>2</sub> market for cogeneration

Integrating H<sub>2</sub>, within cogeneration currently presents a number of barriers and opportunities, which we can classify into three large groups:



### ECONOMIC

- **Production Cost of H<sub>2</sub> (LCOH).** Current state and prospects for evolving production costs of renewable hydrogen and its competitiveness with the other types of hydrogen (grey and blue).
- **Levelled cost of energy (LCOE).** Competitiveness of energy cost compared to that produced by different technologies of cycle turbines and cogeneration, using natural gas and hydrogen.



### TECHNICAL

- **Blending or Hydrogen Injection in the current gas grid.** Current situation of the technical feasibility of transporting hydrogen mixed with natural gas in European networks to supply cogeneration, among others.
- **Transport & Distribution.** Other barriers and conditions associated with the transport and distribution of hydrogen and its challenges for the future.



### REGULATORY

- **Market creation politics.** Different facilitating mechanisms for hydrogen penetration in European energy markets.
- **Infrastructure regulations.** Regulation initiatives that are lacking to be developed at European and above all national level.
- **Norms and Certifications** that allow to boost renewable hydrogen by promoting its contribution towards decarbonization in the national energy sector (green certificates).

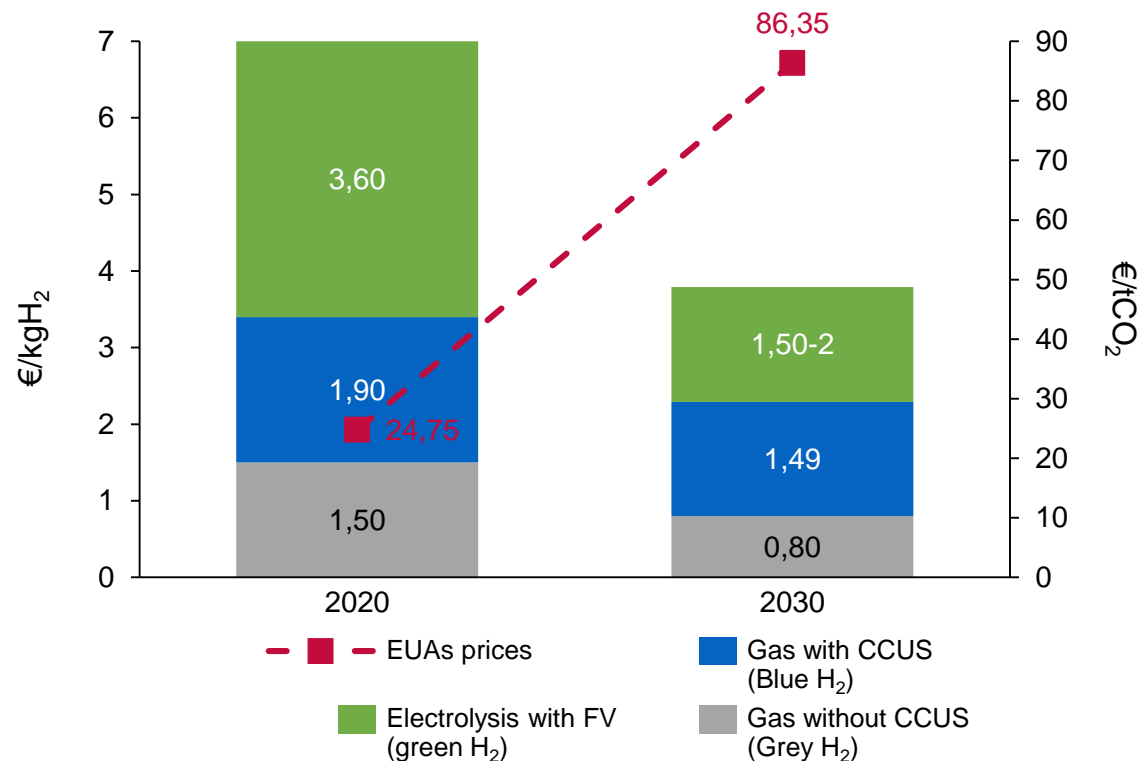
Opportunities and  
Competitiveness levers

## Economic barriers to the development of H<sub>2</sub> – H<sub>2</sub> production cost

Hydrogen production cost varies significantly between different regions, as it depends to a large extent on the prices and availability of energy inputs needed for the process.

### H<sub>2</sub> Production Cost (LCOH)

Comparison of the Level Cost of Production of Renewable Hydrogen (electrolysis) from FV generation in Spain with respect to hydrogen of fossil origin, and price of CO<sub>2</sub><sup>2</sup>, 10-year estimation (2020)<sup>1</sup>



- The entry of **renewable energies** (mainly wind and solar photovoltaic) are playing today and will continue to do so over the next 10 years, an **essential role in lowering the production costs of green H<sub>2</sub>**, with the estimated that by 2030 its cost is around 1.5 – 2 €/kg, matching that of blue and grey H<sub>2</sub>.
- Electrolysis** is an increasingly **technologically evolving process** and also its **costs**, which will be **progressively** and continuously **reduced** thanks to the **larger-scale production** of electrolytes and the **increase in generation capacity** (greater systems).
- In Europe, it is estimated that the **cost of producing low-carbon hydrogen and CCUS**, which today (2020) is 1.9 €/kg, **will decrease over the decade** to around 1.5€/kg by 2030, due to **the lower cost of carbon capture and storage options**.
- Forecasting **upward developments in CO<sub>2</sub> prices** will facilitate the use of **green hydrogen for decarbonization** in many **industries** and sectors that currently use fossil sources such as natural gas or other more competitive types of hydrogen today (grey and blue).

**Green hydrogen has great potential for improvement** to reach and even improve future **cost levels** where other non-renewable hydrogen production technologies are located

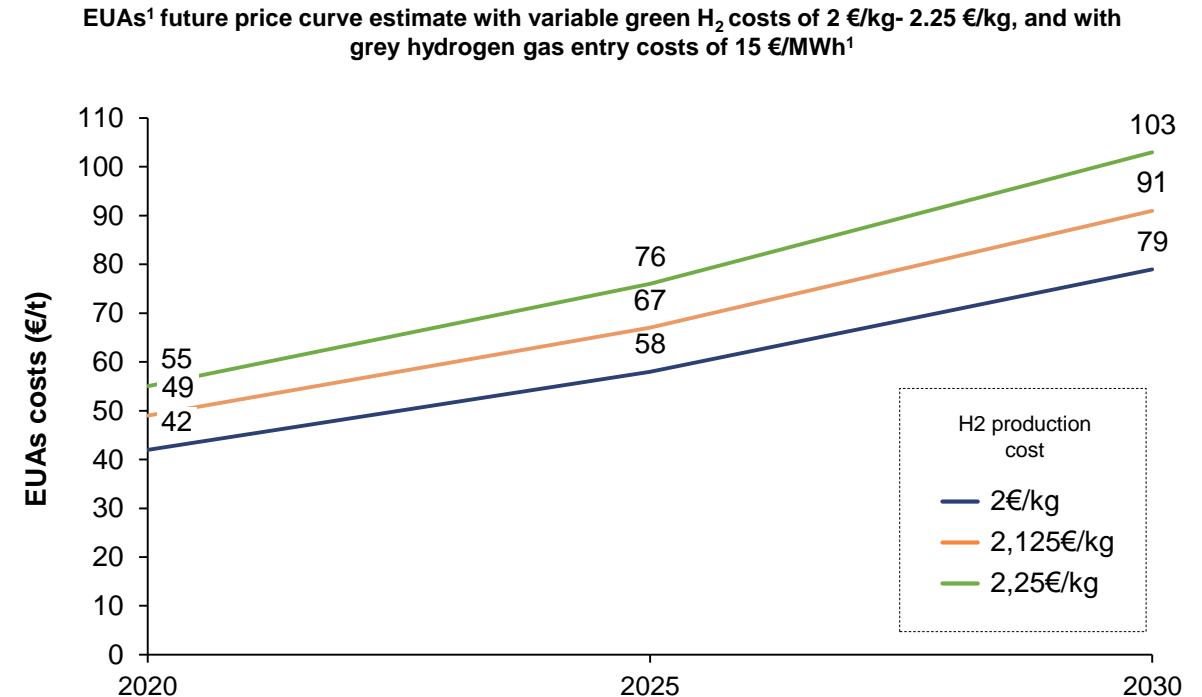
**Sources:** <sup>1</sup>HYDROGEN EUROPE (oct-2020): Clean Hydrogen Monitor 2020. Hydrogen Council (Jun-2020): Path to hydrogen competitiveness: A cost perspective. Note: Average H<sub>2</sub> production costs with and without average CCUS for Europe. Michel Noussan , Pier Paolo Raimondi , Rossana Scita and Manfred Hafner (2021). The Role of Green and Blue Hydrogen in the Energy Transition—A Technological and Geopolitical Perspective. Average H<sub>2</sub> production costs at European level without considering storage, transport and distribution.

<sup>2</sup>BNP PARIBAS ASSET MANAGEMENT (Oct-2020): Green Hydrogen, Net Zero, and the Future of the EU-ETS. Factor CO<sub>2</sub>.

## Benefits of cogeneration using renewable hydrogen – CO<sub>2</sub> cost savings

As seen previously, it is likely that green hydrogen will gain competitiveness through CO<sub>2</sub> price, since other fossil origin hydrogen (grey and blue) cheaper to produce, will have to confront higher costs due to the emissions and catch of CO<sub>2</sub>, respectively.

- Currently, the EU produces about 8.2 Mt of hydrogen, most of which are obtained through the steam and methane reforming (SMR) process using natural gas (grey hydrogen). The problem with the SMR process, however, is that it is highly carbon intensive, with 9 kg of CO<sub>2</sub> produced per kg of hydrogen. This equates to 0.27 tCO<sub>2</sub>/MWh.
- Replacing this current production with green hydrogen generated from electrolysis and renewable energy, EU-ETS emissions would be reduced by 2030 by 80-90 MtCO<sub>2</sub>/year (equivalent to 6% of total EU-ETS emissions in 2019).
- According to verified sources, for three different scenarios of renewable H<sub>2</sub> production costs in 2030 (2 €/kg; 2.125 €/kg and 2.25 €/kg), the price for EUAs would be between 79 and 103 €/tCO<sub>2</sub> (see graph).
- **Under these three price scenarios for 2030, the estimated emissions savings from replacing grey hydrogen production in the EU with green hydrogen would amount to €6.32 - €9.27 billion.**

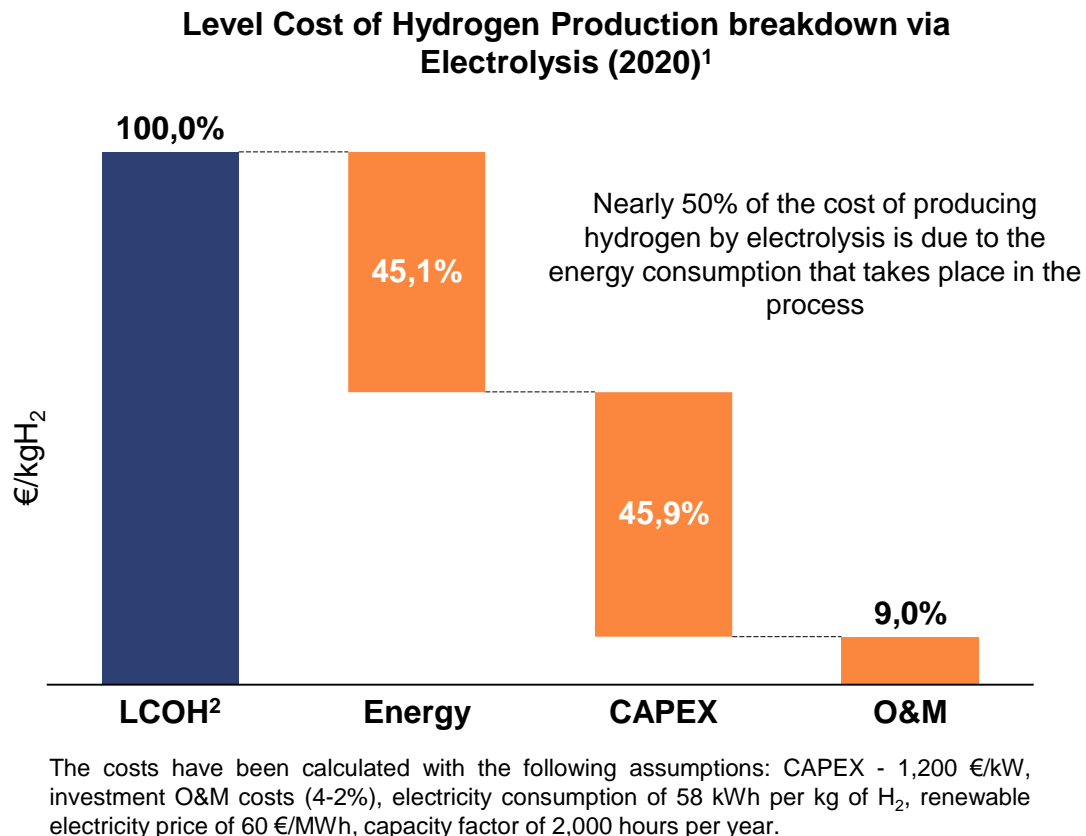


**With these price forecasts for CO<sub>2</sub>, over the next decade the cost competitiveness of renewable H<sub>2</sub> will be reinforced by the increase in costs associated with other technologies that generate emissions.**

## Economic barriers to the development of H<sub>2</sub> – H<sub>2</sub> production cost breakdown

Despite their availability and maturity in the market, PEM and alkaline electrolytes continue to be considered very expensive, both from the point of view of capital expenditures and operating expenses, compared to the production of hydrogen from fossil fuels.

### H<sub>2</sub> Production Cost (electrolysis)



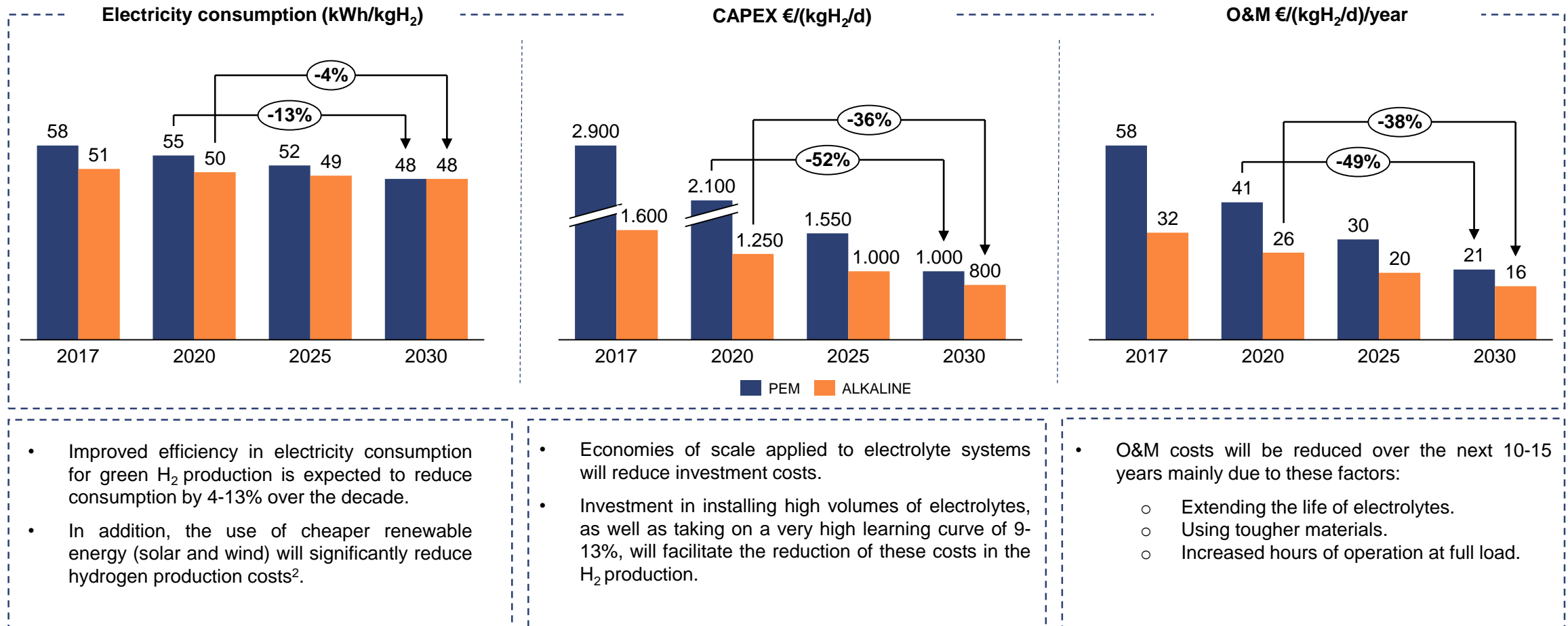
- **CAPEX together with electricity consumption is the largest cost item (45.9%)** and includes the electrolyte (with all the auxiliary systems necessary for its operation) along with the civil works needed to deploy the hydrogen production plant.
- Operation and maintenance (**O&M**) includes all **variable operating costs of the hydrogen production plant**, excluding energy costs. Typically, the O&M costs of electrolytes range from 4% to 2% of the total CAPEX of the electrolyte (depending on the size).
- The **key points** needed to improve **competitiveness** are **reducing the cost of electrolytes and improving their efficiency**, with **high durability and reliability**, by **increasing the deployment scale** or by mass production, both for water and steam electrolysis.

The more the costs associated with the energy required for water electrolysis and CAPEX are reduced, the greater the reductions in production costs of renewable hydrogen or green hydrogen



## Economic barriers to the development of H<sub>2</sub> – H<sub>2</sub> likely production costs evolution

Investments in R&D (public and private) as well as other factors such as economies of scale will make it easier for the costs of producing renewable hydrogen to be significantly reduced during this decade<sup>1</sup>.



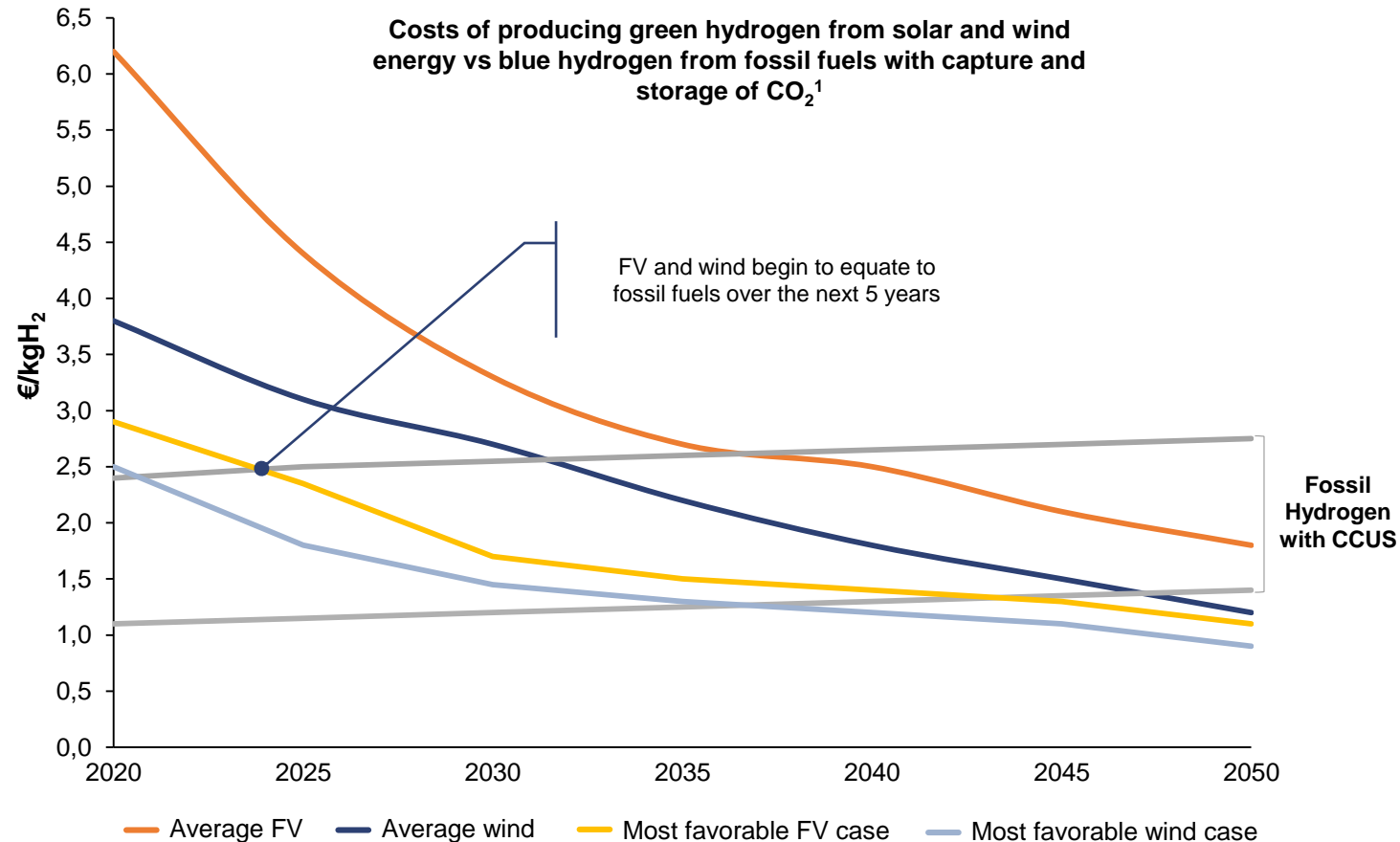
Notes: 1) Electricity consumption measured at the nominal hydrogen production rate of an electrolyzed system under standard conditions..

2) CAPEXs are based on a production volume of 100 MW and a system life of 10 years in continuous operation, defining the end of life as an increase of 10% of the energy needed for hydrogen production. Battery replacements are not included in capital costs. Costs are for installation in a ready-made site (foundations/buildings and necessary connections are available). Transformers and rectifiers must be included in the cost of capital.

3) Cost of operation and average maintenance during the first 10 years of the system. Possible battery replacements are included in the cost of O&M. Electricity costs are not included.

## Economic barriers to the development of H<sub>2</sub> – Levers for improving competitiveness

There are a number of levers through which the cost of producing renewable hydrogen can reach levels of competitiveness equal to or even better than current ones from fossil fuels



□ With the increasing **incorporation of renewable energy** sources for hydrogen electrolysis, it is estimated that by 2030 green H<sub>2</sub> can be produced at a **cost of between 1,5-2 €/kg**.

□ **Larger electrolytes**, along with **advances in reducing the use of noble materials** in electrodes and **automating manufacturing processes**, are expected to **significantly reduce** the electrolyte's CAPEX.

Lowering the electrolyte CAPEX in 200 €/kW would bring the hydrogen cost down by 0,25 €/kg - 0,30 €/kg.

□ It is estimated by 2030 a **substantial decrease in the costs** of electrolysis plants to 300 euros/kW - 400 €/kW from the current more than 800 €/kW, as **industrial-scale** plants capable of producing more than 100 MW are considered, compared to the current 2 MW-3 MW.

□ An increase in capacity **utilization factors** to 50% (from the current 40% on average) would **reduce the cost of hydrogen by 0.15 €/kg - 0.25 €/kg**. Electrolysis plants may not be economical if they depend solely on surplus periods of renewable generation, but they may be if they use renewable generation with high capacity factors.

**Renewable energy as a source of energy supply for green hydrogen production will play an essential role in reducing costs**

## Economic barriers to the development of H<sub>2</sub> – Levelized cost of energy (LCOE)

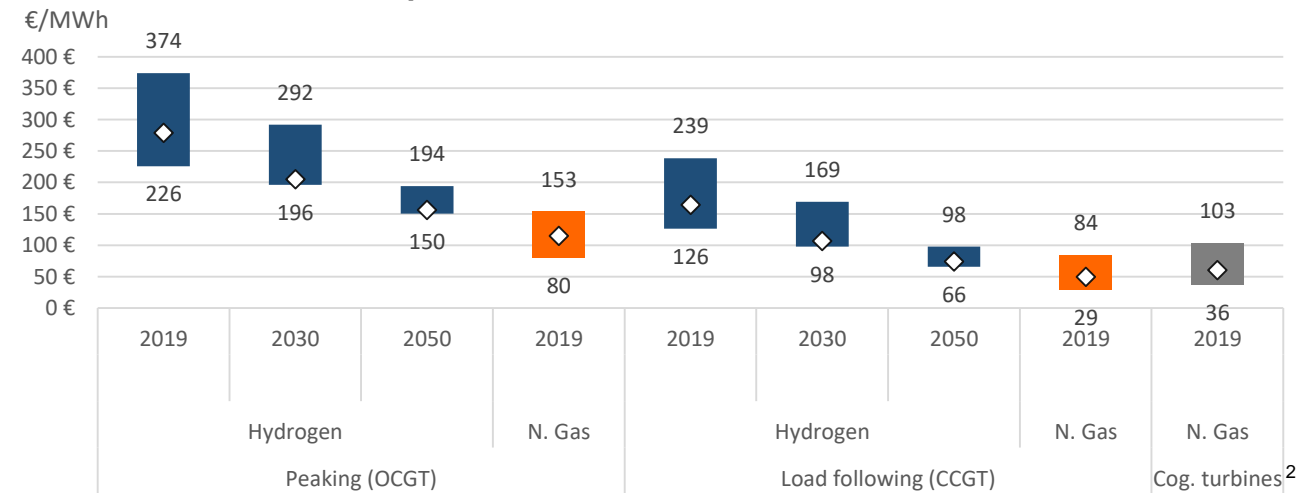
Technically both engines and turbines will be able to use renewable H<sub>2</sub> as an alternative primary energy source to natural gas, with a predictable evolution of favorable costs in the medium and long term

### Levelized Cost of Energy (LCOE)

- 1 If the gas turbines were 100% prepared for hydrogen use, a **carbon price of 26 €/tCO<sub>2</sub>** would be enough to drive the change from natural gas to hydrogen, and generate clean, manageable energy at a competitive price.
- 2 Through economies of scale and the deployment of renewable energy, green hydrogen production will tend to approach cost levels of current forms of fossil fuel production.



Levelized Cost of electricity of power plants with hydrogen-powered turbines vs Natural Gas



A reduction in the cost of hydrogen by between 0.33 €/kg - 0.41 €/kg reduces LCOE by  $\approx 8$  €/MWh<sup>1</sup>, implying that LCOE from H<sub>2</sub> has a large real margin for improvement for the next 30 years.

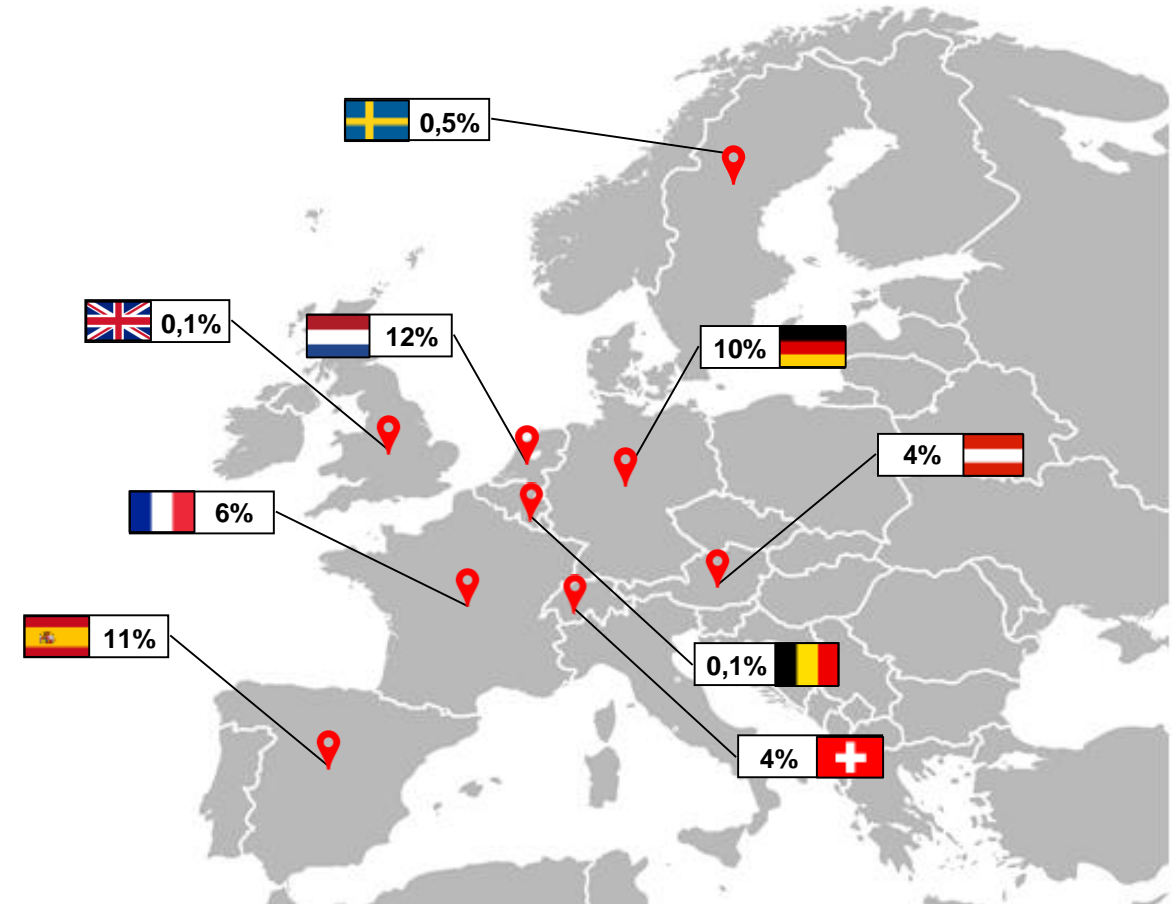
## Technical barriers to the development of H<sub>2</sub> – H<sub>2</sub> injection limits in NG networks (1/2)

Mixing hydrogen in the existing natural gas network would reduce significant investment costs associated with the development of new transmission and distribution infrastructures. However, the current limits of hydrogen mixing in natural gas networks respond to several restrictions.

- Natural gas **transport networks** can withstand **up to 50% mixing**.
- Distribution networks** can withstand a **mix of up to 15%** without the need for significant reforms.
- Due to the lower energy density of hydrogen** (1/3 natural gas), the mixture reduces the energy content of the supplied gas. Therefore, the **tolerance of equipment** connected to the gas network **should be assessed on a case-by-case basis** to establish the upper limit of the hydrogen mixture.
- Gas consumers, such as **boilers and gas engines**, **must be modified to support higher mixing levels**, as the Wobbe index<sup>2</sup> of the inlet gas is changed.

$$W_s = \frac{HCV_s}{\sqrt{GE}} \quad ; \quad \begin{array}{l} W_s: \text{is the superior Wobbe index} \\ HCV_s: \text{is the higher calorific value} \\ GE: \text{is the gas relative density} \end{array}$$

The Wobbe index is an important parameter when mixing fuel gases and air (in a combustion reaction), this index is controlled to ensure satisfactory combustion in a burner. When H<sub>2</sub> is mixed with NG, the resulting gas has different physical properties that modify this index and must be considered to ensure the integrity and correct functioning of the equipment (engines, turbines, boilers, etc.).



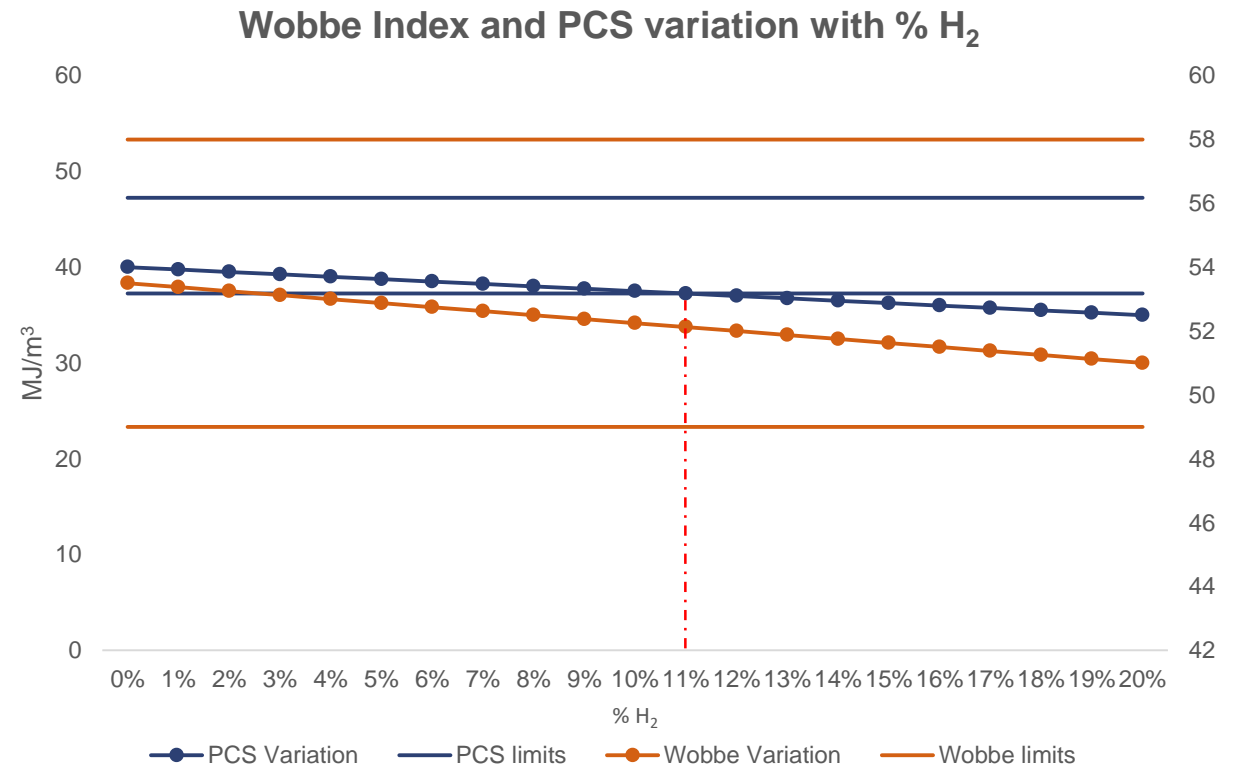
**Sources:** UNE-EN 16723-1: Gas natural y biometano para uso en transporte y biometano para inyección en la red de gas natural. Especificaciones para la inyección de biometano en la red de gas natural. PD-01 "Medición, Calidad y Odorización de Gas" de las normas de gestión técnica del sistema gasista.

<sup>1</sup> In Germany it is reduced to 2% if a CNG charging station is connected on the line. <sup>2</sup>Ameal parameter when you want to mix combustible gases and air (in a combustion reaction). This index is controlled to ensure satisfactory combustion in a burner. Recommendations based on the conclusions issued by the German Gas Association (DVGW), NREL (2019) and NaturalHy Project

## Technical barriers to the development of H<sub>2</sub> – H<sub>2</sub> injection limits in NG networks (2/2)

In the case of Spain, the hydrogen mixture in the current natural gas network is technically feasible up to a volume of 11%<sup>1</sup>.

- **Natural gas circulating through the Spanish gas infrastructure** belongs, according to UNE-EN 437 to the Second Family, Group H. The **upper Wobbe Index** is between **45.7 MJ/m<sup>3</sup>** and **54.7 MJ/m<sup>3</sup>**. And in terms of HCV, it's between **36.94 MJ/m<sup>3</sup>** and **47.74 MJ/m<sup>3</sup>**.
- Mixture of natural gas with H<sub>2</sub> results in another gas, whose main properties (WI and HCV) vary depending on the volume ratio of both.
- Addition of H<sub>2</sub> decreases the calorific power of the mixture faster than the Wobbe index.
- **Permissible technical limit for the mixture of natural gas and H<sub>2</sub> is reached for a percentage of H<sub>2</sub> volume of 11%, so adaptation would be required.**



<sup>1</sup>Sources: Enagás. XVI Congreso Anual de Cogeneración (dic 2020). Nota: 1 kWh = 3,6 MJ. Note: Technical analysis performed based on pure methane.

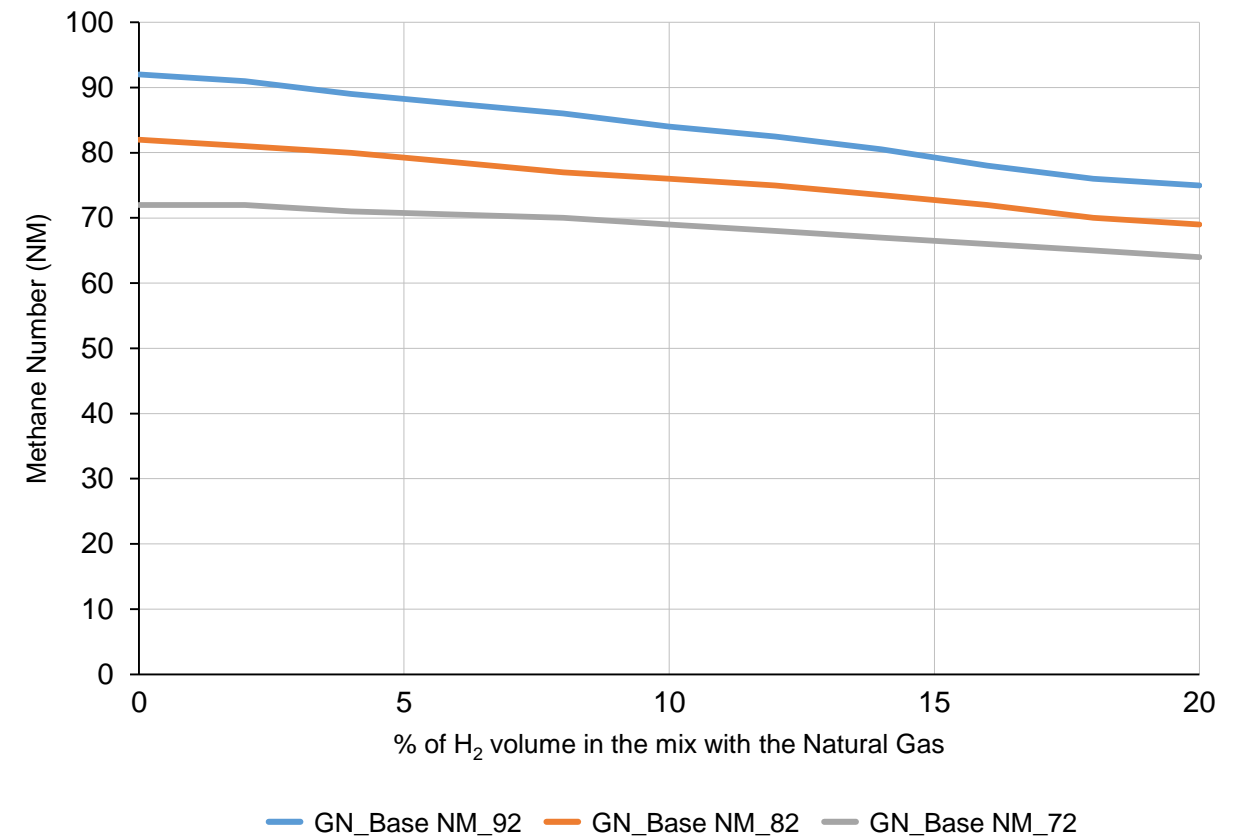
## Technical barriers: H<sub>2</sub> injection limits in NG networks

In addition to the variation in the Wobbe index, another technical limitation to consider in the hydrogen mixture in the natural gas network to power cogeneration engines and turbines, is the Methane Number (MN)<sup>1</sup>

- The **methane number** is the measure of fuel **gas resistance to engine pounding (detonation)** and is assigned to a performance-based test fuel in a tap test unit with the same standard strike intensity. Pure methane is assigned as a pounding-resistant reference fuel with a methane number of 100.
- A **low methane number** involves knocking also called crank chopping, which **can lead to power reductions and/or breakdowns**.
- As in **Spain** the **methane index** is low, in the environment of **70**, (Russian gas has a methane number >80) **by incorporating H<sub>2</sub>, it will reduce it below 70, so the risk of power reductions will be high**.
- If the reference methane quantity is not reached and the chopping regulation is activated, the ignition point is adjusted to full power along with the engine management system; only then is the power reduced.

**Mixtures of H<sub>2</sub> to 3-5 vol.% in the natural gas network are generally not considered serious. The highest rates of addition of H<sub>2</sub> to the natural gas network should be assessed on a project-by-project<sup>1</sup>.**

Effect of the variation in the number of methane (NM) of the H<sub>2</sub> mixture on Natural Gas<sup>1</sup>



<sup>1</sup>Sources: JENBACHER INNIO.

## Technical barriers to the development of H<sub>2</sub> – Hydrogen Treatment & Logistics

Hydrogen logistics (storage, transmission, distribution, conversion) is highly conditioned by its low energy density in the form of gas. Selecting the most efficient handling option can reduce energy losses and costs, and this selection will depend on different factors:



### Infrastructure

Natural gas transport and distribution infrastructure could be used by mixing hydrogen in the gas network. Injection costs<sup>1</sup> are 0.25 - 0.33 s/kgH<sub>2</sub>.

#### Blending challenges:

- 1 Finding **ways to mitigate risks** and detectors due to high hydrogen flammability.
- 2 **International regulation of the upper mixing limit.** The upper limit corresponds to the lowest hydrogen-tolerant component after the injection site (e.g. gas turbines, gas engines, etc.).
- 3 There are currently research projects that analyse the effects of mixing on the network (H21 Leeds City Gate Project in the UK).



### Delivery type

Difficulties related to the low volumetric and energy density of hydrogen gas could be partially mitigated by making it a denser form:

#### 1 Compression

Compression is the most widespread alternative to hydrogen supply, but improvements in compression technology and high-pressure deposits are expected over the next decade.

#### 2 Liquefaction

It is very expensive and requires a lot of energy due to the liquefaction infrastructure and cryogenic technology needed to keep hydrogen at -253 °C. Long-term storage leads to hydrogen boiling losses.

#### 3 Hydrogen carriers

Hydrogen is chemically agglutinate into denser compounds that can be converted back into hydrogen at the destination point (Ammonia, Organic Liquid Hydrogen (LOHCs)<sup>1</sup> and Methanol.



## Regulatory barriers for Hydrogen development in Spain

In the absence of specific regulation, there are a number of key regulatory recommendations for the development of H<sub>2</sub> in Spain

### MARKET CREATION POLITICS



This will boost demand for green hydrogen. Examples in this regard are:

- **Government procurement** (e.g., a percentage of green steel for public infrastructure).
- **Mixing mandates or quotas** are also an attractive alternative. Examples include demanding a percentage or share of industrial hydrogen to turn green, as already envisaged in French and Portuguese strategies.
- Require that a **percentage of gas demand be covered by green hydrogen**, or that a percentage of navigation or aviation fuel be sustainable.

### INFRASTRUCTURE REGULATION



- **Adaptation of existing regulations** regulating the **transport** of existing **natural gas networks**, to include H<sub>2</sub>.
- **Regulatory and ad hoc standardization development for transport through exclusive hydrogen distribution networks.**
- **Regulation** of the minimum safety conditions to be required of hydrogen **storage facilities for supply to residential buildings or tertiary sector**, whether supplied from packaging or produced "on site" by renewable energy sources (e.g., photovoltaic electrical production, **cogeneration**).

### NORMS & CERTIFICATIONS



Applicable from both a production and consumption perspective.

- Technical Standards and Certifications that allow to **differentiate** what is the **hydrogen source** that is produced/consumed, and to **be able to link it to an additional premium or quota**, while the producer can **validate lower CO<sub>2</sub> emissions** and be remunerated accordingly. Under **European Directive 2018/2001 (REDII)**, on the promotion of the use of energy from renewable sources, Member States should have these certificates **available by 30 June 2021**.
- Need for these systems to be **internationally accepted, compatible with other analogues (electricity and gas)** and with an adaptable framework that can be adjusted based on the experience gained once it has been implemented.

## Benefits of cogeneration using renewable hydrogen– General benefits

Cogeneration in Spain can take a very important advantage of the process of transformation that is coming over the energy paradigm with the emergence of green hydrogen



### Zero emissions

Renewable hydrogen will enable the cogeneration sector to become a 100% greenhouse gas-free source of thermal and electricity production.



### Commitment to the system

It will position the cogeneration sector in Spain in its firm commitment to contribute to the creation of an efficient, carbon-neutral, resilient and decentralized European energy system by 2050. Helping to meet the objectives of the PNIEC<sup>1</sup>.



### Sector renewal

Under an umbrella of hydrogen boost incentive policies, cogeneration may benefit from financing instruments that will facilitate the renewal and transformation of the sector.



### Energy protagonism

It will strengthen the prominence of cogeneration when it comes to being part of distributed energy systems that allow the integration of isolated energy communities.

## Main conclusions of the section – H<sub>2</sub> Barriers & Opportunities for cogeneration

Currently the application and use of renewable hydrogen by cogeneration presents a number of barriers of different nature, which for the most part have views of being able to be overcome in the medium/long term

### PRODUCTION COSTS OF RENEWABLE H<sub>2</sub> WITH DOWNWARD TREND

As of today, the costs of producing renewable hydrogen place it at a clear competitive disadvantage compared to the other two most widely used types of hydrogen, such as grey hydrogen and blue.

However, it is estimated that these costs will end up being equated with the help of the increasing penetration of renewable energies, the commitment to their production on a larger scale, the technological improvement in electrolysis processes and the increase in the CO<sub>2</sub> cost.

### BLENDING AS THE MAIN TECHNICAL CHALLENGE FOR H<sub>2</sub> LOGISTICS

Hydrogen injection into today's gas network is technically feasible up to a certain volume that varies depending on the region being considered. In Spain for example this limit is around 11%.

Going forward, it is hoped that the necessary investments will provide a more H<sub>2</sub>-adapted infrastructure, which will facilitate its permeability in order to achieve the objectives of decarbonization of the energy system at European and global level.

### VECTOR OF OPPORTUNITIES AND BENEFITS FOR COGENERATION OF THE PRESENT AND THE FUTURE

Renewable hydrogen is an opportunity for cogeneration to transform and adapt to a decarbonized energy model that will allow it to continue operating without relying on fossil-based primary energy sources.

Factors such as the price of CO<sub>2</sub>, in clear trend and bullish forecasting, together with the opening of other expanding market niches such as residential heat and in the tertiary sector, will be able to allow cogeneration by the hand of H<sub>2</sub>, to become a technology to be taken into account in the energy mix of the coming decades in Spain and Europe.



# 06.

## Business opportunities for cogeneration with Hydrogen

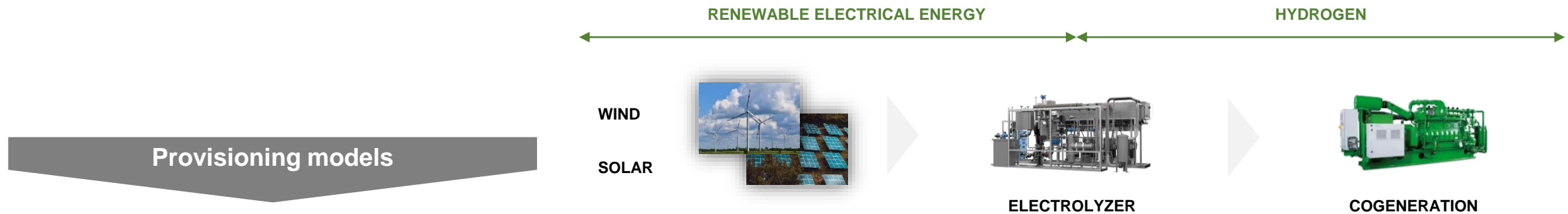


Renewable hydrogen supply models

Hydrogen deployment schemes within the  
cogeneration industry

## Renewable hydrogen supply models

In order to have a broad vision about the market opportunities that may exist in cogeneration, it becomes vital to understand the different procurement models that may exist for obtaining renewable hydrogen



- 1. Merchant model**  
Hydrogen is supplied by a third party, with a supply contract similar to that which may exist with natural gas



- 2. 100% renewable energy purchase**  
A third party supplies renewable electricity so that it in turn is transformed into  $H_2$  by the co-generator.

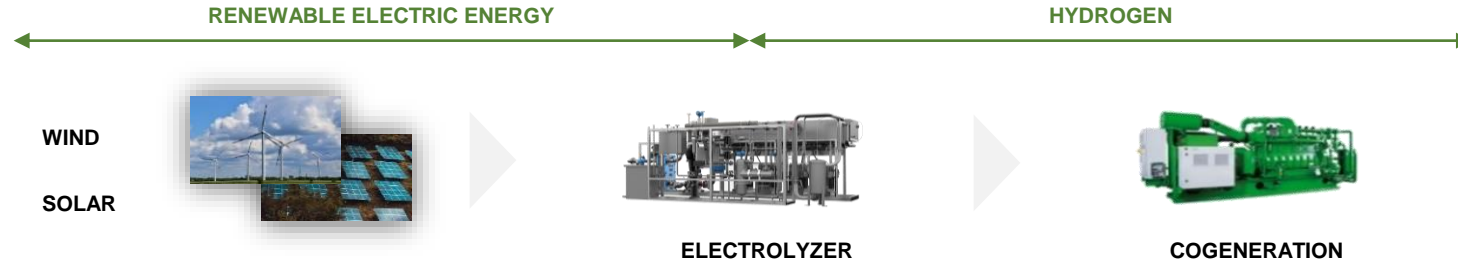


- 3. Local hydrogen production**  
The co-generator has infrastructure for the generation of renewable electricity, as well as for its subsequent transformation to  $H_2$



## Renewable hydrogen supply models – Merchant model

In order to have a broad vision about the market opportunities that may exist in cogeneration, it becomes vital to understand the different procurement models that may exist for obtaining renewable hydrogen



### PROS & CONS

**P** The cogenerator takes care of the core activity they know but using hydrogen instead of natural gas.

**P** At first sight, the only investment needed is to adapt the turbines to the levels of gas mixed with hydrogen or pure hydrogen that will be used for cogeneration.

**C** Poor visibility and management and control capacity of the rest of the hydrogen supply chain for cogeneration.

**C** Vulnerability and exposure to the prices and commercial margins of both production and distribution of H<sub>2</sub>.

Supply of energy from renewable energy generation sources (mainly wind and photovoltaic). Could be:

- Dedicated: directly from an installed generation asset.
- From the grid: taking electricity from the distribution network associated with an asset or set of renewable generation assets, through GOs.

Production of H<sub>2</sub> by a third party via an electrolysis process to generate 100% renewable hydrogen. Major business options:

- Alkaline electrolysis
- PEM electrolysis (protons membrane)
- SOFC (solid oxide)

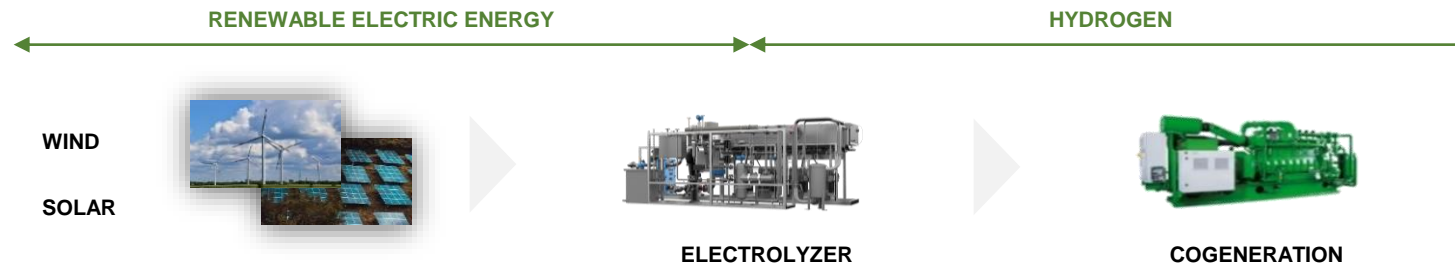
Hydrogen provisioning for combustion. It will come mainly in two ways:

- Transport and Distribution Gas network
- Road transport + plant storage

Cogeneration in the first phase will use hydrogen mixed with other gases (natural gas) to be able to use it exclusively.

## Renewable hydrogen supply models – 100% renewable electricity purchase

In order to have a broad vision about the market opportunities that may exist in cogeneration, it becomes vital to understand the different procurement models that may exist for obtaining renewable hydrogen



Energy supply from renewable energy generation sources (wind and photovoltaic mainly).

The provisioning of this electricity could be through:

- Traditional power supply, with GoOs.
- Bilateral contracts for the purchase and sale of electricity on time (PPA).
- Direct physical sale of the renewable plant to the co-generator.



Cogeneration invests in providing an electrolyzer for the production of green hydrogen, free of CO<sub>2</sub> emissions.

Certification of both the renewable electricity source used in the process and the hydrogen produced through it.



Hydrogen self-provisioning for its combustion, and subsequent generation of heat and electricity.

The development of logistics infrastructure to supply H<sub>2</sub> to the cogeneration plant will depend on where (distance) the electrolyzers are located from the plant, thus being able to be provisioned by:

- Pipes
- Road

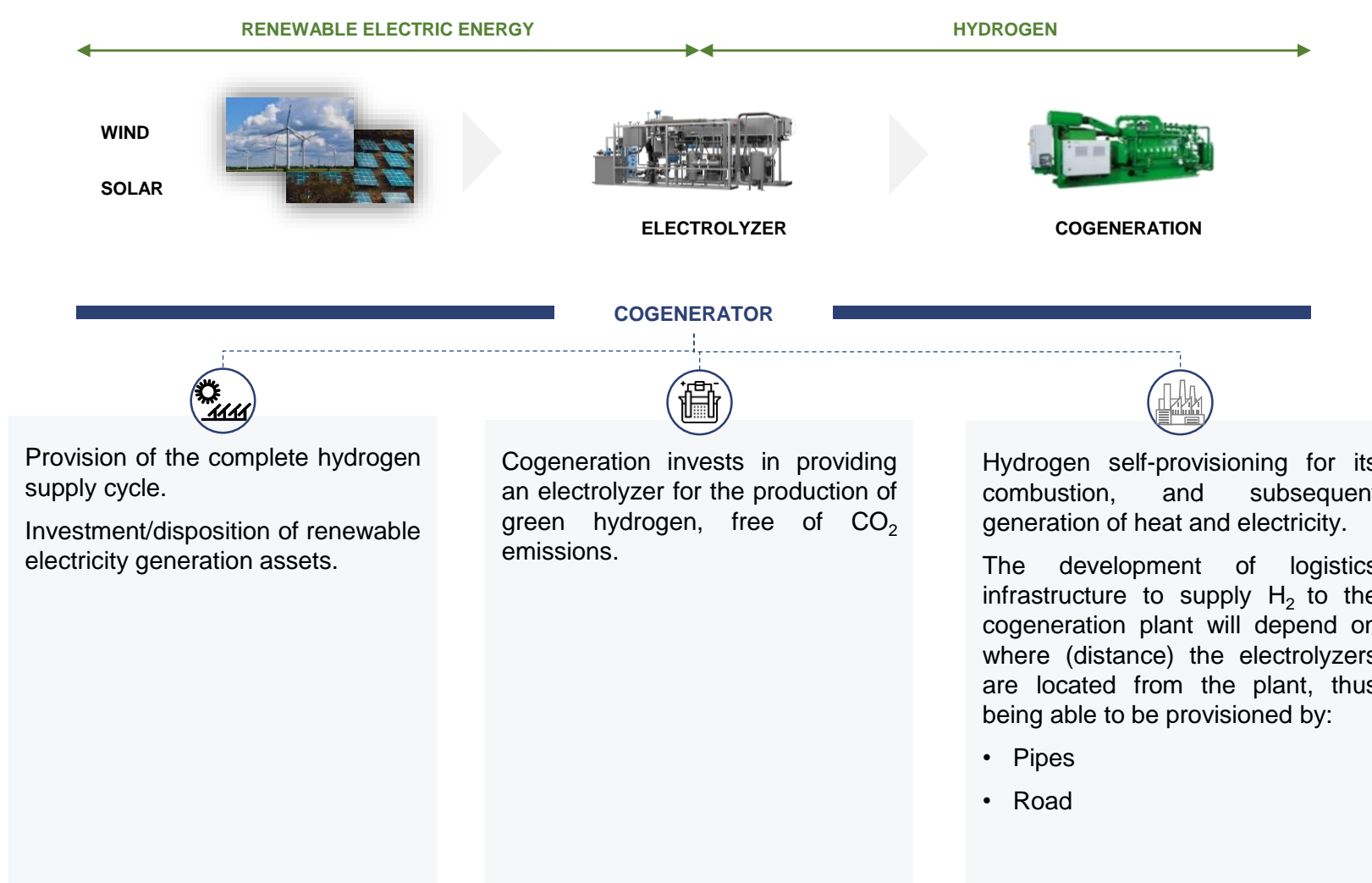
### PROS & CONS

- P** The cogenerator is able to manage the part of the production chain comprising the electrolyzer and its distribution to cogeneration.
- P** The cogenerator improves the visibility and management and control capability of part of the hydrogen supply chain for cogeneration, but still has no complete independence.
- P** Active supply control and management options arise such as PPAs or traditional supply contracts.
- C** The necessary investment increases since in addition to having to adapt the cogeneration technology itself to hydrogen, the electrolyzer must be acquired, exploited and maintained.



## Renewable hydrogen supply models – Local hydrogen production

In order to have a broad vision about the market opportunities that may exist in cogeneration, it becomes vital to understand the different procurement models that may exist for obtaining renewable hydrogen

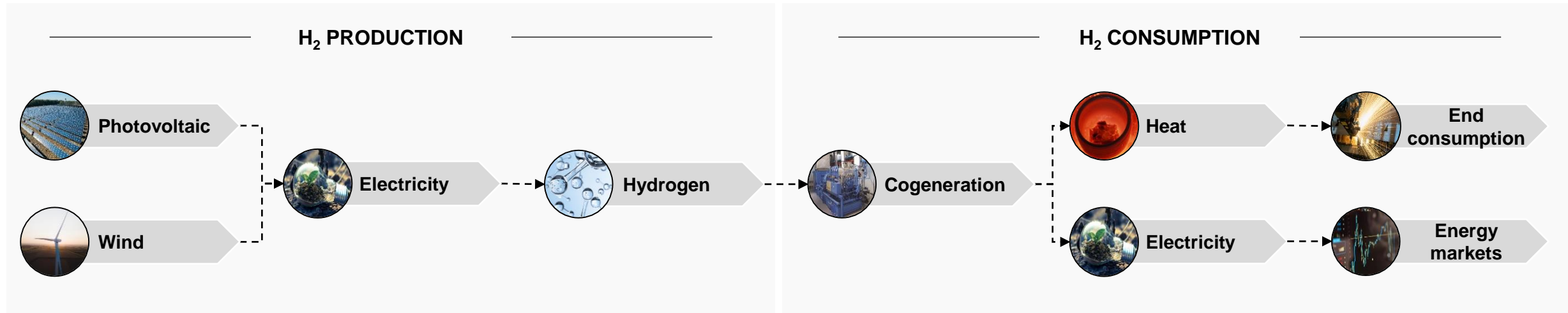


### PROS & CONS

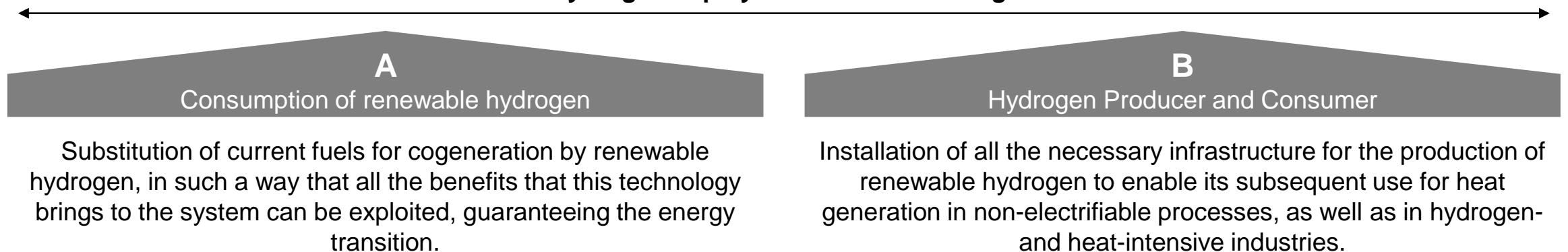
- P** The cogenerator is able to manage the entire hydrogen supply chain they need for cogeneration.
- P** Virtually total energy independence is available so exposure to certain risks is significantly mitigated (margins and prices of third parties).
- C** Business complexity increases and the learning curve takes a set of time for efficient operational running in.
- C** The investment required for the model is undoubtedly the largest of those raised by covering the entire hydrogen supply chain.

## Hydrogen deployment schemes within the cogeneration industry

Based on H<sub>2</sub> implementation scenarios as well as procurement models, two major business opportunities have been identified that can break into the co-generating industry to become 100% renewable.



### Potential hydrogen deployment schemes in cogeneration



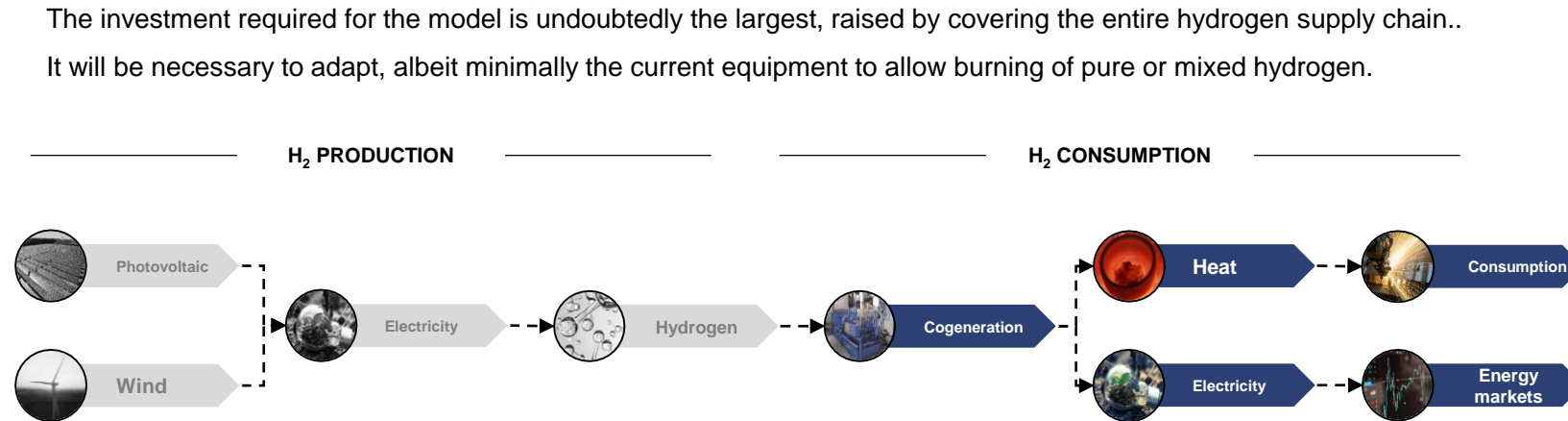
## Business opportunities for hydrogen cogeneration – Individual H<sub>2</sub> self-consumption

### PROS & CONS

- P** As of today, it is technically feasible to cogenerate with pure hydrogen obtaining acceptable electrical and thermal yields.
- P** Low investment risk since it would only be limited to the adaptation or replacement of the cogeneration turbines and some auxiliary elements.
- P** Direct environmental benefit by eliminating CO<sub>2</sub> emissions and being able to certify GoOs.
- C** Requires some investment effort in renewing current technology and equipment for cogeneration plants.

Renewable Hydrogen Consumption

A



#### HYDROGEN

- Current fuel substitution for hydrogen.
- Purchase of hydrogen from third parties for subsequent use in the process of obtaining heat and electricity.
- Direct environmental benefits due to the elimination of emissions currently existing with the consumption of natural gas or other fossil fuels.



#### COGENERATION

- Adaptation and/or replacement of current combustion technology for hydrogen use (mixed and pure)
- Depending on the mode of supply, some additional investments (compressors, hydrogen storage) may be needed).



#### ELECTRICITY



#### HEAT

- Traditional cogeneration to produce heat and electricity for final consumption.



#### INDUSTRIAL CONSUMPTION



#### ENERGY MARKETS

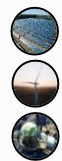
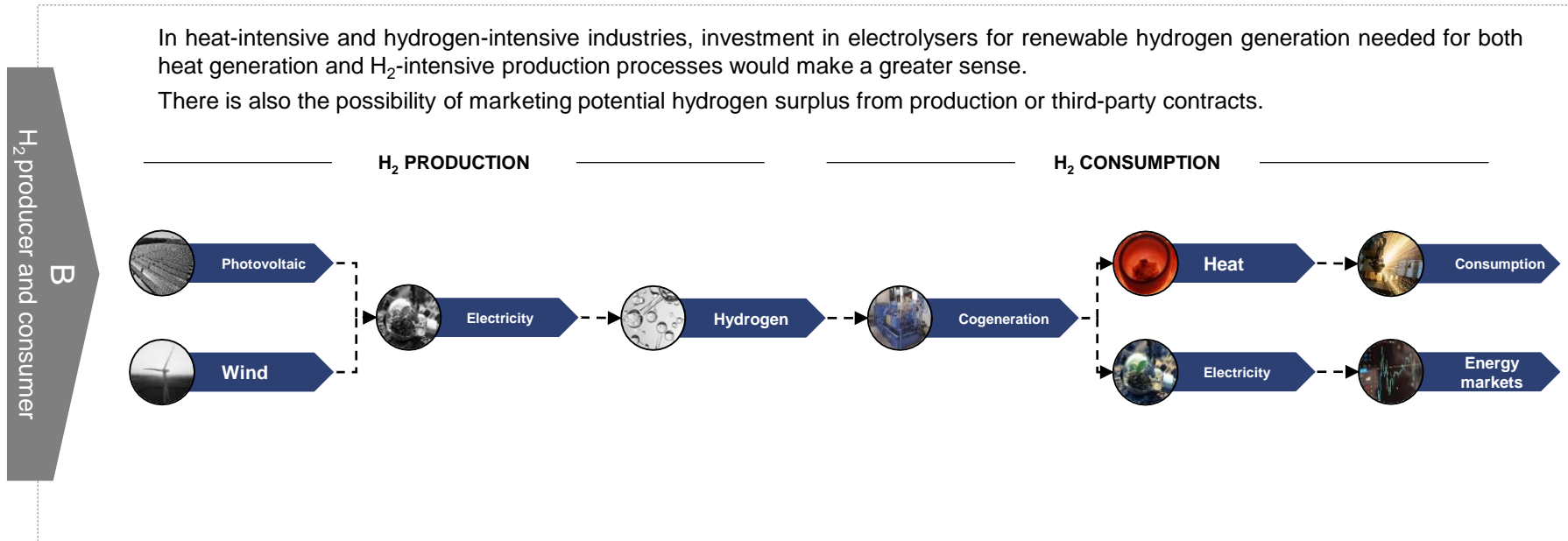
- Total flexibility to maintain current industrial uses of co-generated heat.
- Electricity generated available for incorporation into the distribution and consumption grid (model of sale of energy to the wholesale market).

## Business opportunities for hydrogen cogeneration – H<sub>2</sub> producer and consumer

### PROS & CONS

**P** Total control of the hydrogen value chain, managing the electricity supply source, the production of H<sub>2</sub> and its consumption through the cogeneration process. This enables comprehensive management and planning of H<sub>2</sub> production and consumption by the cogeneration plant, as well as absolute adaptability to variations in consumption needs.

**C** Requires extra investment in renewable power generation technology (for PEM electrolysis between 55-70 kWh/kgH<sub>2</sub>)<sup>1</sup>. For photovoltaic energy, current costs are around 24.47 euros/MWh and for wind power the 25.31 euros/MWh<sup>2</sup>.



#### PHOTOVOLTAIC

#### WIND

#### RENEWABLE ELECTRICITY

- Sourcing models based on electrical self-consumption or the purchase of renewable electricity (GoOs and PPAs market) .
- If a renewable installation is opted for, there is complete independence in renewable energy production for heat generation.



#### HYDROGEN

- Replacing current fuel with hydrogen.
- Control and management of the rate of hydrogen production (adaptation to consumption)
- Direct environmental benefits due to the elimination of current emissions from natural gas consumption.



#### COGENERATION

#### ELECTRICITY

#### HEAT

- Traditional but CO<sub>2</sub> emission-free cogeneration processes.
- Use of co-generated electricity to:
  - Self-consumption.
  - Market selling.



#### INDUSTRIAL CONSUMPTION

#### ENERGY MARKETS

- Total flexibility to maintain current industrial uses of co-generated heat.
- Electricity generated available for incorporation into the distribution and consumption network (model of sale of energy to the wholesale market).

## Main conclusions of the section – H<sub>2</sub> business models in cogeneration

Business models adapted to the next energy transformation scenario with renewable hydrogen appear under different forms of supply of both energy and fuel

### DIFFERENT PROVISIONING SCENARIOS FOR COGENERATION

Three different models of renewable hydrogen supply are proposed, each with greater decision-making capacity by the co-generator throughout the H<sub>2</sub> value chain:

- *Merchant*: hydrogen is supplied by a third party, similar to what might exist with natural gas.
- *100% renewable electricity purchase*: only the supply of electricity for renewable H<sub>2</sub> production is negotiated.
- *Local hydrogen production*: the role of producer of electricity and hydrogen are assumed to obtain a final scheme similar to self-consumption.

### BUSINESS MODELS WITH THE SAME ESSENCE BUT AIMED AT TRANSFORMATION

With renewable hydrogen, cogeneration in Spain is opened up to a number of business opportunities to consider:

- *Renewable hydrogen consumption*: in heat and hydrogen intensive industries.
- *H<sub>2</sub> producer and consumer*: in heat-intensive and hydrogen-intensive industries.



# 07.

## Conclusions



Main conclusions drawn from the analysis

By way of summary and compilation, the main conclusions of this study are shown below:

## 1 H<sub>2</sub>: A GROWING MARKET

- Spain is currently the 5<sup>th</sup> country in Europe in annual consumption of H<sub>2</sub> with 500 kt. It is anticipated that with the commitment to hydrogen as a vector for the decarbonization of industry, transport, tertiary sector, etc. it will increase.
- With renewable energy surpluses planned for 2030, hydrogen is running as a firm candidate for use under the Power-2-Gas formula.

## 2 SPAIN AND THE UE BET ON H<sub>2</sub> AS THE DECARBONIZATION VECTOR

- Spain is strongly committed to the development of hydrogen with planned investments of 8.9 billion euros up to 2030.
- The set target is to reach 4 GW of installed electrolyze capacity, which is the target set by the H<sub>2</sub> roadmap for 2030 and 10% of the target set by the EU for the same time horizon.
- In this sense, Spain, thanks to its wind and solar resources, its geographical location and current natural gas network infrastructure, has the opportunity to become a hub for renewable H<sub>2</sub>, not only for domestic consumption but also for export to other EU countries.

## 3 DECARBONIZATION OF NON-ELECTRIFIABLE INDUSTRY

- Taking into consideration the objectives of climate neutrality or the projection of CO<sub>2</sub> prices, use of H<sub>2</sub> or other renewable gases in technologies such as cogeneration, can substitute other more polluting fuels, when it comes to decarbonizing industry intensive in domestic heat demand.



By way of summary and compilation, the main conclusions of this study are shown below:

## 4 RENEWABLE HYDROGEN PRODUCTION TECHNOLOGY IS IN CONSTANT EVOLUTION

- Hydrogen production technologies are constantly evolving. Thanks to public and private research efforts, systems are expected to become more economical, robust and durable. This will make green H<sub>2</sub> more competitive in the future.

## 5 REGULATION

- A favorable policy and regulatory framework will be key for the development of H<sub>2</sub> at the national level. In this sense, it is key to establish market creation policies (such as, for example, minimum blending quotas), the use and capacity of infrastructures, in terms of blending and safety, the development of regulations that do not block any business model or the operating structure of certificates of origin for renewable H<sub>2</sub>.

## 6 HIGH BUT DECREASING COSTS

- Over the decade ahead, production costs for renewable H<sub>2</sub> are expected to fall to 1.5-2 €/kg compared to 3.5-5 €/kg at present.
- Its main levers of competitiveness will revolve around improved technology, operational efficiencies, economies of scale and the price of CO<sub>2</sub>.

## Main conclusions – Use of H<sub>2</sub> for cogeneration

By way of summary and compilation, the main conclusions of this study are shown below:

### 7 H<sub>2</sub> AND COGENERATION, TECHNICALLY VIABLE

- Hydrogen is one of the most promising alternatives for the renewal of current cogeneration plants, which are reaching the end of their useful life, and which will be necessary, according to the PNIEC, to maintain the management of the electricity system.
- The technological adaptation of cogeneration to hydrogen consumption is a reality, with a wide variety of suppliers able to provide engines and turbines suitable for H<sub>2</sub> consumption.
- Limitations to its consumption come from the adaptability of existing natural gas transport and distribution networks (blending of up to 11% by volume).

### 8 THERE ARE EXISTING BUSINESS MODELS FOR COGENERATION AND HYDROGEN

- Based on emission-free heat and power generation, to meet the future demands of industry and the tertiary sector, while maintaining its values of self-consumption, high efficiency and flexibility.
- Cogeneration will be key to the efficient integration of the energy system at a local level, complementing the electrification and decarbonization of industrial and residential heating/cooling.

### 9 COMPETITIVENESS, FLEXIBILITY AND NETWORK STABILITY

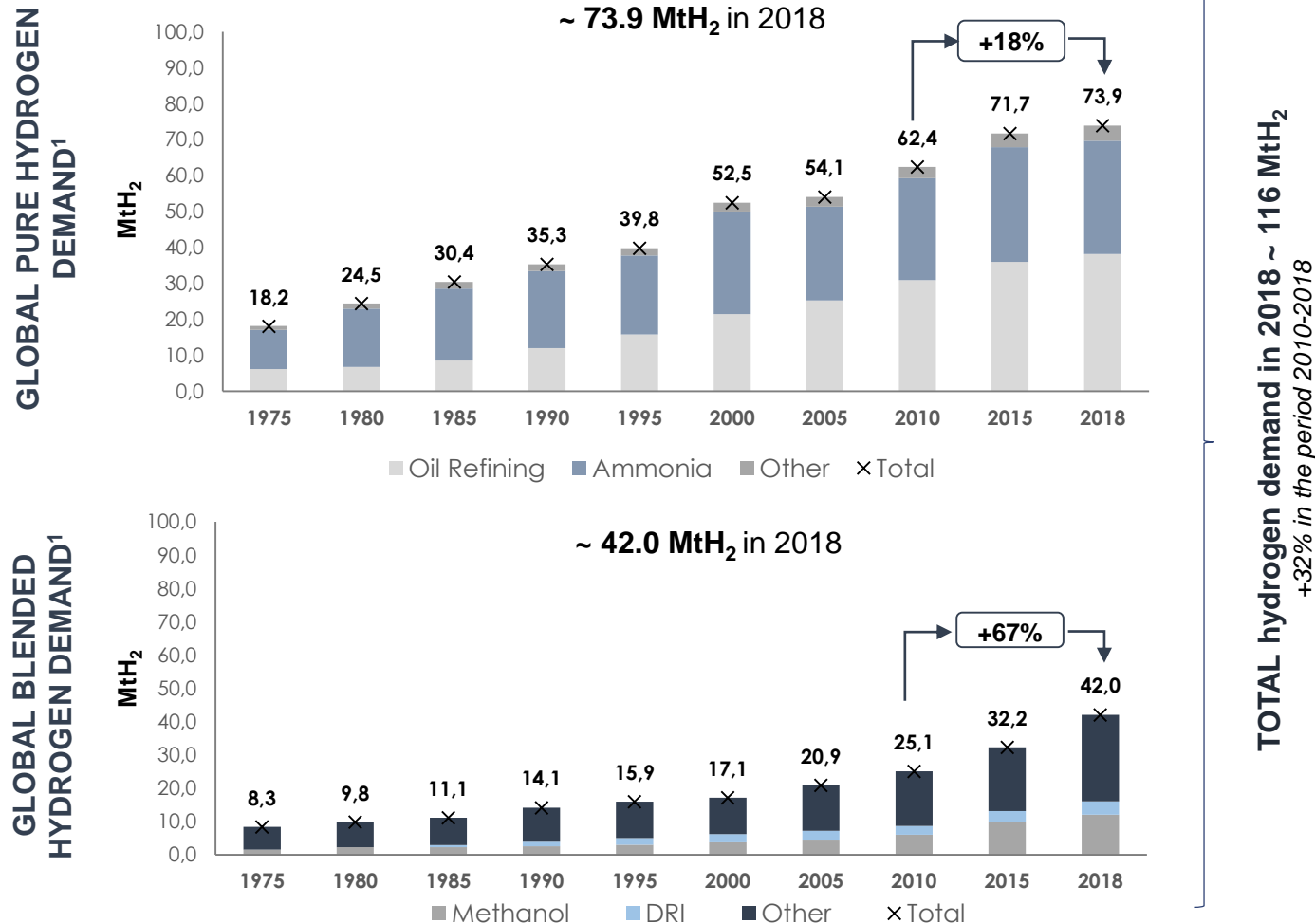
- Cogeneration provides competitive advantages that have already been demonstrated and are in line with the objectives of European directives, such as high efficiency (providing savings of at least 10% of primary energy compared to other technologies), industrial self-consumption and distributed generation.
- This is particularly relevant in a scenario of high renewable penetration, where conventional generation technologies such as cogeneration will be needed to maintain grid stability.
- Cogeneration will in turn provide capacity to serve as a balance to the electricity system under a distributed generation scheme, satisfying as much as possible the flexibility needs demanded by the System Operator.

# ANEXES

- H<sub>2</sub> global market
- H<sub>2</sub> value chain
- Current uses for H<sub>2</sub>
- H<sub>2</sub> production
- H<sub>2</sub> Logistics

## Global H<sub>2</sub> market – Historical consumption

The demand for hydrogen has increased since 1975 due to the rise in the global market for its main applications: refining and production of ammonia (Pure Hydrogen) and methanol (Blended Hydrogen).

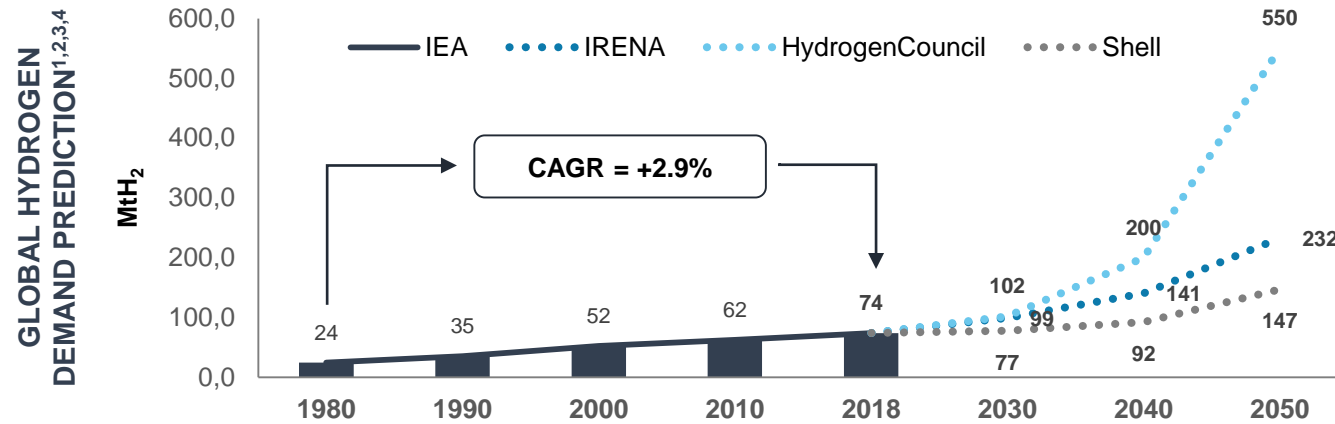


### WHY HAS THE HYDROGEN DEMAND INCREASED?

- The **main reasons** that have contributed to the increase of the global **pure hydrogen** demand are:
  - Stricter oil quality standards**, aiming at a progressive reduction of sulphide content in refinery products, resulting in an **increased demand for hydrogen** for impurity removal processes.
  - The demand for hydrogen for ammonia production is **related to the growth of the fertilizer industry** (where the main uses of ammonia occur), which has increased by an average of 1.4% per year over the last decade (2006-2016)<sup>2</sup>.
- Global demand for blended hydrogen has also increased due to the **growth of the methanol production industry** (CAGR 14-19=5.4%)<sup>3</sup> and the high use of hydrogen as a mixed gas in industrial processes.

## Global H<sub>2</sub> market – Growth prospects

Over the coming decades, new end-use applications are expected to drive hydrogen demand, potentially reaching a 7.5-fold increase by 2050 under the most ambitious scenarios.

Source<sup>2,3,4</sup>CAGR  
2018-2050

Growth prospects

Hydrogen  
Council

+ 6,3%

- ~100% market share in current industrial uses.
- Disruption of new end-use applications: 25% FCEVs in transport, 25% industrial heating processes.
- ~20% heating and electricity of buildings, 5% overall electricity generation, 15% of energy storage, etc.



+ 3,5%

- Significant growth in the use of hydrogen for transport.
- Hydrogen will continue to be used in certain industrial applications related to chemical processing and steel production.



+ 2,1%

- Hydrogen to be used in industry and transport.

### MARKET DYNAMICS<sup>1,2,3,4</sup>

#### USES

Related to the penetration of hydrogen in new **uses and consumption typologies**: hydrogen as a fuel for vehicles (FCEVs), "Power-to-Gas" technologies as a complement to renewable generation.

#### ECONOMY

Linked to trends in energy prices (natural gas, coal, electricity and CO<sub>2</sub>). Cost reductions in green hydrogen production and supply chain driven by effective improvements and economies of scale.

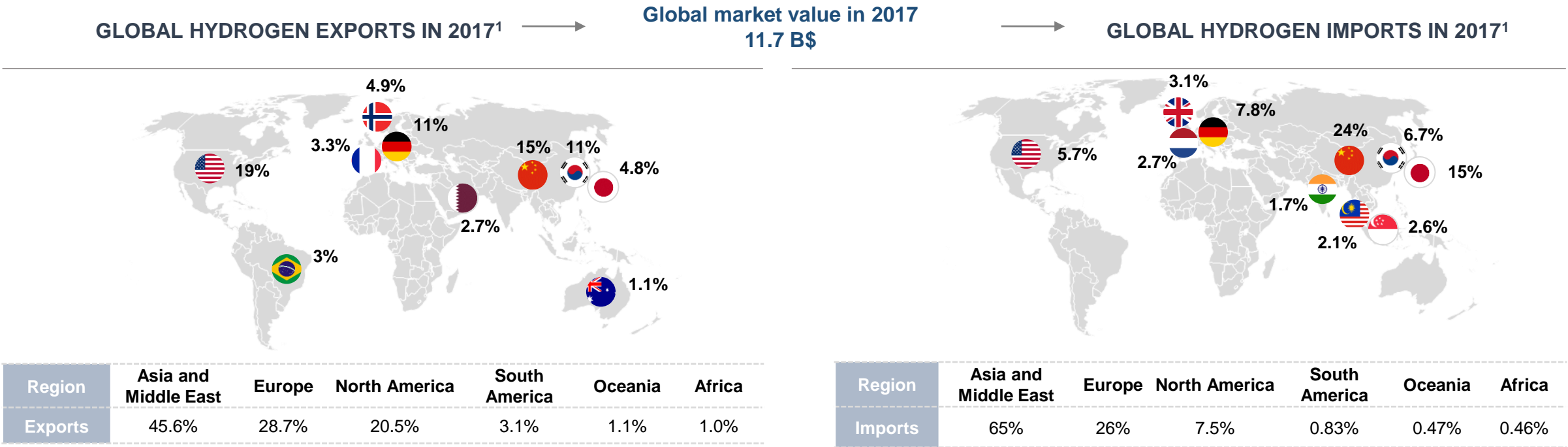
#### REGULATORY FRAMEWORK

Related to **decarbonization policies set by national hydrogen plans, roadmaps and support policies** aimed at promoting the integration of hydrogen into the energy system and creating supply chains (shipping routes, exchanges, etc.).

Although all predictions show a **growth in global hydrogen demand** in the medium (2030) and long term (2050), there are **notable divergences** between the different sources, indicating a perspective with an unpredictable component based on **major market dynamics**.

H<sub>2</sub> Global Market – Exports and Imports

The export/import trend shows that Asia Pacific has been the leading region in the hydrogen market, aligning with the high demand rate for today's industrial applications.



FUTURE TRENDS

- **Asia Pacific is the largest hydrogen exporting/importing region** due to its high traffic in ammonia production and oil refining<sup>2</sup>. It is expected to continue like this in the coming years
- **The Asia Pacific market** (especially China, Japan and South Korea) **is expected to grow** in the short term due to the development of national policies that seek to stimulate hydrogen penetration into the transport and heating and electricity sectors of buildings<sup>3</sup>.
- **Australia**, due to its generation mix, geographic positioning and LNG shipping routes, **is well positioned** to meet the demand for Asia Pacific hydrogen by developing its productive capacity.
- The hydrogen market in Europe has been led by **Germany**, which has had hydrogen support policies since 2010<sup>3</sup>.
- **North America** is a net exporter of hydrogen due to its competitive production costs driven by low natural gas prices<sup>4</sup>.

Sources: <sup>1</sup>Observatory of Economic Complexity; <sup>2</sup>MarketsandMarkets; <sup>3</sup>ACIL ALLEN (2018): Opportunities for Australia from Hydrogen Exports; <sup>4</sup>IEA (2019): The Future of Hydrogen.

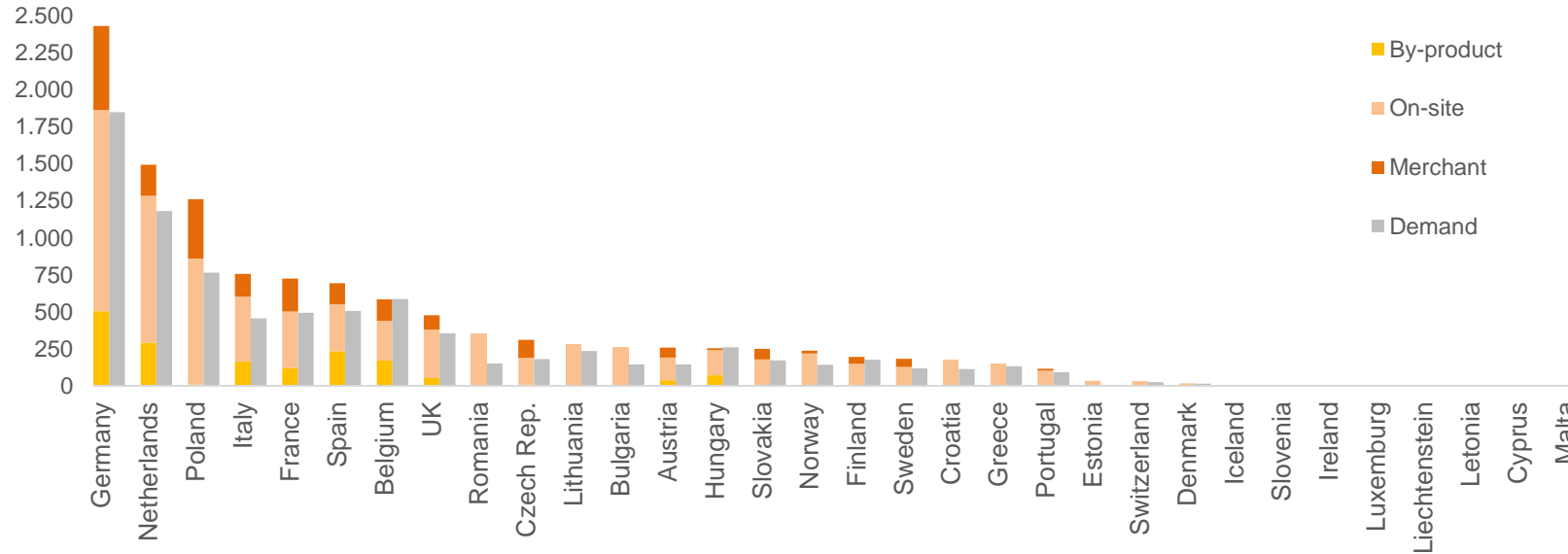
## H<sub>2</sub> Value Chain – European context - Production

Europe is now a net hydrogen exporter. Its hydrogen generation capacity is largely the so-called "grey H<sub>2</sub>", with Germany and the Netherlands being the largest producers of H<sub>2</sub>

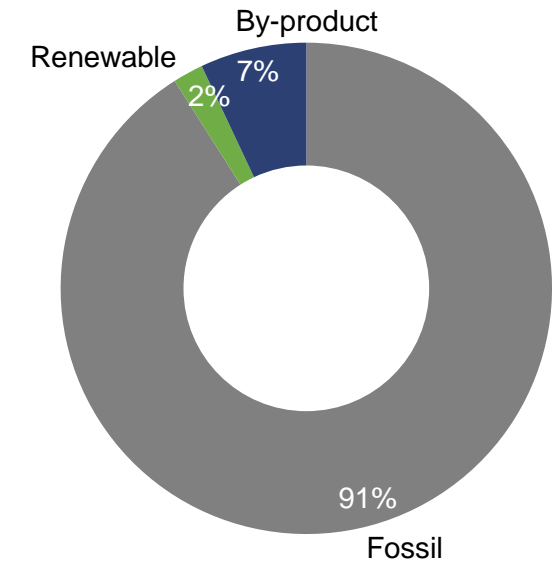


Hydrogen generation and demand capacity by country<sup>(1)</sup>

Metric tons per year (in thousands), 2020



H<sub>2</sub> generation capacity by technology  
%, 2020<sup>(2)</sup>



Technology suppliers



Engineering and construction



Industrial gases



Energy companies & traders





## H<sub>2</sub> Value Chain – European context– Secondary sources; Transport & Distribution

Much of the H<sub>2</sub> consumption is done in the production of ammonia and methanol, which in turn can be used to port H<sub>2</sub> to destination, which has generated international projects to increase transport infrastructure.

### Production

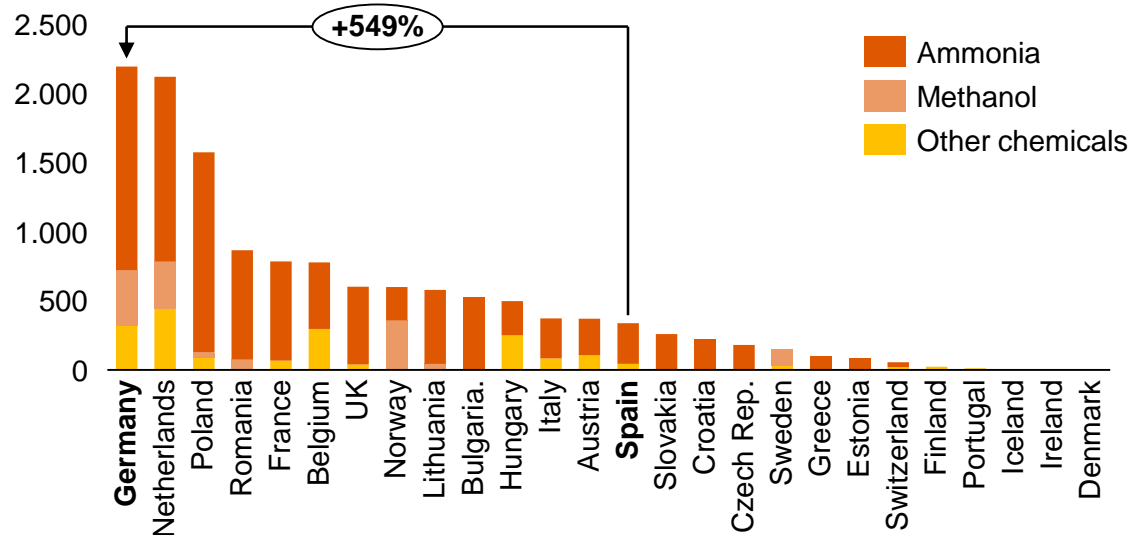
### H<sub>2</sub> carriers (Secondary sources)

### Transport & Distribution

### Consumption

#### H<sub>2</sub> generation capacity for chemical applications

Metric tons per day, 2020<sup>(1)</sup>



#### European project backbone

Infrastructure development prospects for transport and distribution<sup>(2)</sup>



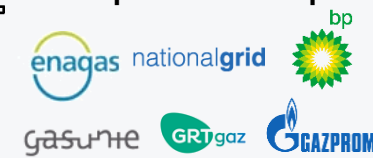
#### Ammonia Producers



#### Methanol Producers



#### Transportation companies



#### Distribution companies

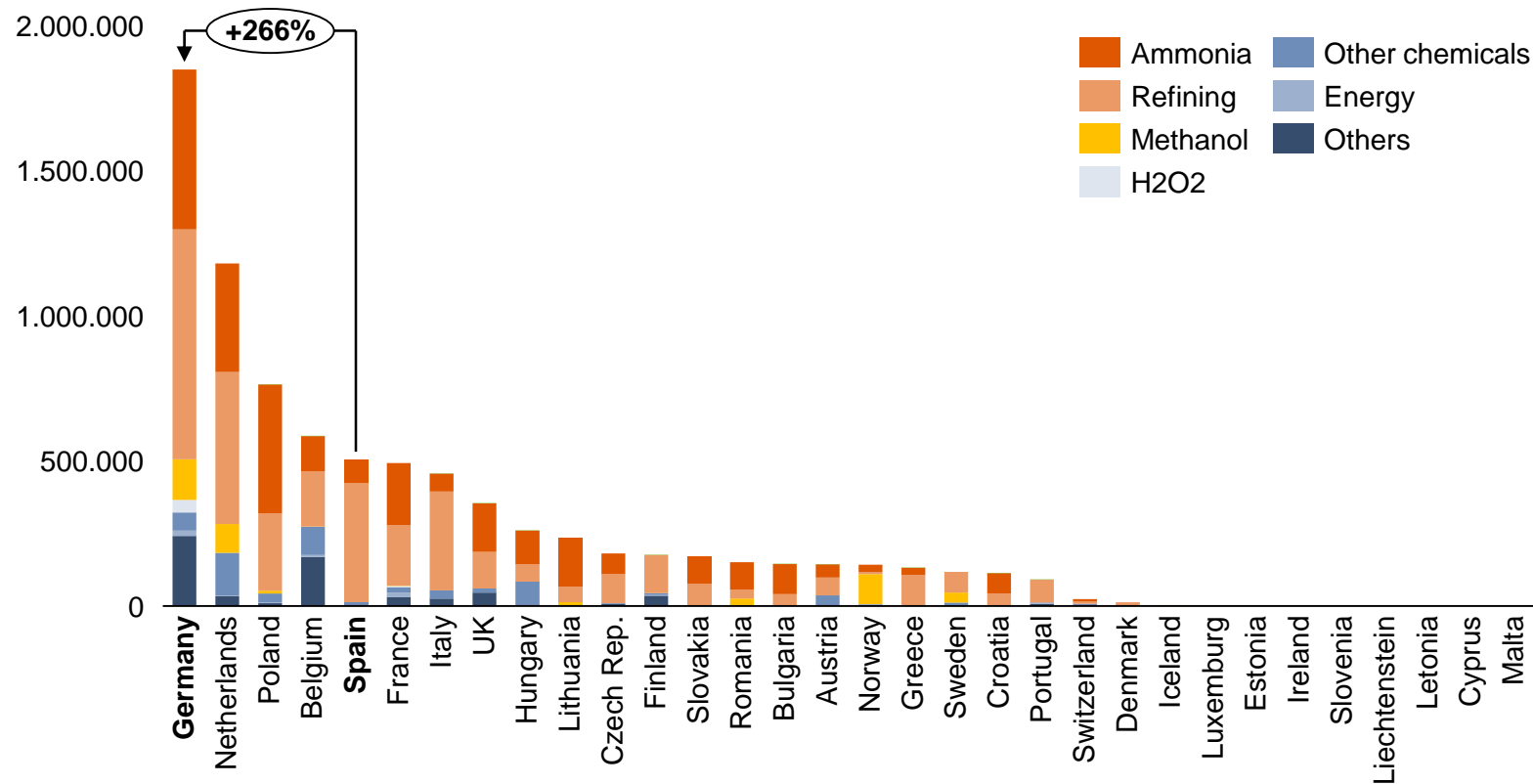


## H<sub>2</sub> Value Chain – European context - Consumption

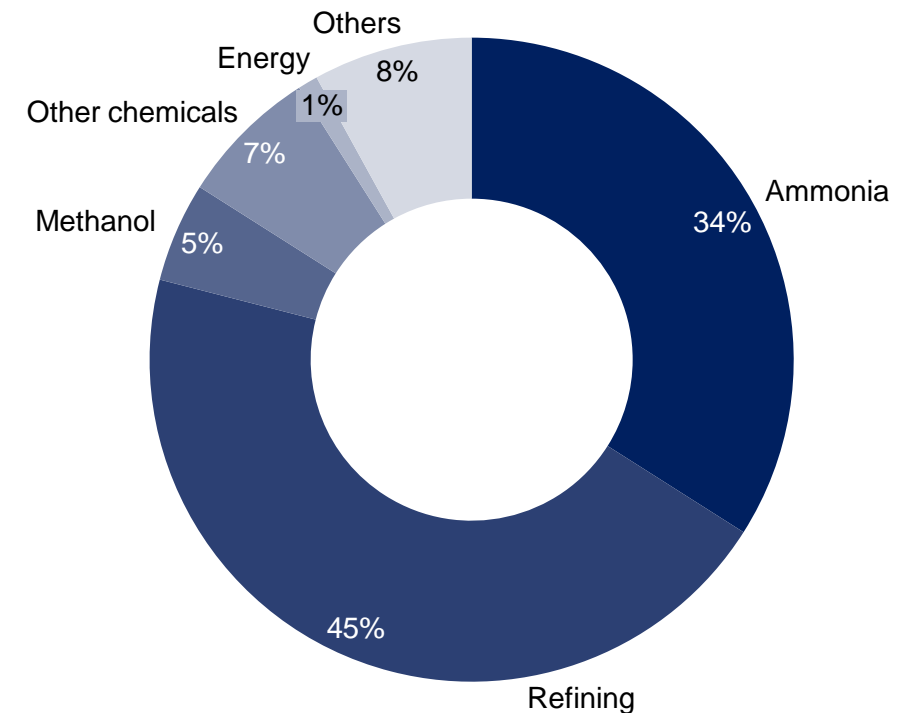
Industries with a high H<sub>2</sub> consumption are refining and chemical industry, with the most consuming countries being those with the largest generation capacity, which reaffirms that there is currently no widespread international market for H<sub>2</sub>.



**Estimated hydrogen consumption by sector**  
Metric tons per year, 2020<sup>(1)</sup>



**Estimated hydrogen consumption by sector**  
Metric tons per year, Europe, 2020<sup>(2)</sup>



## Current hydrogen uses

Currently, hydrogen is used in various industrial processes in certain industries, with the vast majority of this consumed hydrogen being rated as 'grey'.



### REFINING

33.0%<sup>1</sup>



### CHEMICAL INDUSTRY

37.4%<sup>1</sup>



### METAL INDUSTRY

3.5%<sup>1</sup>



### OTHER APPLICATIONS

26.1%<sup>1</sup>

#### CURRENT USES

- **Oil hydrotreatment process.**
- **Oil hydrocracking process.**
- Biofuels hydrotreatment process
- Oil sands upgrading.
- Lubricant plants and other petrochemical processes.

- **Ammonia production**, is mainly (80%) used in the agriculture industry as a feedstock for fertilizers (urea and ammonium nitrate).
- **Methanol production**, used in solvents manufacture, industrial chemicals and fuel applications (gasoline, olefins or others).

- Manufacture of steel through the **DRI (Direct Reduction of Iron)** process, which uses a solid (coal) or gaseous reducing agent (hydrogen, synthesis gas (CO + H<sub>2</sub> mixture)).

- **Agri-food industry:** oil hydrogenation.
- **Synthetic hydrocarbons.**
- Cooling system.
- Glass production.
- Semiconductor production (electronics).

#### CONSUMERS



USA<sup>1</sup>



China<sup>1</sup>



Europe<sup>1</sup>

ASIA  
PACIFIC<sup>2</sup>



China<sup>2</sup>



China<sup>3</sup>



India<sup>3</sup>



Japan<sup>3</sup>



Iran<sup>3</sup>

Depends on industry

#### Δ 2030

Δ 7%<sup>1</sup>

Δ 31%<sup>1</sup>

Δ 100%<sup>1</sup>

Depends on industry

## Current hydrogen uses – Oil refining








### HYDROGEN USES DESCRIPTION<sup>1</sup>:

- In 2018, **38 MtH<sub>2</sub>**, **33% of global hydrogen demand**, were used for oil refining processes dedicated to the **production of fuels** such as gasoline, diesel, aircraft fuel, etc.
- Among others, the greatest hydrogen use was in two refining processes:
  - Hydrotreatment**: dedicated to improving the quality of petroleum fractions from desulfury processes, removal of impurities, conversion of olefins to paraffins, and other.
  - Hydrocracking**: dedicated to breaking down long-chain hydrocarbons to form shorter chains in the gasoline range.
- The hydrogen demand of refineries depends on the configuration of their processes and the quality of their raw materials, relative to their sulfide content. On average, **hydrogen supply to refineries** in 2018 came from:
  - On-site hydrogen production** (~40%).
  - Hydrogen derived from the refining process** (~33%).
  - Hydrogen supplied by marketers (Merchant)** (~27%).

### GLOBAL MARKET VISION<sup>2</sup>:

Oil refining capacity (thousands of barrels/day)				
Region	Refining Capacity 2018	Market share	CAGR 07-17	CAGR 17-18
Asia-Pacific	34,752	34.7%	+2.4%	+2.8%
North America	22,333	22.3%	+0.5%	+1.1%
Europe	15,681	15.7%	-1.3%	+1.7%
Middle East	9,704	9.7%	+2.3%	+2.5%
Eurasia	8,166	8.2%	1.6%	-0.3%
South America	5,979	6.0%	-0.5%	-3.9%
Africa	3,434	3.4%	1.3%	-0.1%

COUNTRIES BY REFINING CAPACITY		18,762 thousand barrels/day (18.8%)	} Total globally: 100,049 thousand barrels/day
		15,655 thousand barrels/day (15.6%)	
		6,596 thousand barrels/day (6.6%)	
		4,972 thousand barrels/day (5.0%)	
		3,346 thousand barrels/day (3.3%)	
		3,343 thousand barrels/day (3.3%)	
		2,835 thousand barrels/day (2.8%)	

### PERSPECTIVES:

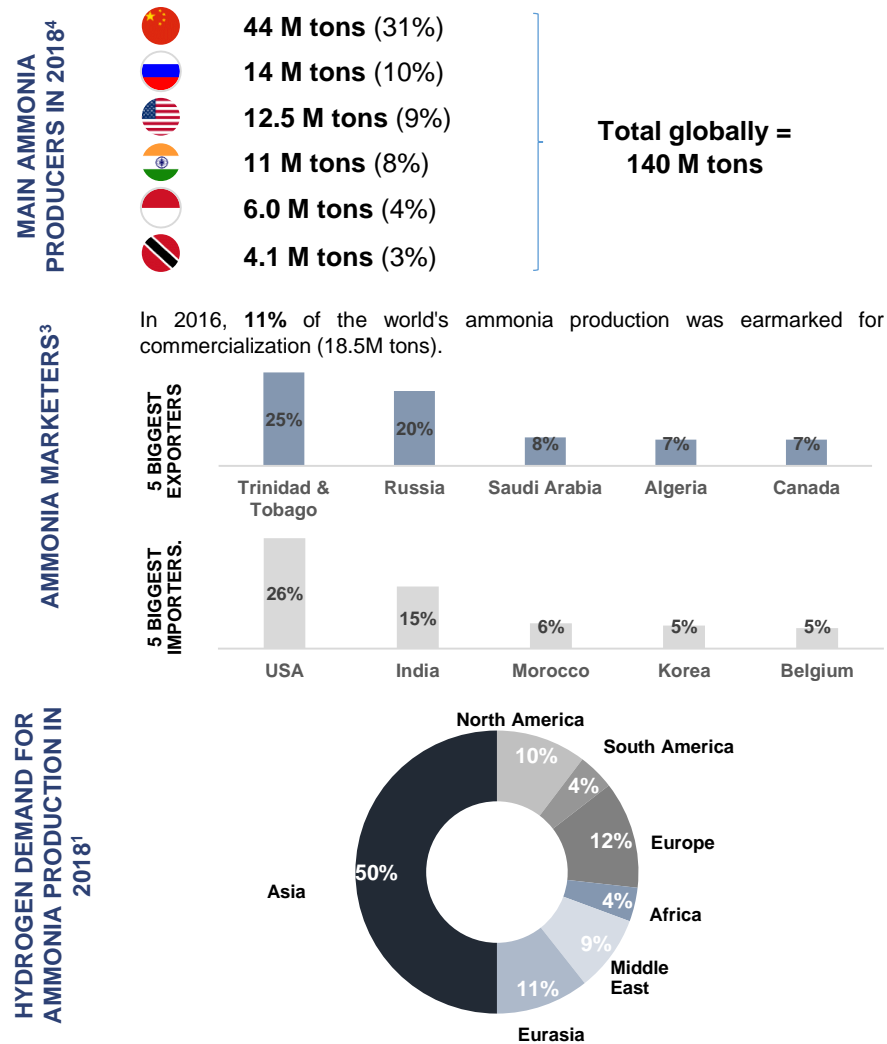
- Current environmental fuel requirements** are facilitating the **growth of demand for hydrogen as a raw material in refineries**. These requirements, among others, are forcing the reduction of sulphur content levels in fuels (e.g., China), **increasing the demand for hydrogen in Hydrotreatment and Hydrocracking**.
- Environmental restrictions and high CO<sub>2</sub> prices** could increase investments in the **association of hydrogen production from the reform/gasification of fossil fuels with CCUS and the reduction of costs in CO<sub>2</sub> refining**. Obtaining green hydrogen from water electrolysis is being analyzed and Shell is developing a pilot project with a 10MW unit.

## Current hydrogen uses – Chemical Industry - Ammonia

### HYDROGEN USES DESCRIPTION:

- In 2018, **31 MtH<sub>2</sub>** were used for ammonia production, forming **27% of global hydrogen demand** and **67% of demand in the chemical industry**<sup>1</sup>.
- Most of the production of ammonia (**~80%**)<sup>2</sup> was subsequently used as a **raw material for the manufacture of nitrogen-based fertilizers**, which in turn accounts for around 57% of the global fertilizer industry<sup>3</sup>:
  - Urea (~53%).
  - Ammonium nitrate (~27%).
  - DAP/MAP, NPK, other nitrogen-based products. (~20%)
- Remaining production of ammonia (**~20%**) is used for **industrial applications**:
  - In heat exchange processes such as refrigerant gas.
  - Manufacture: plastics, synthetic fibers, explosives, resins and other materials.
- Hydrogen is the **main cost** in ammonia production. Most ammonia exporters are located in natural gas-rich countries with cheap access to these resources.

### GLOBAL MARKET VISION:



### PERSPECTIVES:

- Global ammonia production** is estimated to **increase** by 6% over the next 3 years<sup>4</sup>.
- The IEA considers that global hydrogen demand for ammonia production will increase from 31 MtH<sub>2</sub> in 2018 to 38 MtH<sub>2</sub> in 2030 **(+22% or CAGR 18-30 x 1.7%) due to growth in the fertilizer market, industrial ammonia applications and the use of ammonia as a hydrogen carrier**. This assumption by the EEA corresponds to the growth in ammonia demand by +1.9% per annum between 2006 and 2016<sup>3</sup>.
- The production of ammonia from green hydrogen is expected to increase costs by 60% (480 s/ton NH<sub>3</sub>)<sup>5</sup>.

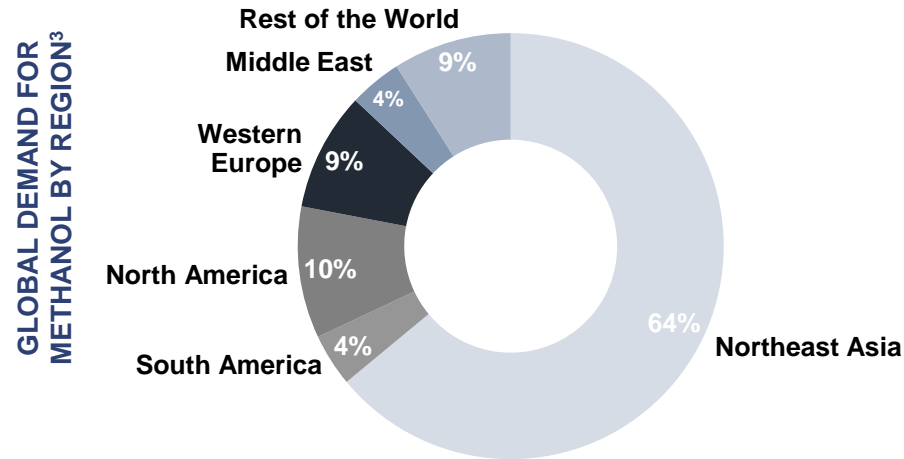


## Current hydrogen uses – Chemical Industry - Methanol

### HYDROGEN USES DESCRIPTION:

- In 2018, **12 MtH<sub>2</sub>** were used for methanol production, which accounted for **10.4% of global hydrogen demand** and **26% of the chemical industry's hydrogen demand**<sup>1</sup>.
- Main methanol uses are:
  - Manufacture of chemicals (~52%)<sup>2</sup>** such as formaldehyde (later treated to form resins, glues and plastics), acetic acid, etc.
  - Methanol for fuels (~19%)<sup>2</sup>**: mostly gasoline and biodiesel.
  - Methanol for value-added chemicals (~25%)<sup>2</sup>** which are the precursors of most plastics, including:
    - Methanol for olefins**: production of light olefins, such as ethylene and propel it, for the plastics industry through the decomposition of hydrocarbons with steam (ethanol and naphtha). It is currently being marketed, especially in China.
    - Methanol for aromatics**, which is in the demonstration and development phase, and not at a marketing stage.

### GLOBAL MARKET VISION:



### RELEVANT POINTS IN THE METHANOL MARKET<sup>3,4</sup>

- Demand for methanol is the main demand for a chemical, with the **highest growth rate** in recent years (CAGR 2007-2017 = 8.0%)<sup>3</sup>.
- In 2017, the **North Asian area** (led by China) accounted for **54% of global methanol production capacity**.
- Demand for methanol for fuels has declined in recent years but it has been offset by the **growing demand for chemicals and the construction of methanol units for olefins** in China.

### PERSPECTIVES<sup>4</sup>:

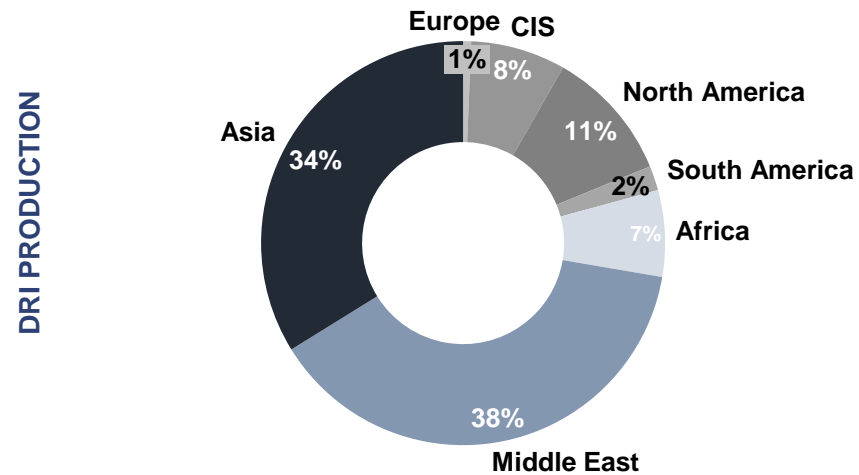
- In the short term (2025), the addition of **new methanol production capacity** is highly concentrated in the **North American and Asia-Pacific markets** given the availability of low-cost fuels such as natural gas (United States) and coal (China).
- The IEA believes that global hydrogen demand for methanol production will increase from 12 MtH<sub>2</sub> in 2018 to 18.3 MtH<sub>2</sub> by 2030 (**+53% or CAGR 18-30 x 3.6%**) due to the increasing demand for methanol in industrial applications, but **especially due to the disruption of methanol for olefins and methanol for aromatic processes in China (CAGR 18-30 = 4.1%)**.
- Methanol from CO<sub>2</sub> and H<sub>2</sub> is currently being produced on a low scale and sold by a Premium** (approx. 2-3x cost of fossil methanol). Green hydrogen significantly increases the costs of methanol, and the **equilibrium point could be around 1.8 €/kg with a CO<sub>2</sub> cost of 90 €/ton<sup>5</sup>**.

## Current hydrogen uses – Metal Industry

### HYDROGEN USES DESCRIPTION:

- In the iron and steel industry, hydrogen is used as raw material for production processes that transform iron ore into steel (primary production methods). There are two main routes:
  - High Furnace - Basic Oxygen Oven (~90% of current steel production):** Hydrogen obtained as a by-product is produced in mixture with other gases as a result of the use of coal and coke. Part of it is consumed in the same process (9 Mt H<sub>2</sub>/year mix) and the other part is transferred for other on-site applications, such as the production of electricity in steel power plants (14 Mt H<sub>2</sub>/year mix). The production of value-added chemicals from hydrogen containing waste gases is being studied.
  - Direct Iron Reduction (DRI) (7% of current steel production):** Synthetic natural gas (CO+H<sub>2</sub>) is generated in specialized facilities (Reformed from methane to steam using natural gas or coal gasifiers producing 4 MtH<sub>2</sub>/year) and used as raw material for the reduction process, in which the oxygen of the iron ore is removed to produce sponge iron. The root can be mixed with the steel residues and sent to an electric arc converter where the steel is produced.

### GLOBAL MARKET VISION<sup>2</sup>:



### DRI MARKET HIGHLIGHTS

- The **Middle East** and **Asia** are the leading regions in DRI. The countries that contribute the most to these regions are respectively **Iran** (64% of Middle Eastern production) and **India** (97% of Asian production).
- In addition to the Middle East, which represents the largest **CAGR between 2010-2018 (+9.5%)**, only **CIS (Russia)** has a growth rate between 2010-2018 (+5.9%) above the global average (+4.3%).
- In relation to the export/import ratio of DRI products, Russia is currently the largest supplier while the United States, Italy and Turkey are the largest consumers<sup>3</sup>.

### PERSPECTIVES<sup>1</sup>:

- The IEA estimates that **global demand for steel will increase by 6% by 2030**.
- The shift towards **production processes with low carbon intensity** will depend to a large extent on CO<sub>2</sub> emission prices.
- DRI production has grown in countries with cheap fossil fuels (Iran or India). DRI's biggest driver in other countries is CO<sub>2</sub> prices. European producers are first considering changing their current processes to CCUS adaptation processes. The **green H<sub>2</sub> is expected to progressively replace natural gas and the high furnace process – basic oxygen furnace from 2035**. The cost of steel is expected to increase by 20-30%, although the CO<sub>2</sub> emission cost can reduce that difference. Various steel producers such as Voestalpine, Thyssenkrupp, Tata Steel, SSAB and ArcelorMittal are researching and carrying out pilots.
- The demand for hydrogen for iron and steel applications will also depend on **DRI's share of primary steel production**. In this regard, the IEA estimates a **demand of 8 MtH<sub>2</sub> in 2030** and, in the case of a 100% DRI share in steel production, 62 MtH<sub>2</sub> by 2050.



## Current hydrogen uses – Other uses

HYDROGEN USES DESCRIPTION<sup>1,2</sup>:

In 2018, **30 MtH<sub>2</sub>** were used for various applications and consumed as hydrogen by-product in a gas mixture (87%) or as pure hydrogen (13%):

Sector	Description	Plant production	H <sub>2</sub> consumption	H <sub>2</sub> flow	Electrolytic capacity
<b>Silicon production</b>	As a reducing agent for the production of silicon from SiO <sub>2</sub> in the Siemens process and its variants. A small demand could make the use of water electrolytes attractive.	5,000-40,000 ton Si/year	100-300 kgH <sub>2</sub> /ton Si	600-6,000 Nm <sup>3</sup> /h	2 MW
<b>Plain glass production</b>	Molten glass is cooled into an N <sub>2</sub> -H <sub>2</sub> , where H <sub>2</sub> is used to prevent oxidation.	300-700 ton glass/day	0.07 mil M Nm <sup>3</sup> /year	100 Nm <sup>3</sup> /h	0.5 MW
<b>Food Industry</b>	Hydrogen is used for the hydrogenation of fats for margarine, vegetable fats and animal fats.	1,000-100,000 ton oil/year	4-6 kgH <sub>2</sub> /ton oil	10-50 Nm <sup>3</sup> /h	1.6 MW
<b>Electronics</b>	Hydrogen is used in the manufacture of semiconductor materials, especially in wafer manufacturing processes, which last about 60 days. Other applications include the manufacture of screens, LEDs and photovoltaic plates.	80-120,000 wafers per month	1,200 kgH <sub>2</sub> /month	500 Nm <sup>3</sup> /h	2 MW
<b>Metallurgy</b>	Hydrogen is used to prevent oxidation and reduce oxides during heat treatments.	-	-	-	-
<b>Refrigeration</b>	Cooling alternators in power plants such as BWR nuclear plants.	150-1,200 MW	0.007 Nm <sup>3</sup> /MW	1-10 Nm <sup>3</sup> /h	-

PERSPECTIVES<sup>1,2</sup>:

Hydrogen uses in **other applications** are **expected to grow** in the short/medium term thanks to the disruption of new and future applications:



**Electricity generation**



**Mobility**



**Heating and electricity in buildings**



**Thermal Industry**

## Hydrogen uses with great potential – H<sub>2</sub>-to-Gas

Hydrogen is able to connect power generation and energy transport using the natural gas grid and reducing the need for greater investment by being able to use existing infrastructure.

### HYDROGEN INJECTION INTO THE GAS NETWORK

Natural gas will play a **key role in helping to meet environmental targets** for which the use of hydrogen in two different ways could accelerate the transition to a decarbonized future.

#### H<sub>2</sub> Blending



Although at low shares, blending H<sub>2</sub> into the existing gas grid could become a great option for renewable energy transmission and storage in the near-term.

- It is estimated that with minor adaptations, equipment such as boilers, cookers, engines and turbines could accept 20% blends. The 2030 target (4 GW) could be met if 5% of the gas grid were hydrogen (which is possible today according to PD01).
- A **3% hydrogen blend in natural gas grids** would require **around 100 gigawatts (GW)** of electrolysis capacity.
- **Incentives** should be in place for **renewable gases** such in the case of biomethane in certain countries to make it competitive with **much cheaper**

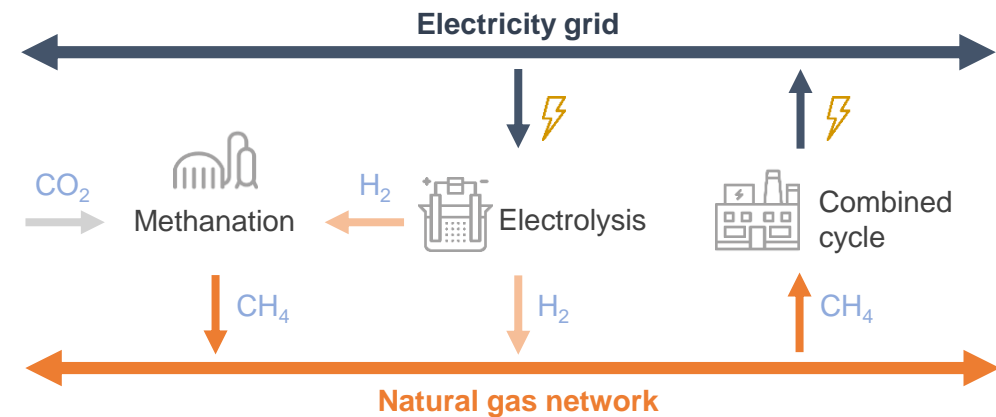
#### Methanation



Synthetic methane (SNG) can be directly produced from CO<sub>2</sub> and hydrogen in a methanation process:

- SNG key advantage is its **compatibility** with **natural gas infrastructure for transport, distribution and generation**.
- Estimated SNG costs of 135 €/kWh (~6x fossil natural gas). **It is unrealistic that SNG can be massively deployed unless it is heavily subsidized.**

### ELECTRICITY AND GAS GRID INTERCONNECTION<sup>3</sup>



The **injection of renewable hydrogen** into the natural gas network has special relevance in a context of high penetration of wind and photovoltaic energies, as is the case in Spain. Power-to-Gas **allows electricity to be stored massively** through the **interconnection of the electricity grid and the gas network**, with technologies such as electrolysis, which converts electricity into hydrogen.

## Hydrogen uses with great potential – H<sub>2</sub>-to-Liquid

Hydrogen can be mixed with other compounds, such as carbon dioxide, to produce renewable fuel, which can replace other traditional raw materials, such as petroleum derivatives.

### CONVERTING HYDROGEN INTO LIQUIDS

**Synthetic fuels** are produced by combining **CO and Hydrogen**. Hydrogen can be produced from any source such as water electrolysis, electricity, biomass or fossil fuels:

- Synthetic fuels are **compatible with fossil fuel engines, turbines and transport and distribution infrastructure**.
- If electricity is used for hydrogen production, synfuels are also called **e-fuels or electro fuels**.
- **E-fuels** are an **alternative to biofuels** as they do not compete with food (1st gen) and have no production constraint as waste-based biofuels (Advanced biofuels)

### MAIN PRODUCTION COST DRIVERS

Significant amounts of **electricity and generation capacity are required** for the production of synthetic hydrocarbons because of the **low overall efficiency** of production processes.

- **Between 45–60% of the electricity** used for the production of synthetic hydrocarbons **is lost during the process**.
- Hydrogen-based fuels **production costs is 2-3 times over** today's **fossil fuel cost**. They can vary significantly, depending on the availability of **low-cost renewable energy**.

### MAIN PATHWAYS

#### Synthetic Diesel or Kerosene



The production of synthetic diesel or kerosene requires hydrogen and carbon monoxide (CO) as inputs.

Hydrogen and CO<sub>2</sub> are transformed into CO through Reverse Water Gas Shift reaction. CO plus additional H<sub>2</sub> (syngas) is then converted via Fischer-Tropsch synthesis to raw liquid fuels and later into synthetic diesel or kerosene.

H<sub>2</sub>O and CO<sub>2</sub> co-electrolysis in SOEC electrolyzers followed by FT reaction can substantially reduce fuel production costs.

#### Synthetic Methanol



Methanol is the **simplest alcohol**, with a **80% higher energy density than liquid hydrogen**.

- CO<sub>2</sub> can be directly hydrogenated into methanol.
- Around 40% of global methanol production today is used for fuel use (directly blended with gasoline, in the synthesis of MTBE fuel additive, in biodiesel production or as DME substituting GLP or blended with diesel fuel).

#### Other alternatives



Other less developed e-Fuels are possible:

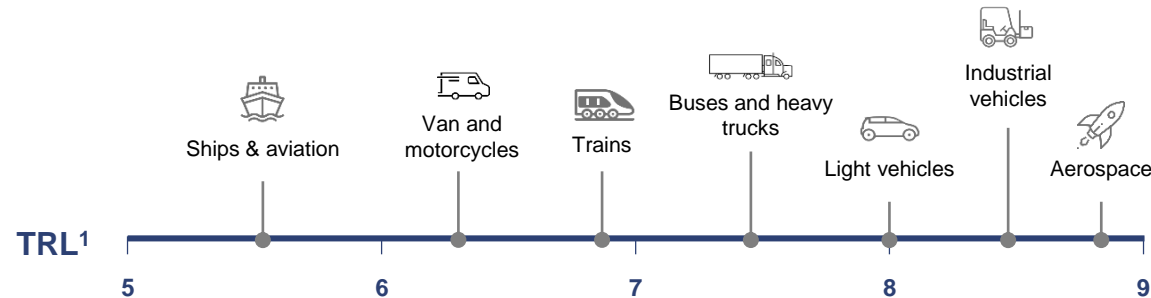
- Ammonia is a carbon-free e-fuel. The synthesis process is well known although its deployment in power generation and transport is still very limited
- Ethanol production from CO and H<sub>2</sub> using biological pathways is being developed although its economics are much worse than 1st generation bioethanol

E-fuels are seen as a long-term alternative (beyond 2030) for transport decarbonization (mainly air and marine shipping) in combination with biofuels. Commercial scale e-fuels production plants would require hydrogen production at GW scale.

## Hydrogen uses with great potential – H<sub>2</sub>-to-Liquid - Mobility

The transport industry is preparing for potential hydrogen penetration as a real alternative to oil, but this makes it essential to raise costs, as well as to develop all the infrastructure needed to do so.

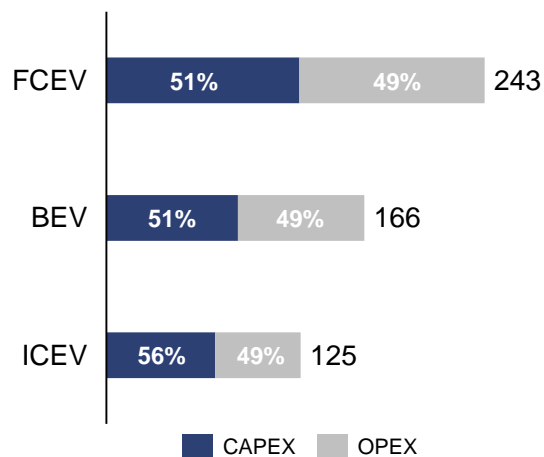
### STATE OF THE ART



- Currently, the state of development of the technology that allows the use of hydrogen as fuel depends to a large extent on the transport sector, with the aerospace sector and industrial machines being the ones that have the highest level of maturity.
- The most important advantage of transport using H<sub>2</sub> fuel cells, compared to battery-powered electric vehicles, is functionality comparable to today's combustion engines.

### COST EFFICIENCY

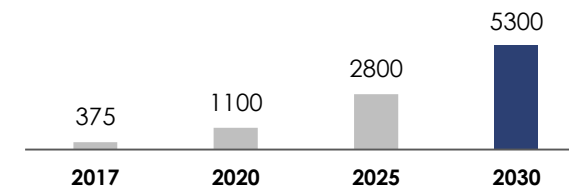
Acquisition and Maintenance Cost by vehicle type - 2019<sup>2</sup>



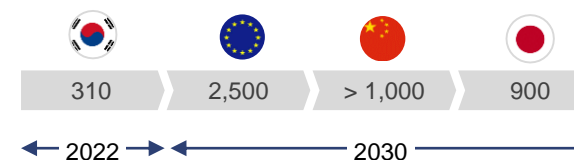
- Currently, FCEV (fuel cell vehicles) have not yet reached the degree of maturity needed to compete with other vehicles using other technologies (BEV – battery; ICEV – gasoline combustion), and they have developed economies of scale to have much more competitive and affordable prices for the general public..
- According to this same report, a competitive breakeven in FCEV costs is expected to be achieved with ICEV by 2026, and with BEV by 2027.

### INFRASTRUCTURE DEVELOPMENT

EESS H<sub>2</sub> global network<sup>3</sup>



EESS development plans in key countries<sup>3</sup>

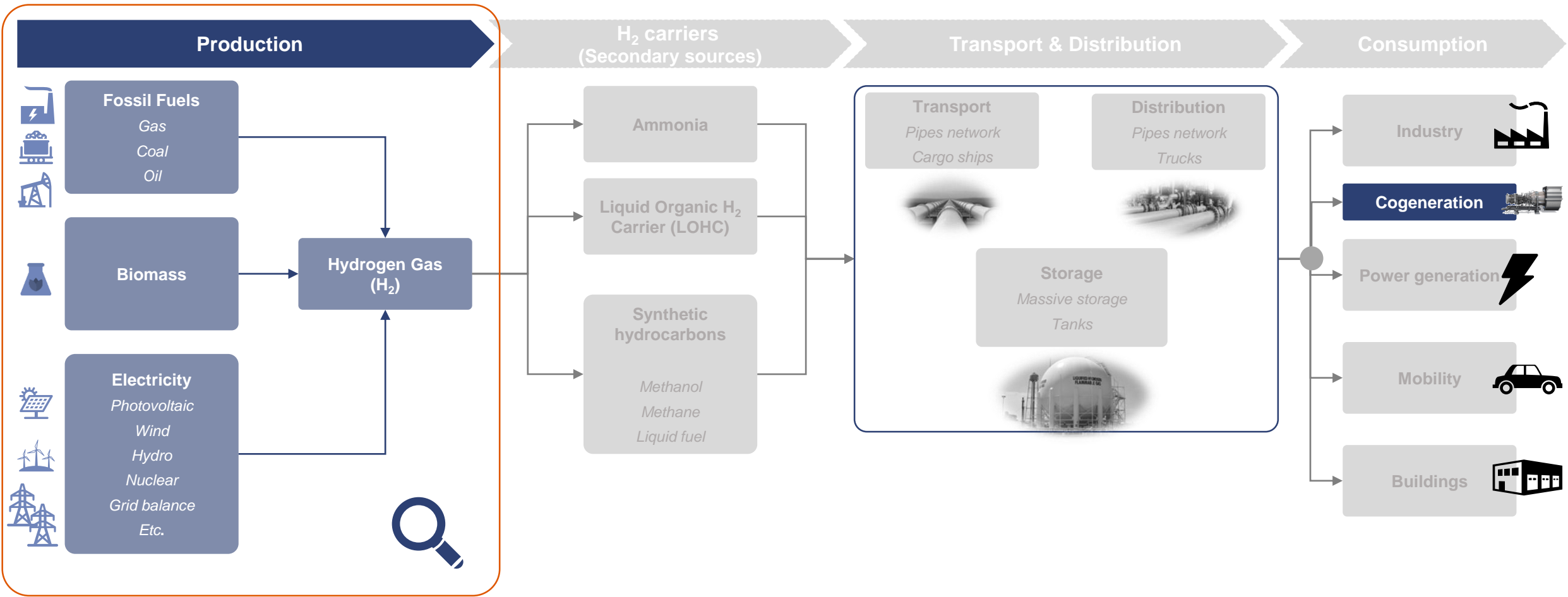


2030 Perspectives<sup>3</sup>

- Overall increase in the number of H<sub>2</sub> vehicles to an estimated total of 10-15 MM.
- Germany, South Korea, Japan and California are the ones best positioned to be global market leaders.
- Manufacture of around 500,000 trucks representing 2.5% of % of annual sales.
- 10% of buses sold will be fuel cell.
- 10% of non-electric trains will use H<sub>2</sub> as fuel.

## H<sub>2</sub> production

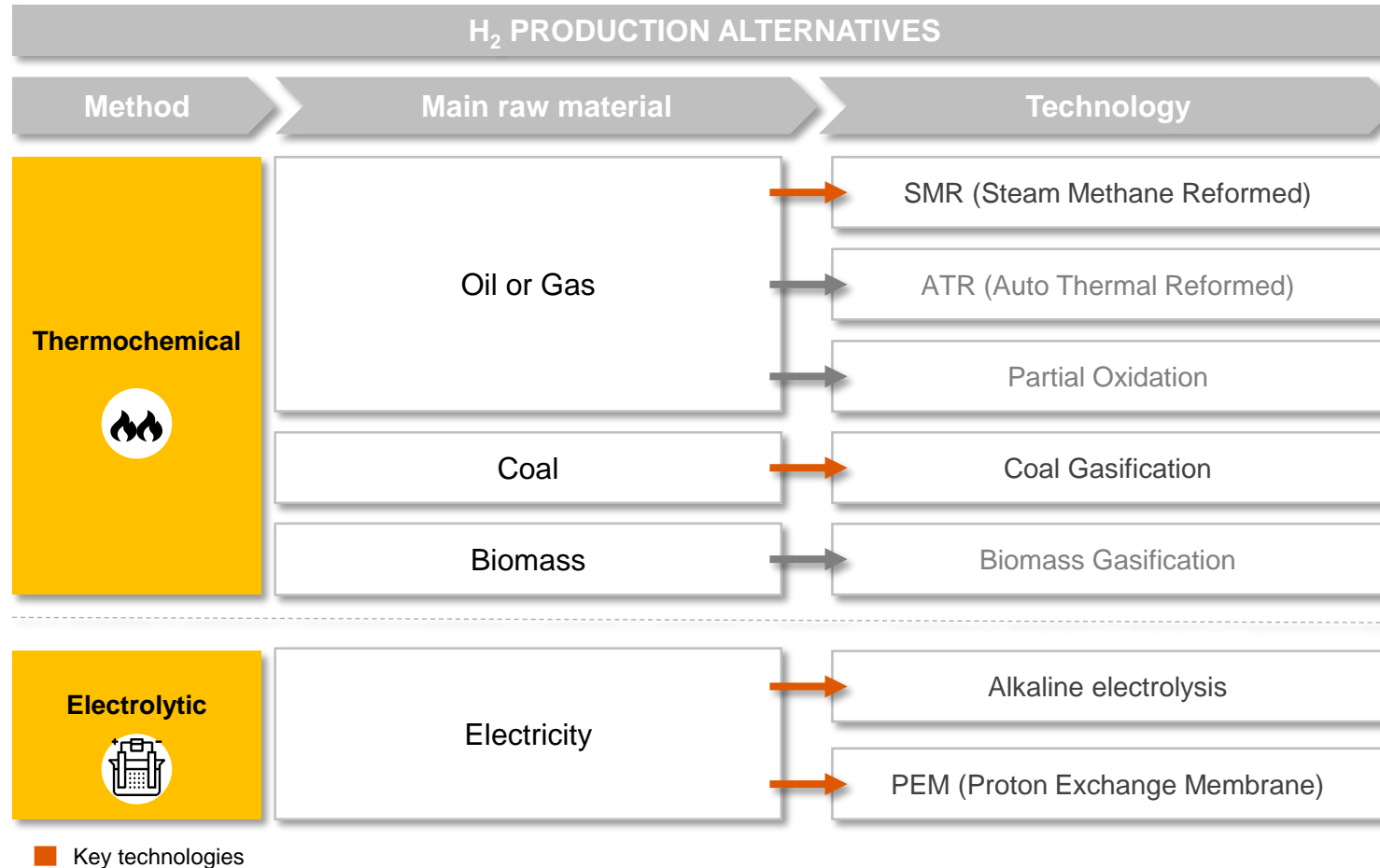
In the hydrogen value chain, there are different sources of production depending on the nature and origin of the energy from which it is generated.



**Almost 98% of hydrogen is produced from fossil raw materials (natural gas and coal). The need to decarbonize the industry is driving the combination of CCUS<sup>1</sup> with fossil hydrogen generation or its complete replacement by green hydrogen.**

## H<sub>2</sub> production – Production technologies

There are currently two main pathways for hydrogen production (H<sub>2</sub>), depending on the raw material and technology used.



Hydrogen can be extracted from fossil fuels, biomass and water through thermochemical and electrolytic processes. The main technologies are described below:

- **SMR technology** is the **most widespread method for extracting hydrogen from natural gas** for the ammonia and methanol refineries and industries (where large volumes of hydrogen are required). Represents **75% of the world's dedicated hydrogen production**.
- **Coal gasification** accounts for **23% of the world's dedicated hydrogen production**. This technology is **mainly used in China** due to the supply of cheap coal.
- **Electrolysis** options represent the **rest of the world's production**, about **2%**. Electrolysis plays a minor role in total hydrogen production today, especially in the chlorine-alkaline industry where hydrogen is a by-product.
- Other options for H<sub>2</sub> production such as carbon cracking are currently being studied.

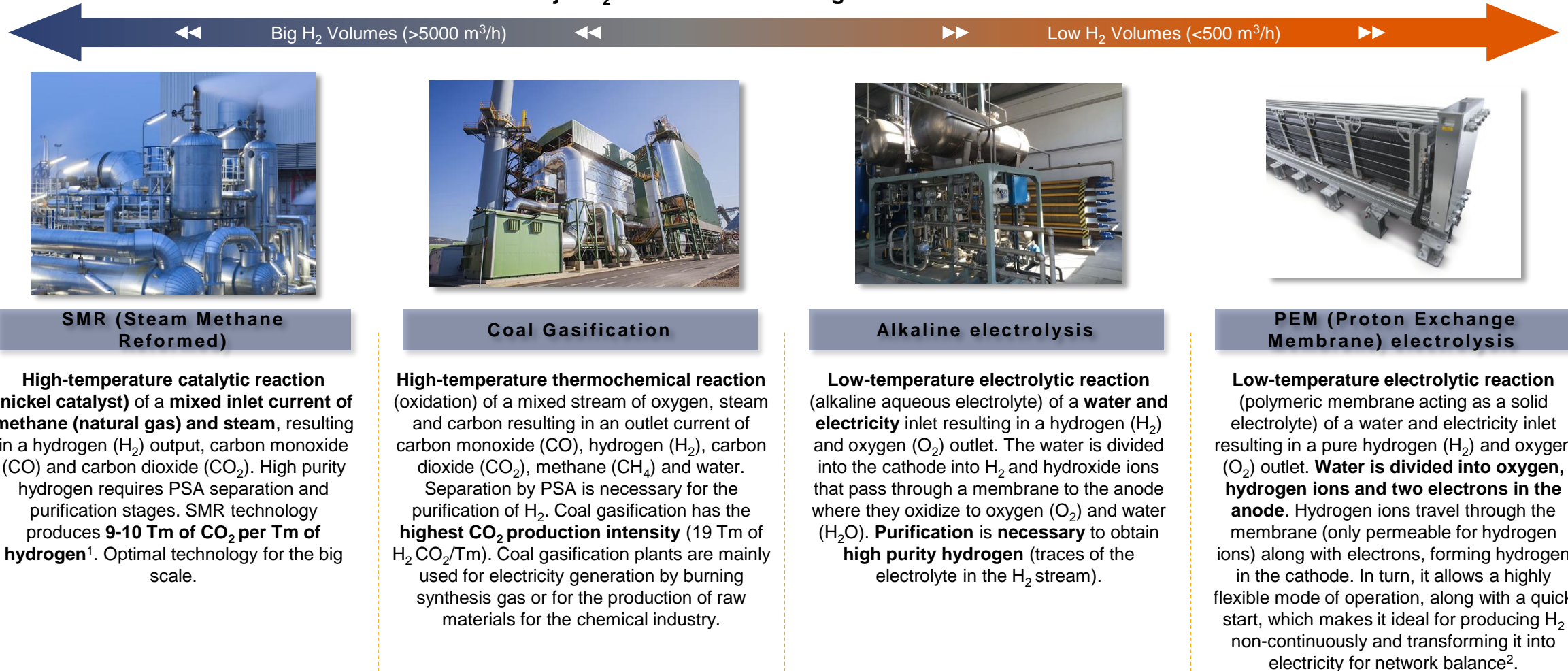
**Fossil fuel-based production pathways cover virtually all hydrogen demand. Natural gas is the main source of hydrogen produced mainly through SMR technology**



## H<sub>2</sub> production – Most commercially widespread production technologies

Today, fossil hydrogen conversion technologies play a dominant role when large volumes of hydrogen are demanded, while applications based on electrolysis are primarily intended to meet on-site demand for hydrogen in low volumes.

### Major H<sub>2</sub> Production Technologies at commercial scale





## H<sub>2</sub> production – Emerging renewable H<sub>2</sub> production technologies

In addition to the previous ones, solid oxide cell-based electrolysis (SOFC) technology is the most promising technology, with relevant development potential due to its high efficiency and inverse mode operating capacity.

### What does it consist in?

**High temperature steam** electrolysis for the production of H<sub>2</sub> and O<sub>2</sub> by dividing water molecules. SO electrolytes use a **solid oxide electrolyte**, a ceramic membrane that is only **permeable to oxygen ions** (O<sub>2</sub><sup>-</sup>), so only water and electricity are needed to produce H<sub>2</sub>.

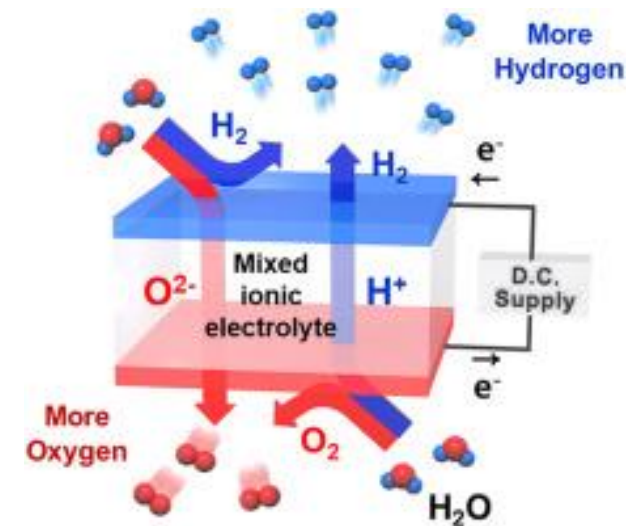
### H<sub>2</sub> Production Process

Steam is divided into H<sub>2</sub> and O<sub>2</sub> in the cathode. Oxygen ions (O<sub>2</sub><sup>-</sup>) pass through the solid oxide membrane and form O<sub>2</sub> in the anode. The process requires an operating temperature of between 500 and 750 °C. SOFC can also be used to produce syngas (CO+H<sub>2</sub> raw material for synthetic fuels) through coelectrolysis.

### Key Points

- The **technology** is in the **R&D phase** and the first trading units are entering the market through different suppliers.
- **High efficiency (>70%)** due to the low voltage of the cell (since steam facilitates the process of dividing).
- **Limited** solid membrane **life** due to **thermal stress**, but with a large margin of improvement both at this point and in the cost of the unit.
- **Low operational flexibility** due to high temperature operating requirements.

### SOEC Process Outline



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SO electrolytes **can operate** in reverse mode **as a fuel cell**, turning the H<sub>2</sub> into electricity, meaning they **could provide equilibrium services to the grid** in combination with H<sub>2</sub> storage facilities

## H<sub>2</sub> production— Evolving technologies prospects for renewable H<sub>2</sub>

In the long term, a dominant technology is not expected to lead the H<sub>2</sub>'s production horizon, but a mix of different technologies depending on specific applications<sup>1</sup>.

		Efficiency % of LHV	Service life Battery working hours	CAPEX <sup>1</sup> €/kW <sub>e</sub>
Alkaline	Today	63 - 70	60.000 – 90.000	445 – 1190
	2030	65 - 71	90.000 – 100.000	360 – 760
	Long term	70 - 80	100.000 – 150.000	180 – 625
PEM	Today	56 - 60	30.000 – 90.000	980 – 1.600
	2030	63 – 68	60.000 – 90.000	580 – 1.335
	Long term	67 – 74	100.000 – 150.000	180 – 800
SOFC <sup>1</sup>	Today	74 – 81	10.000 – 30.000	2.500 – 5.000
	2030	77 – 84	40.000 – 60.000	710 – 2.500
	Long term	77 – 90	75.000 – 100.000	445 – 890

### Relevant aspects to consider

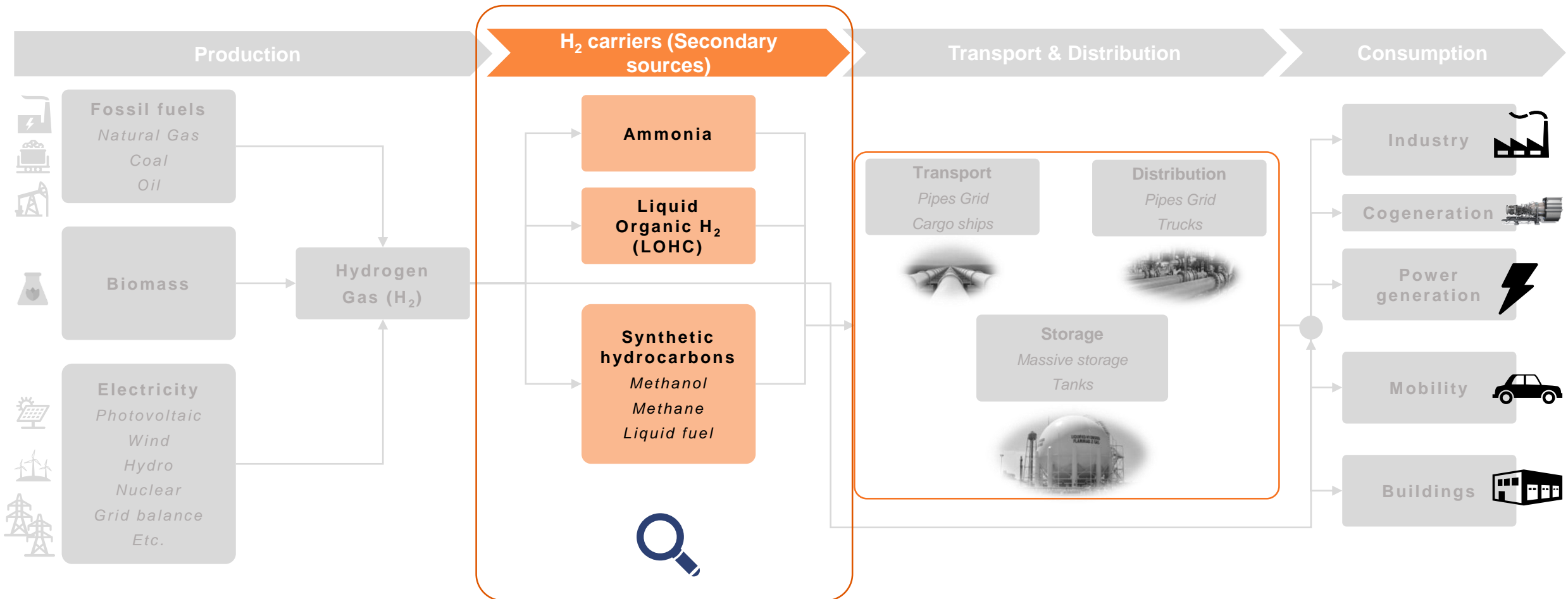
- **Alkaline technology** shows **limited room for improvement**. Being the least CAPEX alternative and mayor lifespan, along with its good efficiency levels, it makes it very suitable for large and continuous (stable) renewable hydrogen demands.
- **PEM electrolytes** are expected to be the **technology** that experiences the **highest improvement** in terms of medium- and long-term **efficiency**. Its potential to capture additional revenue streams from grid equilibrium services would push PEM electrolytes to play an important role.
- **Solid Oxide Electrolytes (SOFCs)** are estimated to **reduce their CAPEX by half** over the next decade, experiencing the biggest cost reduction for all technologies. The solid oxide electrolyte requires continuous operation to reduce performance losses associated with start and stop cycles. A very low flexibility prevents the adaptation of the SOFC to price variations from neglecting some of its higher efficiency advantage.

Sources: <sup>1</sup>IEA (2019): The Future of Hydrogen;

Notes: (1 USD = 0,89 Euro); \*For SOFC, electrical efficiency does not include steam-generated energy; \*\*CAPEX represents system costs, including power generation, gas conditioning and plant stabilization. CAPEX ranges reflect the different sizes and uncertainties of the systems.

## H<sub>2</sub> logistics

Within the supply value chain to cogeneration, hydrogen logistics would encompass transmission or transport, distribution and storage.



15% of the total volume of H<sub>2</sub> currently produced worldwide is transported and distributed by pipes and trucks<sup>1</sup>

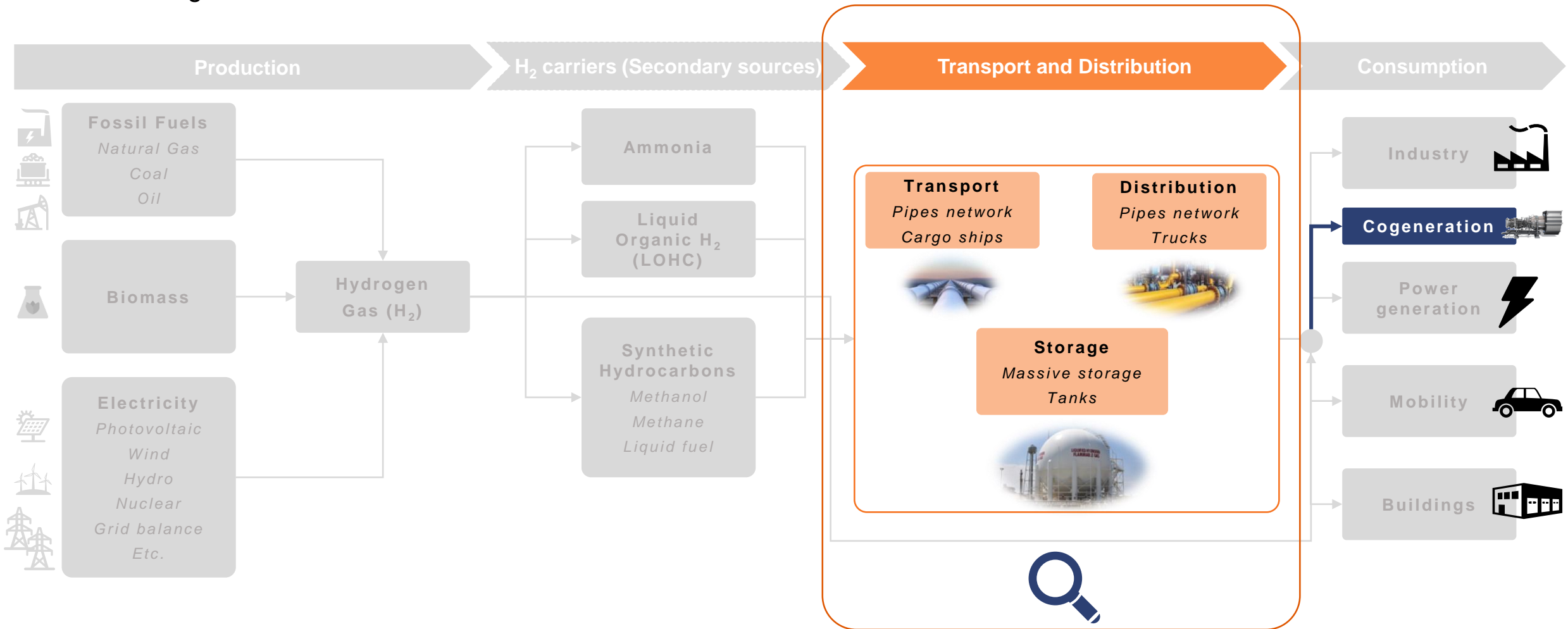
## H<sub>2</sub> carriers

One way to transport hydrogen is to use carriers, which are hydrogen-containing compounds. Hydrogen can be extracted in different ways depending on the end use to which it will be intended.

	AMMONIA	LIQUID ORGANIC H <sub>2</sub> (LOH)	SYNTHETIC HYDROCARBONS
Properties, uses and benefits	<ul style="list-style-type: none"> <li>It can be used as raw material, fuel or converted into hydrogen depending on the end use needed for the hydrogen it contains. Supply chain already established and matured globally.</li> <li>It has 50% higher volumetric energy density than liquid H<sub>2</sub>, making its transport more cost-effective in certain cases (long distances).</li> </ul>	<ul style="list-style-type: none"> <li>They have properties similar to crude oil and can use their infrastructure to be transported.</li> <li>Its main advantage is that they can be transported as liquids without the need for refrigeration.</li> </ul>	<ul style="list-style-type: none"> <li><i>Methane</i>: naturally sourced gas produced by decomposition of organic matter.</li> <li><i>Methanol</i>: type of alcohol that is produced from the previous one and is flammable and toxic.</li> <li><i>Liquid fuel</i>: is hydrogen in a liquid state. To keep it in this state it is necessary to compress it and cool it up to -253 °C.</li> </ul>
Drawbacks	<ul style="list-style-type: none"> <li><b>Toxicity, corrosion, flammability</b>, leakage risks and high-water solubility.</li> </ul>	<ul style="list-style-type: none"> <li>Methylcyclohexane, for example, the most cost-effective LOHC, contains toluene, which is <b>flammable and toxic</b>.</li> </ul>	<ul style="list-style-type: none"> <li>Some of these compounds are <b>toxic and flammable</b> so their <b>handling is complex and dangerous</b>.</li> </ul>

## H<sub>2</sub> logistics

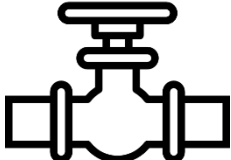
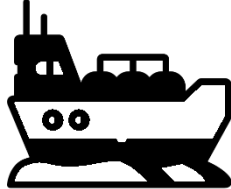
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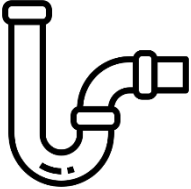
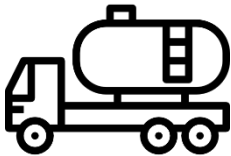
## H<sub>2</sub> logistics – Transport

The low density of hydrogen makes its transport expensive and inefficient. Developing cost-efficient and cost-competitive technology is one of the main challenges of the hydrogen value chain to bridge the gap between generation (supply) and demand.

Transport Technology	Description	Pros and Cons
<b>Pipes network</b> 	<ul style="list-style-type: none"> <li>Today, refineries and chemical industries operate dedicated pipelines and pipelines to meet their own demand.</li> <li>There are <b>different options</b> related to the <b>hydrogen transport by pipes</b>: <ul style="list-style-type: none"> <li>Development of a new transport infrastructure (high CAPEX).</li> <li>Taking advantage of high-pressure pipelines that are no longer in use (asset renewal)).</li> <li>Hydrogen mixing in the NG network (additional costs related to hydrogen injection, separation, NG recompression, etc.)</li> </ul> </li> <li>Ammonia and LOHC can also be transported by pipeline, but their economy depends on the conversion costs, delivery distance and reverse logistics of LOHC.</li> </ul>	<ul style="list-style-type: none"> <li>✓ Low OPEX and lifespan of more than 40 years</li> <li>✓ Use alternatives for infrastructure.</li> <li>✗ High CAPEX that may be the biggest disincentive for investors (new infrastructure)</li> </ul>
<b>Cargo ships</b> 	<ul style="list-style-type: none"> <li>The transport of liquid hydrogen is based on keeping tanks below -253 °C using cryogenic technologies and special insulating materials.</li> <li>Hydrogen transport value chain requires additional infrastructure in exporting/importing countries: storage tanks, liquefaction and regasification plants, conversion and conversion plants, etc.</li> <li>Ammonia transport is currently possible and transported in semi-cooled LPG tanks along existing ammonia trade routes.</li> </ul>	<ul style="list-style-type: none"> <li>✓ Exploitation of existing LNG trade routes</li> <li>✓ The return could be used to transport other high-value liquids</li> <li>✗ Technological maturity is at the demonstration level</li> <li>✗ Energy losses due to boiling of the liquid</li> </ul>

## H<sub>2</sub> logistics – Distribution


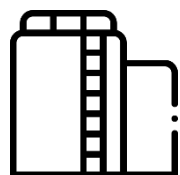
Currently, hydrogen distribution is done by road transport (trucks) for short distances and reduced volumes. If hydrogen demand increases due to new end applications, distribution technologies will need to be improved.

Distribution technology	Description	Pros and Cons
<b>Pipes network</b> 	<ul style="list-style-type: none"> <li>The natural gas distribution network can be used, on a limited basis, for local hydrogen distribution (H<sub>2</sub>) mixed.</li> <li>Modern pipe materials, such as polyethylene or fiber-reinforced polymer (e.g., the UK gas distribution network), are suitable for hydrogen with small improvements.</li> <li>New network infrastructures motivated by the demand for heat and electricity from hydrogen buildings could increase the price of the product for end users.</li> <li>The distribution of ammonia and LOHC<sup>1</sup> by pipe is not attractive from the point of view of conversion, conversion and purification costs.</li> </ul>	<ul style="list-style-type: none"> <li>✓ The natural gas distribution network is viable for the distribution of H<sub>2</sub></li> <li>✗ CAPEX investments are needed to build new infrastructure and improve existing infrastructure.</li> <li>✗ High distribution costs for hydrogen carriers due to conversion costs.</li> </ul>
<b>Trucks</b> 	<ul style="list-style-type: none"> <li>Hydrogen is compressed and loaded into tubular trailers. Other hydrogen-carrying products (ammonia and LOHC) can also be distributed by truck.</li> <li>Low-compression hydrogen (200 bar) distributed per truck is currently the most widespread solution for deliveries of less than 300 km and small volumes(&lt; 300 kgH<sub>2</sub>)<sup>1</sup>.</li> <li>Higher-pressure transport trailers (1,100 kg of hydrogen compressed in cylinders at 500 bar) are expected to reduce road distribution costs by 2025 (Projected CAPEX from 590 euros/kg H<sub>2</sub> versus 470 euros/kg H<sub>2</sub> for transport trucks from H<sub>2</sub> to 200 bar)<sup>2</sup>.</li> </ul>	<ul style="list-style-type: none"> <li>✓ Market maturity for small volumes of H<sub>2</sub> at low pressure.</li> <li>✓ Cost reduction by 2025 thanks to high-pressure composite deposits.</li> <li>✗ High costs, especially for long distances</li> <li>✗ Distribution of liquid hydrogen to be transformed into gas (added cost)</li> </ul>






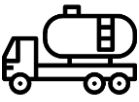
## H<sub>2</sub> logistics – Storage

Optimal integration of the hydrogen sector depends on the feasibility of storing large volumes at low cost. Although storage technologies depend on volume, duration, download speed, and end-use, bulk and tank storage are the solutions currently used.

Storage technology	Description	Pros y Cons
<b>Massive storage</b> 	<ul style="list-style-type: none"> <li>Hydrogen (gas) is stored long-term (seasonally) for large-scale applications: <ul style="list-style-type: none"> <li><b>Salt caverns:</b> efficiency of 98%<sup>1</sup> and low risk of H<sub>2</sub> contamination. They are currently in operation for industrial applications (e.g., a 10-20 ktH<sub>2</sub> salt cavern in the United States)<sup>1</sup></li> <li><b>Reserves of natural gas and depleted oil:</b> higher capacity but higher costs than salt caverns due to the presence of pollutants to be removed from hydrogen.</li> <li><b>Water aquifers:</b> their suitability has not yet been demonstrated due to the presence of reactive microorganisms.</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>✓ High efficiency</li> <li>✓ Low cost</li> <li>✓ High discharge rates</li> <li>✗ Geographic availability</li> <li>✗ Low maturity technologies</li> </ul>
<b>Tanks</b> 	<ul style="list-style-type: none"> <li>Hydrogen is compressed or liquefied to increase its energy density. There are currently two main solutions for short-term storage and small-scale applications<sup>2</sup>: <ul style="list-style-type: none"> <li><u>Stationary steel storage (P&lt;400 bar):</u> <ul style="list-style-type: none"> <li>Welded steel tanks: low pressure (50 bar) and 50 m<sup>3</sup> capacity.</li> <li>Steel cylinder packages: P&gt;200 bar.</li> </ul> </li> <li><u>Compound storage (P&gt;400 bar):</u> used when high pressure is needed.</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>✓ High efficiency (99%)<sup>1</sup></li> <li>✓ High discharge rates</li> <li>✗ Low energy density even when hydrogen is compressed.</li> <li>✗ Need for high-volume tanks</li> </ul>

## H<sub>2</sub> logistics – Transport & Distribution costs

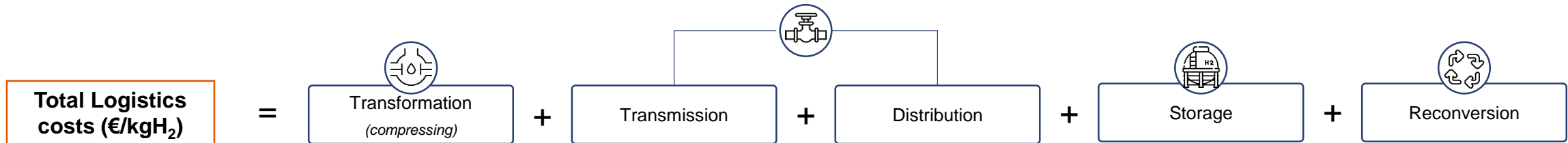
The balance point is defined by the adequacy of hydrogen carriers' technologies and transmission and distribution costs, including their conversion and conversion costs.

	Technology	Balance point	Hydrogen	Ammonia	LOHC <sup>1</sup>	
Transport	<b>Pipes network</b> 	Hydrogen (gas) transport costs increase rapidly with delivery distance due to compression station costs.	<b>0.82 €/kgH<sub>2</sub></b> (gas)	<b>1.24 €/kgH<sub>2</sub></b>	-	Transport + Conversion cost (1.500 km)
	<b>Cargo ships</b> 	The increase in shipping costs with distance is lower than in the case of the pipe network, which is linear.	<b>1.65 €/kgH<sub>2</sub></b> (liquid)	<b>0.99 €/kgH<sub>2</sub></b>	<b>0.49 €/kgH<sub>2</sub></b>	
Distribution	<b>Pipes network</b> 	Pipeline distribution is more cost-competitive than truck distribution for long-distance, high-volume deliveries.	<b>Depending on volume</b>	-	-	Distribution + reconversion costs (500 km)
	<b>Trucks</b> 	Despite high costs, compressed hydrogen trailers and liquid tankers are the most widely used distribution methods.	<b>1.48 €/kgH<sub>2</sub></b> (gas) <b>0.33 €/kgH<sub>2</sub></b> (liquid)	<b>1.24 €/kgH<sub>2</sub></b> 0.33 €/kg H <sub>2</sub> for direct use in ammonia industry	<b>2.39 €/kgH<sub>2</sub></b>	

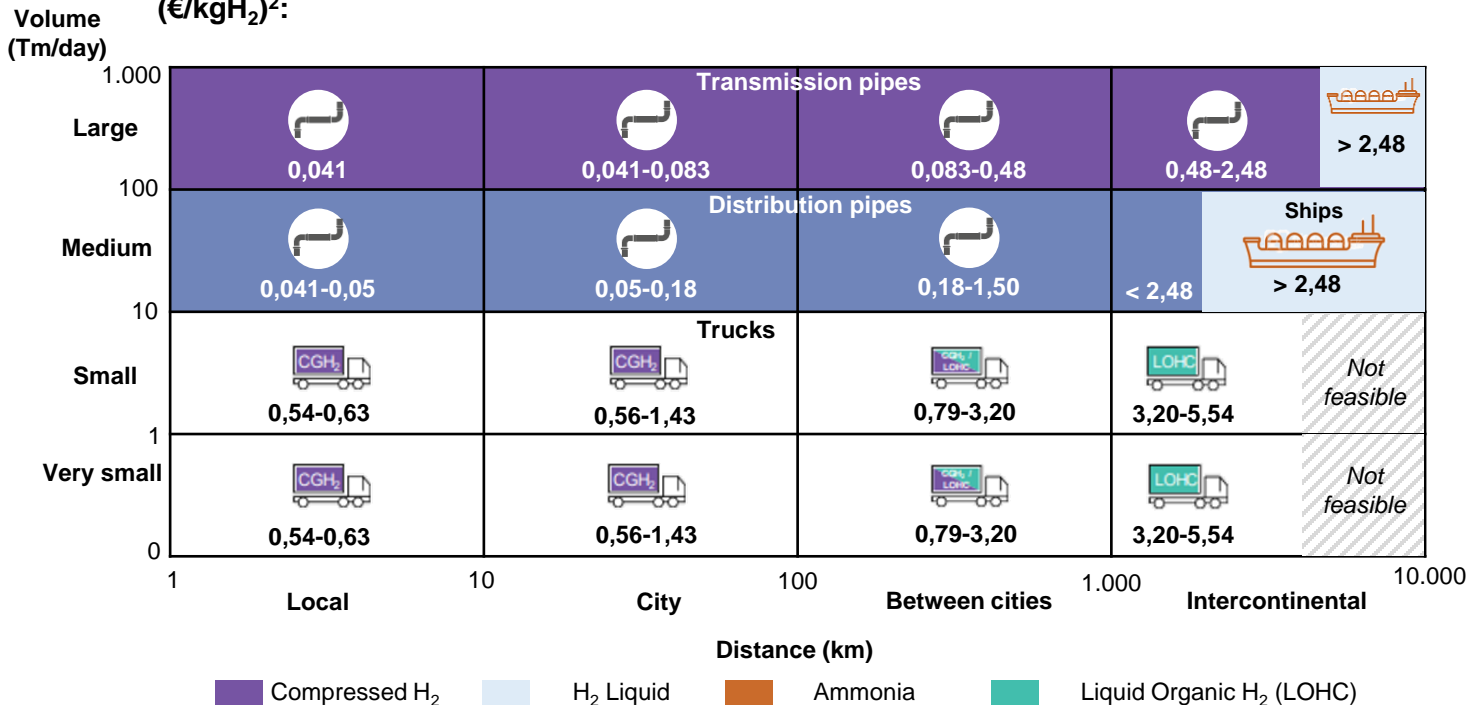
Ammonia is a promising hydrogen carrier for long-distance hydrogen transport due to its established supply chain and preventing reverse logistics, as in the case of LOHC

## H<sub>2</sub> logistics – Management & Logistics total costs

Although total handling costs increase with the number of value chain stages required prior to supply, hydrogen carriers are more competitive than hydrogen (gas) at certain delivery distances.



**Total costs of hydrogen transport and distribution based on distance and volume (€/kgH<sub>2</sub>)<sup>2</sup>:**



### Conclusions:

- 1 Depending on the mode of transport and the hydrogen carrier used, total handling costs could currently triple hydrogen generation costs.
- 2 Nevertheless, handling and logistics costs are expected to be reduced by 2030 through technological improvements and research projects.
- 3 Reducing management/logistics costs can make hydrogen exports/imports profitable:
  - Exports: countries with low-cost renewable generation costs.
  - Imports: countries with end-use ammonia applications (conversion cost savings) and large volumes of H<sub>2</sub> consumption with insufficient production capacity.

**Sources:** <sup>1</sup>IEA (2019): The Future of Hydrogen. **LOHC:** Liquid organic hydrogen carriers;

<sup>2</sup>BloombergNEF (2020): Figures include the cost of moving, compression (reconversion) and associated storage (20% assumed for pipes in a salt cavern). Ammonia is supposed to be inadequate on a small scale due to its toxicity. Although the LOHC is cheaper than THE LH<sub>2</sub> for long-distance transport, its transport is less likely than the LH<sub>2</sub> (more commercially developed). 1 USD = 0,83 €.



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