

Hydrogen Economy 2023-2033: Production, Storage, Distribution & Applications

Comprehensive review of the entire hydrogen value chain. Company profiles, technology analysis, key players and hydrogen market forecasts.

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IDTechEx Research



Report Overview



Slides:

627

Forecasts to:

2033

Companies:

28

The global low-carbon hydrogen market is expected to reach US\$130B by 2033

Hydrogen Economy 2023-2033: Production, Storage, Distribution & Applications

This report provides an overview of the entire hydrogen value chain, drawing on IDTechEx's extensive knowledge across many aspects of the sector. Covering hydrogen production, storage, distribution, fuel cells and end-use applications, the report provides:

- An introduction and motivation for the hydrogen economy
- Recent policy developments in the hydrogen industry.
- Discussion of key trends in the hydrogen industry.
- Analysis of underlying technologies across all value chain components, including hydrogen production (e.g., electrolyzers), storage (e.g., metal hydrides), distribution (e.g., pipelines) and end-use sectors (e.g., sustainable steelmaking).
- Techno-economic comparisons and benchmarking of hydrogen production, storage and distribution methods.
- Recent innovations and new technologies across all value chain components.
- Potential decarbonization pathways for hydrogen end-use sectors.
- Commercial activities including key players and projects under development.
- SWOT analyses and key takeaways from various parts of the value chain.
- Assessments of technical and commercial readiness.
- Granular 10-year market forecasts for hydrogen demand by applications (7 sectors), hydrogen production by source (grey, blue and green) and the hydrogen market (grey, blue and green).
- 28 company profiles covering established and emerging players across various parts of the value chain.

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- Technology assessment
- Technology scouting
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The Hydrogen Economy

The hydrogen economy is a conceptual framework where hydrogen, a low-carbon energy carrier, becomes a cornerstone in minimizing carbon footprint across various sectors. This concept embodies a future where hydrogen, due to its high-energy content and clean-burning properties, replaces traditional fossil fuels, ultimately reducing greenhouse gas emissions and meeting the growing demand for low-carbon energy.

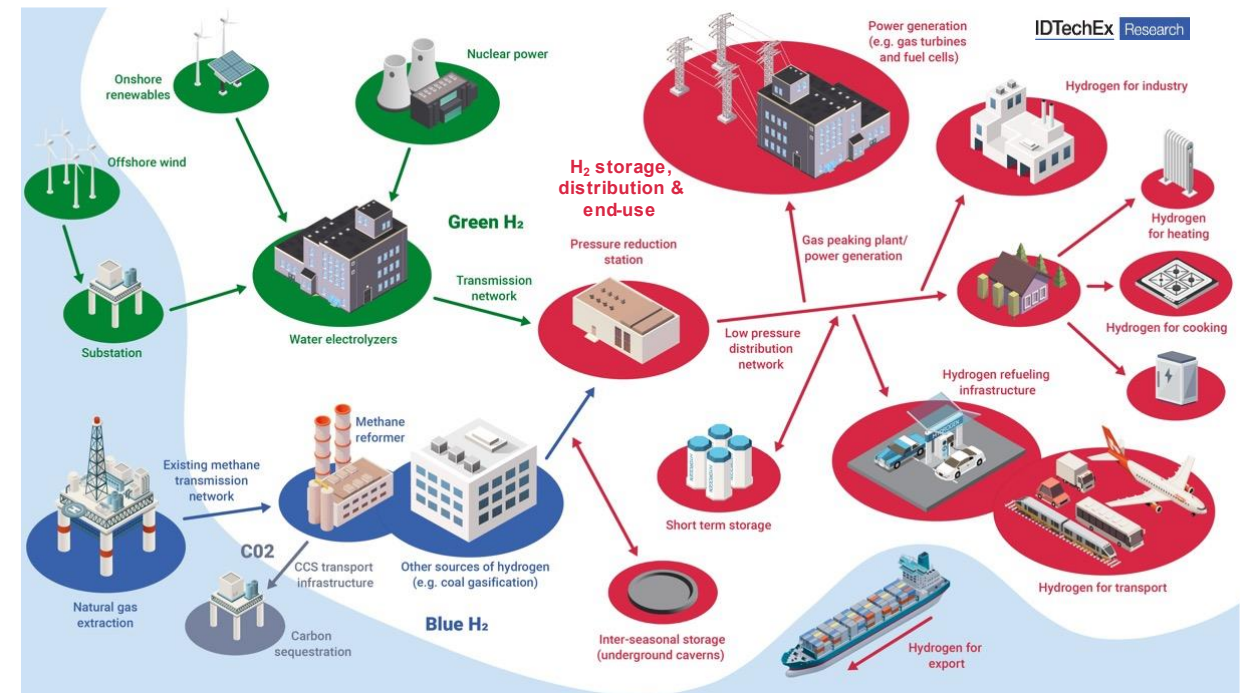
In essence, the hydrogen economy represents a pivotal shift in the world's approach to energy use and industry practices, with hydrogen technology playing a central role in this transformation.

Key components of the hydrogen economy

Successful implementation of the hydrogen economy necessitates the development and optimization of three crucial value chain components:

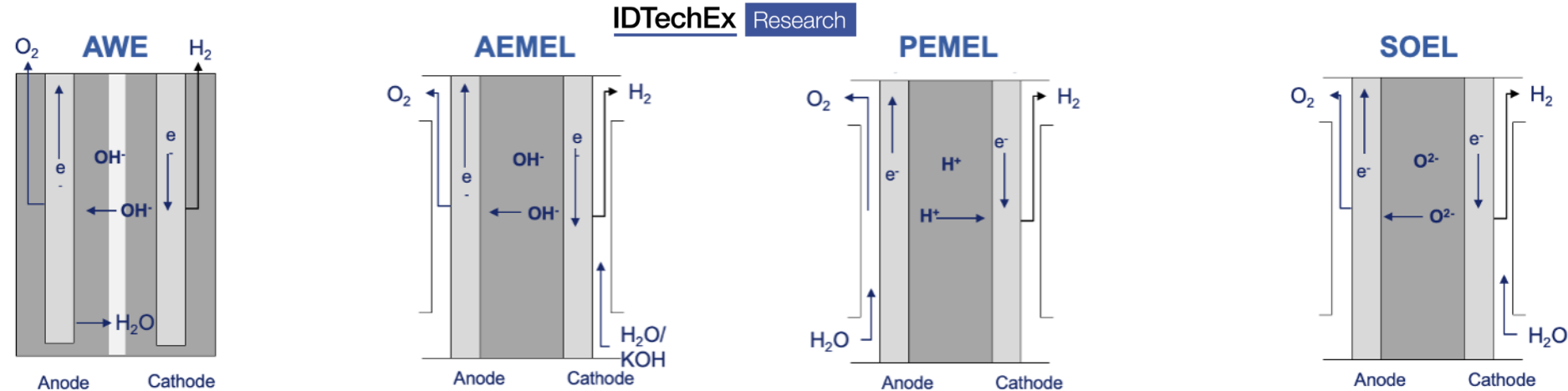
1. **Production (upstream):** development of efficient and sustainable methods for hydrogen production, with a focus on low-carbon or zero-carbon production methods (blue and green hydrogen).
2. **Distribution (midstream):** creation of a robust infrastructure capable of storing and transporting hydrogen from production sites to places of use.
3. **End-use sectors (downstream):** innovation in technologies and devices that can utilize hydrogen efficiently, such as fuel cells for vehicles and power generation systems.

The future hydrogen value chain will consist of a complex integration of production, storage, distribution and end-use sites, on both national and global scales.



Three broad types of electrolyzers have been developed: alkaline water electrolyzer (AWE), proton exchange membrane electrolyzer (PEMEL), and solid oxide electrolyzers (SOEL). The three types of systems employ water and electricity to split water into hydrogen and oxygen. The three systems are characterised by different ions exchanged between the two electrodes, OH^- , H^+ , and O^{2-} for AWE, PEMEL, and SOEL respectively, and the electrolyte and electrode materials used. Alkaline exchange membrane electrolyzers (AEMEL) are a hybrid between AWE and PEMEL. However, their technological readiness level and commercial uses are still quite limited compared to other types.

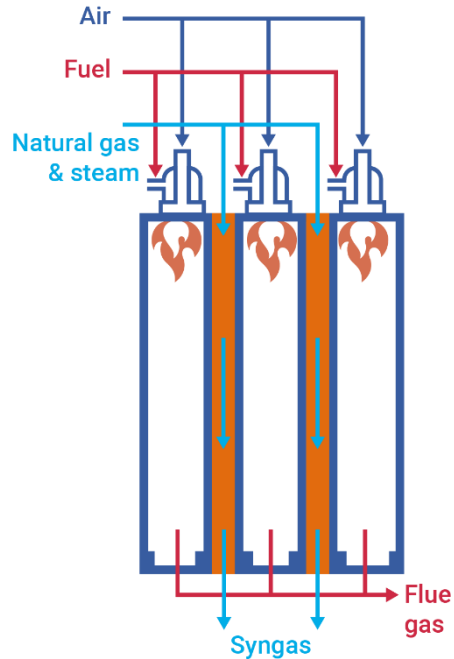
AWE systems are the oldest and most adopted at industrial scale, with the first installations from the 1920s. PEMEL have benefitted from the development and improvement of PEM fuel cells. First installations of PEMEL systems were recorded in the 2000s. The electrolyzer market is currently split between the two older technologies: alkaline and proton exchange membrane with SOEL are starting to enter the market. The latest and youngest technology, SOEL systems are currently approaching the market.



Electrolyte	KOH solution	Polymer (e.g., Aemion)	Polymer (e.g., Nafion)	YSZ (yttrium stabilized zirconia)
Cathode	Ni, Ni-Mo alloys	Ni-based but Pt & Ir can also be used	Pt, Pt-Pd	LSM/YSZ (lanthanum strontium manganite)
Anode	Ni, Ni-Mo alloys		IrO ₂ , RuO ₂	Ni/YSZ

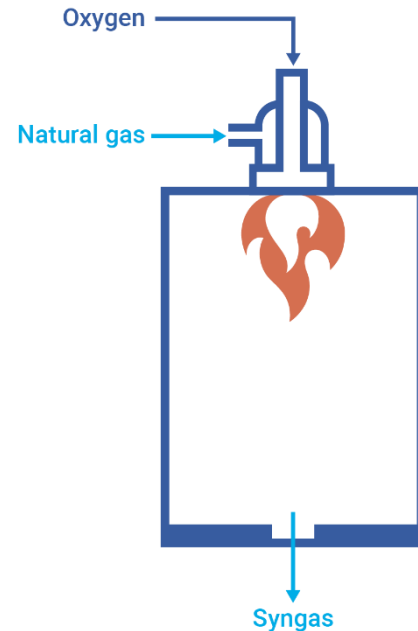


Steam-methane reforming (SMR)



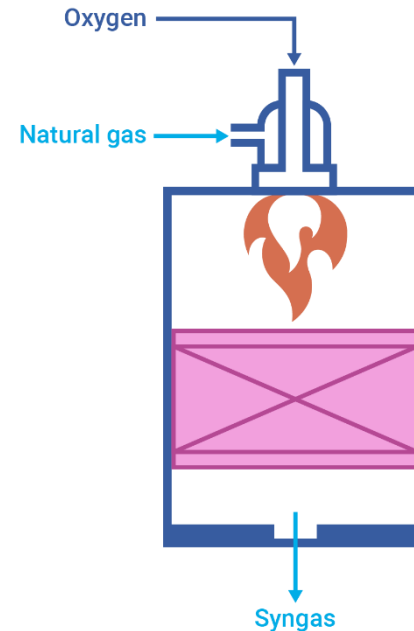
- Incumbent technology
- Can be retrofitted with CO₂ capture by pre- or post-combustion CCS

Partial oxidation (POX)



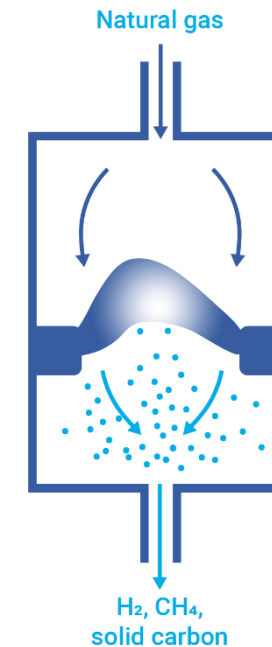
- Commonly used for on-site hydrogen production, e.g. petroleum refining
- Useful for conversion of waste oil feedstocks

Autothermal reforming (ATR)



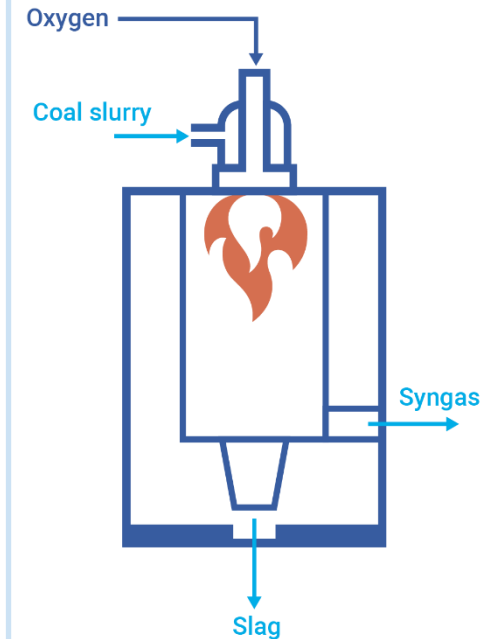
- Relatively new technology
- Combines principles of SMR & POX
- Promising & popular for greenfield projects

Turquoise hydrogen Methane pyrolysis (e.g. plasma pyrolysis)

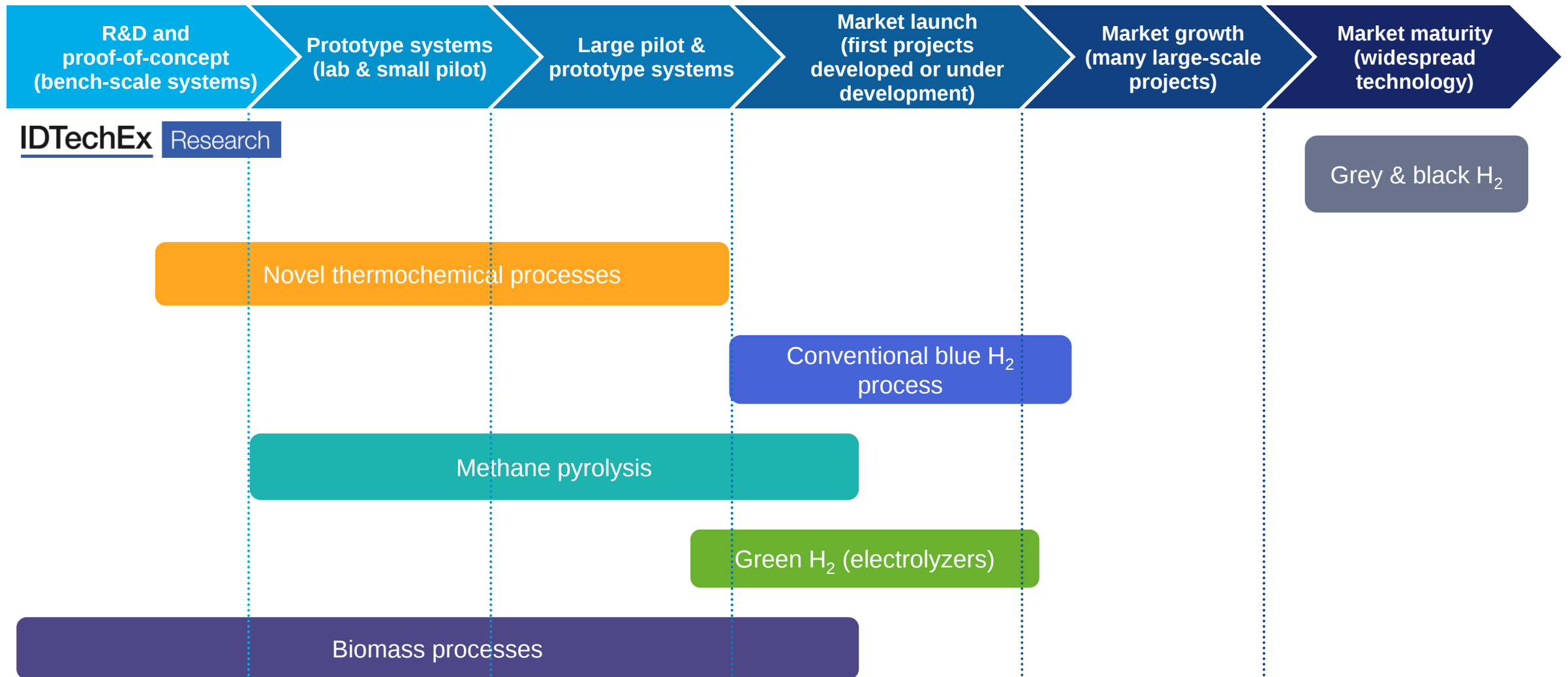


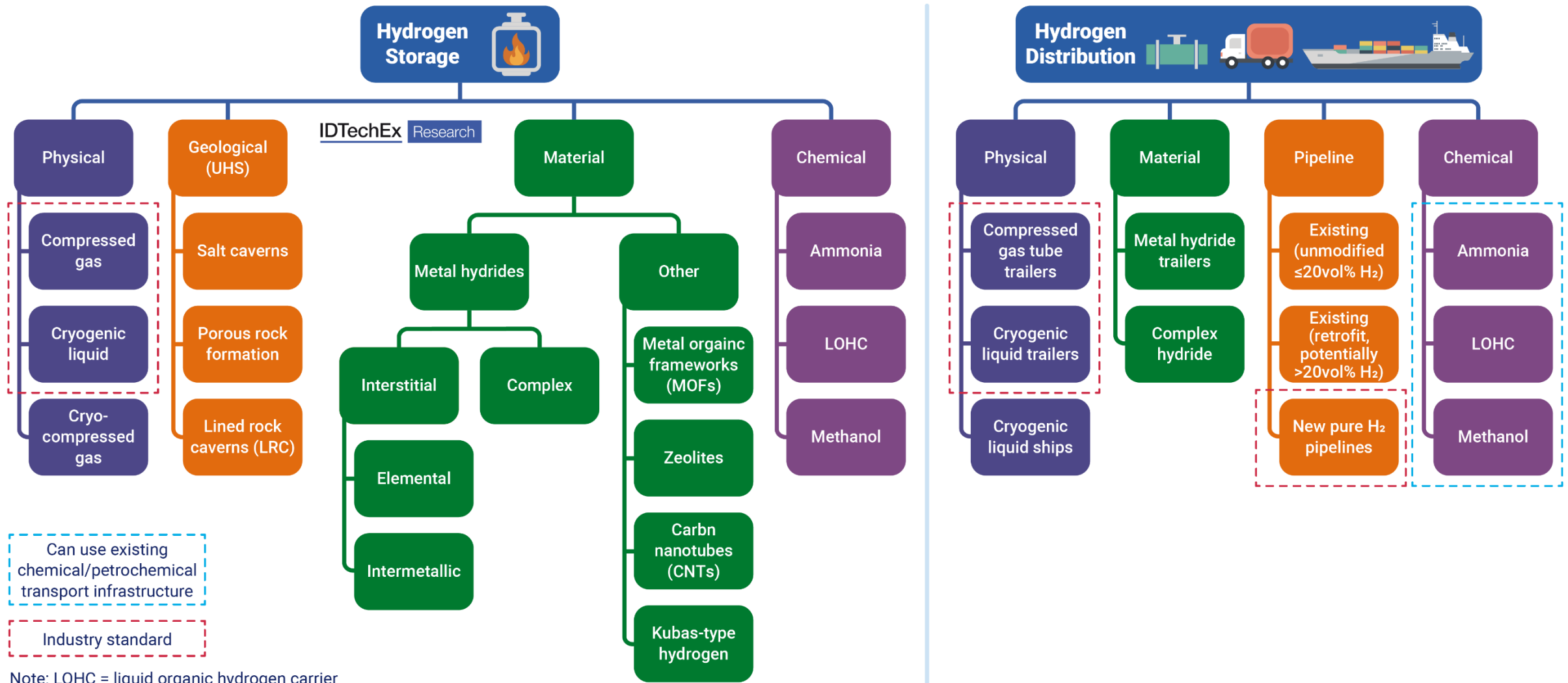
- Promising technology that generates no CO₂.
- Can use electricity
- Hydrogen classified as turquoise

Coal (or biomass) gasification (CG)



- Commonly used in power generation and chemical production
- Popular in China
- Very carbon intensive





Hydrogen's high energy density and low weight

Hydrogen is a promising fuel due to its extremely high energy density, the highest among any fuels, reaching up to 120 MJ/kg (33.33 kWh/kg). This high energy density is offset by its extremely low density of only 0.08375 kg/Nm³ at normal temperature and pressure conditions (NTP, 20°C, 1 atm). As the lightest known gas, a kilogram of hydrogen occupies a significantly larger volume than that of any other gas, which leads to an extremely low volumetric energy density, about 0.01 MJ/L at NTP.

Challenges with storage and distribution

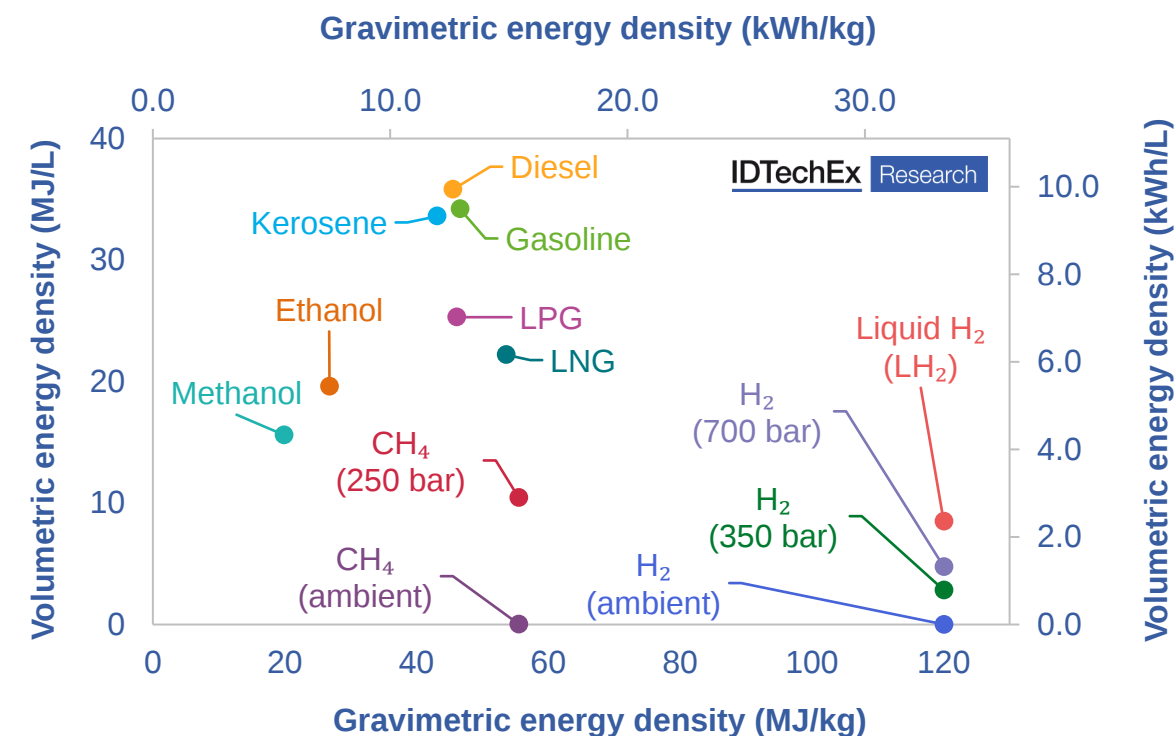
One of the main challenges with hydrogen, despite its attractive energy characteristics, is its difficult storage and transportation. Because of hydrogen's low density, large volumes of it need to be compressed to high pressures or liquefied at cryogenic temperatures to store adequate amounts. The majority of the hydrogen stored and transported today is in pressurized or liquefied form, which involves very high pressures, typically ranging from 100 to 700 bars, and extremely low temperatures, matching its boiling point of -253°C.

Energy inefficiency of incumbent storage methods

Incumbent storage methods come with their own drawbacks. They consume significant amounts of energy, thereby reducing the effective energy content of the hydrogen. Compression uses between 10-30% of hydrogen's original energy content, depending on the pressure involved. Liquefaction is even more energy-intensive, consuming 30-40% of the hydrogen's energy content. This can significantly impact applications in mobility and energy storage, as the overall energy efficiency is drastically reduced.

Safety concerns

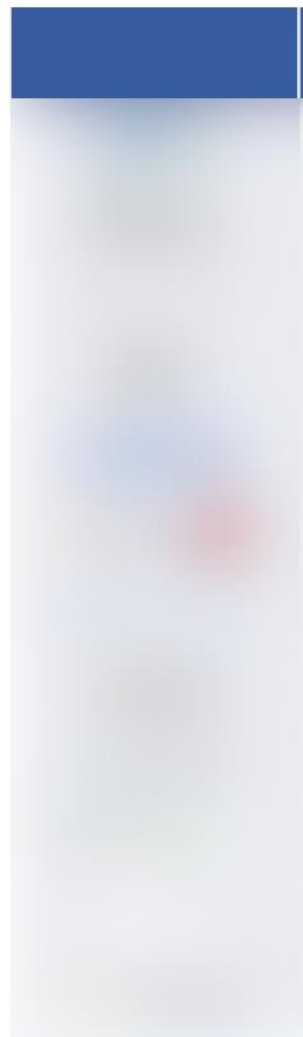
Compressed hydrogen tanks are prone to rupture and explosion, presenting a significant safety risk. In the case of liquefied hydrogen, heat exchange with the surroundings can cause "boil-off," resulting in a portion of the stored hydrogen evaporating. This not only results in wasted hydrogen but can also lead to additional safety issues.



Technology	Key players	Major applications	TRL rating (1-9)
CGH ₂ : Types I – III tanks	Large number of players worldwide, e.g., Chesterfield Special Cylinders, Luxfer Gas Cylinders	Stationary storage (industry, refueling, other) Type III can be used for automotive.	Highly commercialized across a range of applications (9)
CGH ₂ : Type IV tanks			
CGH ₂ : Type V tanks			
LH ₂ tanks			
LH ₂ spheres (aka Hortonspheres)			
CcH ₂ : cryo-compressed storage			
Underground hydrogen storage (UHS) – salt caverns, porous rocks,			
Metal hydrides			
Metal-organic frameworks (MOFs) & other solid-state materials			

Full data available in report
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	Company / Organisation	HQ Country	Company type (no employees)	Technology	Type	Application
						

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Strengths	Weaknesses	Opportunities	Threats
- Storage of hydrogen underground is a proven and reliable storage method. - UHS enables the storage of large amounts of hydrogen as a buffer reserve, which could be especially useful in hydrogen economies and energy storage applications. - UHS provides a natural containment method meaning that large and expensive compressed gas or liquid hydrogen facilities can be avoided. - Salt caverns offer the easiest and most reliable method of storage, particularly in Europe where salt deposits are vast. - Many projects are considering the use of UHS, particularly salt caverns, for bulk storage.	- Large cycling rates have not been tested yet. - Some parts of the world may not have access to suitable salt deposits or porous rock formations. - UHS requires extensive geological studies that are long and expensive. This is especially the case for porous rock formations. - Hydrogen gas becomes contaminated with water and/or hydrocarbons during storage. - Surface facilities are still needed for gas storage. - Porous rock formations are yet to be demonstrated for storage of pure hydrogen. - Porous rock UHS requires the construction of many more wells than caverns. - Hydrogen embrittlement is still a major issue in UHS.	- Significant opportunity to develop new caverns in Europe, particularly in Germany, UK, Netherlands and central Europe where salt deposits are vast. - Significant opportunity to repurpose existing underground and surface infrastructure used for natural gas. - Many companies, including gas suppliers, are active within the field. These companies also have vast experience in natural gas storage. - Potential to produce methane through bacterial methanogenesis in porous rock formations.	- The construction and commissioning time for UHS is quite long and may take up to 10 years. This will limit its adoption, at least in the medium term. However, this will likely decrease as this storage method develops. - There is always a risk that costly and extensive geological assessment may not lead to the site being appropriate for hydrogen storage. This is particularly the case with porous rock formations. - Lined rock caverns will probably not see significant uptake.

Key things to note:

- Liquid NH₃ is superior to MCH in terms of volumetric and gravimetric H₂ capacities. It is also superior to LH₂ in volumetric capacity.
- The energy efficiency of LH₂ may seem attractive at first but that decreases significantly during storage & transportation due to the significant boil-off.
- The energy efficiencies of NH₃ & MCH may differ in reality (especially considering transportation of toluene back) but this analysis illustrates that the two methods are similar in terms of the overall energy efficiency.
- More efforts in NH₃ cracking and dehydrogenation steps are needed to reduce the energy requirement.

	LH ₂	Liquid NH ₃	MCH LOHC
Energy requirement (kWh/kgH ₂)**			
Total energy requirement (kWh/kgH ₂)**			
Power-to-H ₂ efficiency (%)**			
Boil-off rate (%/day)			
Boiling point (°C)			
Storage & transportation method			
Hydrogenation temperature (°C)			
Dehydrogenation temperature (°C)			
Volumetric H ₂ content (kgH ₂ /m ³)			
Gravimetric H ₂ content (wt%)			

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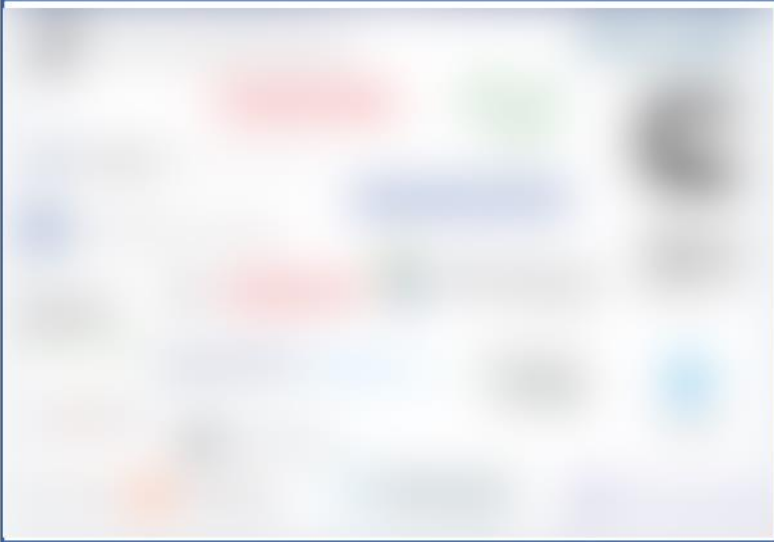
* H₂ production considers total natural gas (feedstock & heating) & electricity used. ** Values exclude transport and boil-off losses.

Converting natural gas pipelines for the transportation of pure H₂ is attractive as it can reduce the amount of capital and time needed to transport H₂ on a large scale. For example, Siemens Energy estimated that repurposing would cost 10-15% of building a new pipeline. However, it presents several challenges due to differences in the properties of H₂ and natural gas. Major challenges include:

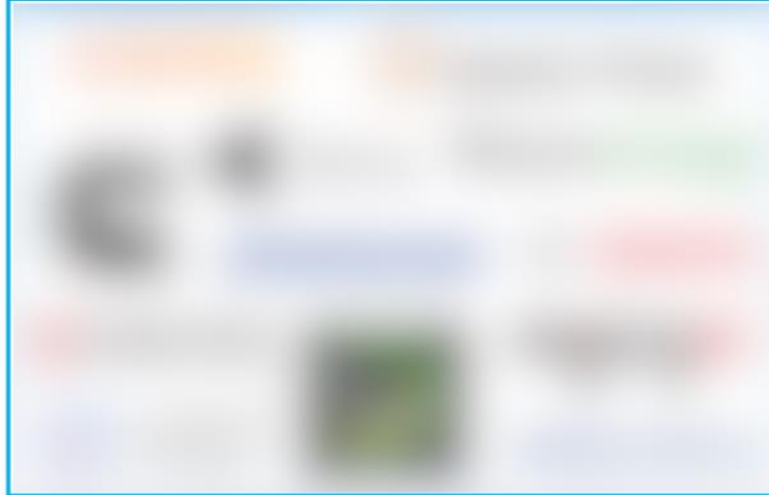
Challenge	Impact	Potential solutions
Hydrogen embrittlement (HE) & material compatibility	Hydrogen adsorbs onto the metal surface and diffuses into the microstructures leading to cracking under high pressure. HE is influenced by a range of factors, which not only concern the hydrogen concentration but also other environmental, material and stress-related factors. This will be a major problem for existing gas pipelines as they use carbon steel.	• Lower pressures: some experts say that using lower pressures (e.g. <35-40 bar) will limit HE. • Gradual replacement with HE-resistant pipeline segments and components (e.g. austenitic steel). • Coatings that limit HE.
Leakage & permeation	H ₂ a smaller molecule than CH ₄ , making it more prone to leakage through seals, joints, and even the pipeline material itself.	• More robust sealing materials & advanced welding • Regular inspection and maintenance • Leak detection systems
Lower energy density	H ₂ has a lower energy density by volume than natural gas, so for the same volume, a H ₂ pipeline will transport less energy than a natural gas pipeline at the same pressure. This also means that H ₂ users will receive less energy per volume of gas received.	• Operators can increase the pressure in the pipeline • Gradual replacement of the pipeline to increase its diameter. • Replacement of residential & commercial power and heating appliances for 100% H₂.
Compressor station incompatibility	Existing compression plants used for natural gas may only be suitable for hydrogen blends of up to 10-20 vol% H ₂ . For up to 40% H ₂ , adjustments to the compressor impellers and other components will be needed. New compressors will be required for anything over that.	No potential solution except new compressor stations.
Regulation	Conversion to 100% H ₂ raises safety & regulatory concerns	Demonstration projects & new regulatory frameworks.

The following companies were identified as active players in the market. Most players are developing PEMFCs, followed by SOFCs. Please note that these lists are non-exhaustive.

PEMFC



SOFC



PAFC



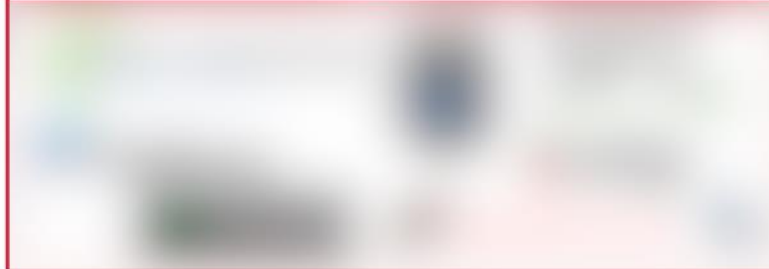
MCFC



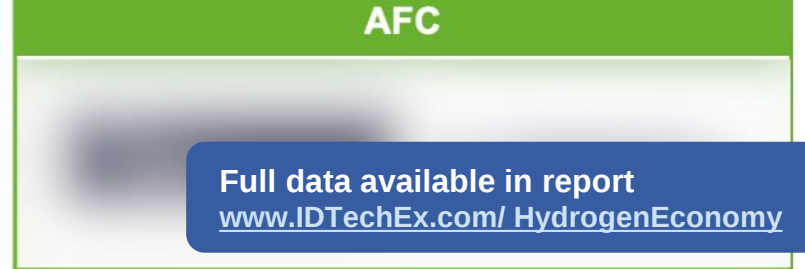
HT PEMFC



DMFC



AFC



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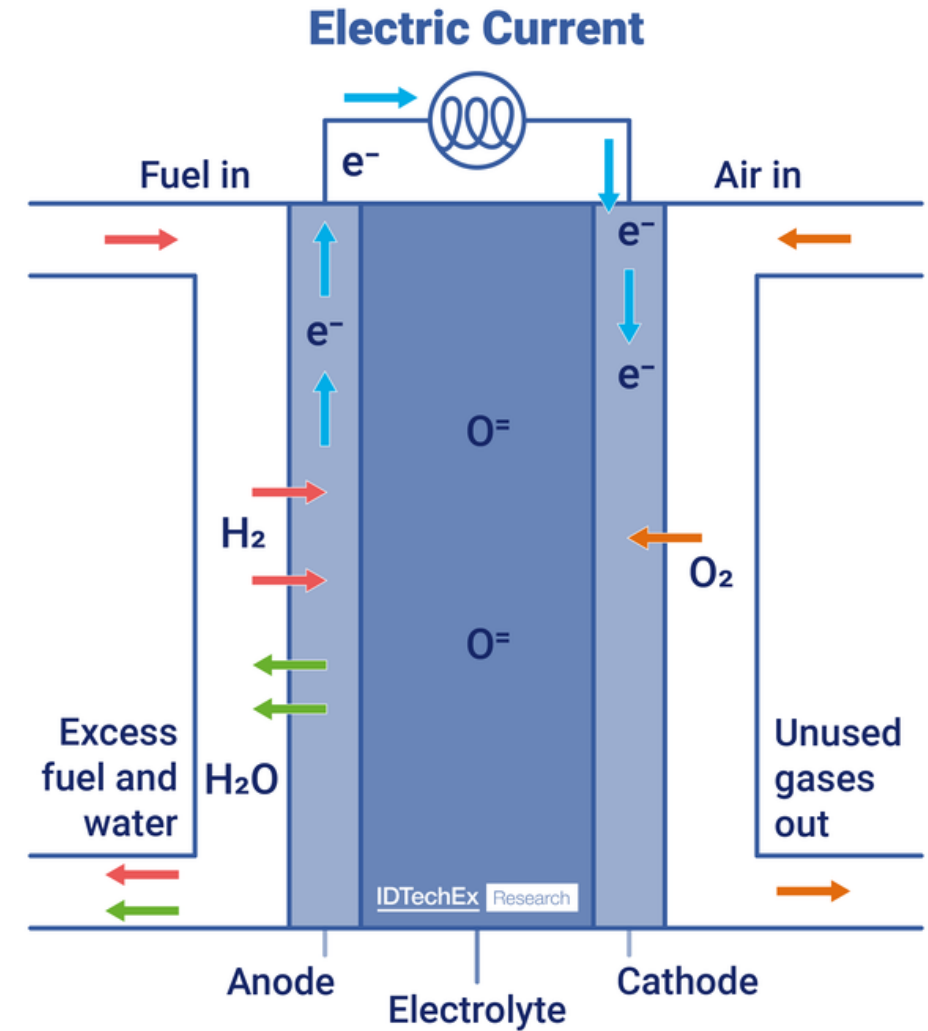
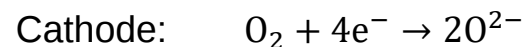
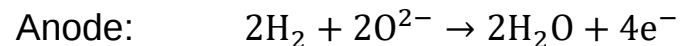
Hydrogen and oxygen are pumped into channels on either side of the fuel cell. The hydrogen is pumped into the anode flow field, while oxygen is pumped into the cathode flow field. SOFCs run at a high operating temperature (650-1000°C) to allow the ceramics used to become both electrically and ionically active.

Unlike PEM fuel cells, molecular hydrogen is not required as a fuel. Due to the high operating temperature of SOFCs, light hydrocarbons (methane, propane, etc) can be internally reformed at the anode. It is also possible to fuel a SOFC by externally reforming heavier hydrocarbons (gasoline, diesel, etc), producing a mixture of hydrogen, carbon monoxide, carbon dioxide, steam, and methane.

Oxygen is reduced at the cathode, producing negative oxygen ions. These ions pass through the solid electrolyte and reach the anode.

At the anode, an oxidation reaction occurs, producing water, heat, and electrons. The electrons travel from the fuel cell to the load to do electrical work, before arriving at the cathode to reduce fresh oxygen fuel – restarting the cycle.

The anodic and cathodic reactions are:

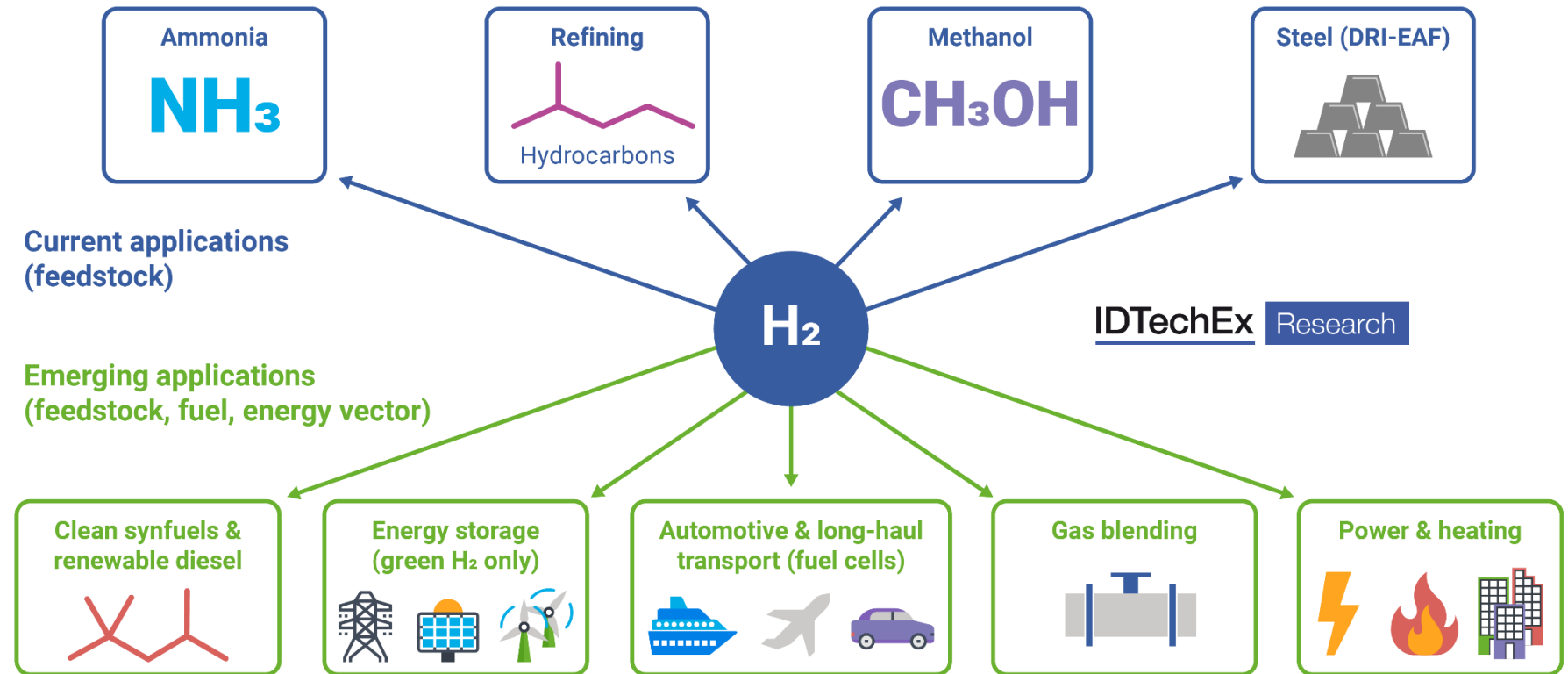


AFC technology	Pros	Cons
Mobile electrolyte	- Circulating electrolyte can be used as coolant. - Very low-cost KOH electrolyte.	- Risk of electrolyte leakage. - The electrolyte requires constant stirring to avoid its excessive concentration. - Electrolyte required regeneration due to the CO₂ side reaction. - Extra equipment, (pumps, valves and tanks), is required for the liquid electrolyte. - Production of water means that the evaporation may be needed to concentrate the electrolyte.
Static electrolyte	- Compact cell configuration, with cells stacked in series. - Possibility to place the fuel cell in any orientation with minimized risk of electrolyte leakage. - The solid electrolyte would allow the stack to be use in any orientation, and the internal short-circuit due to the liquid electrolyte would be avoided. - While water management has to be considered it is less restrictive than in a PEMFC, as water content does not strongly affect the electrolyte conductivity as much as in the PEMFC.	- Because the KOH is contained in a solid matrix, the side reaction with CO₂ must be avoided, due to the difficulty in exchanging the electrolyte. Impurities or contaminants in the electrolyte are more difficult to remove, potentially impacting the cell performance over time. Therefore, pure O₂ must be used. - A cooling heat exchange system is required to manage the stack temperature. - The solid electrolyte, similarly, to a PEMFC, requires a proper distribution of the water produced at the anode, to avoid the dilution of the KOH electrolyte. - While this technology has found better application in the aerospace projects due to its mechanical simplicity, for terrestrial application it encounters several difficulties, from the hazardous materials employed, to the complete absence of CO₂ in the oxidant gas. - A key challenge is ensuring the uniform distribution of reactants, and preventing the formation of gas bubbles that could affect the efficiency of the cell.
Dissolved electrolyte	- It can potentially handle fuels that are otherwise difficult to use in a traditional AFC, increasing the range of potential applications. - Hydrazine is a relatively low-cost fuel. - The device configuration and refuelling methods are simple, making it potentially more straightforward to use and maintain.	- Catalytic degradation using NaBH₄ if Pt is not used in the catalyst. - NaBH₄ fuel cells are not commercial due to the high cost of fuel. - NaBO₂ product needs to be recycled and hydrogenated back to NaBH₄ for use. - Controlling the rate of fuel delivery to the anode can be more challenging, potentially affecting the efficiency and stability of the cell.

While electrification is the primary pathway to decarbonization, some sectors are hard to electrify (hard-to-abate). Sectors where electrification will not be the dominant technology include:

- **Heavy industry** – steel, petrochemical refining, ammonia, etc
- **Industrial heating** – cement, ceramics, etc
- **Residential & commercial heating**
- **Long range and heavy-duty transport sectors** – aviation, marine, rail and heavy-duty on-road transport

In these sectors, H₂ can not only be used as a clean feedstock, but also a clean fuel or energy carrier.



IDTechEx analyzed hydrogen use in the following sectors:

- Traditional industry: refining, ammonia, methanol
- Emerging industry: alternative fuel production, sustainable steelmaking, heat & power generation
- Mobility: on-road transport, marine, rail, aviation

Key Takeaways for Hydrogen Use in Low-Carbon Ammonia Production

IDTechEx believes that **low-carbon ammonia production will remain as one of the largest uses for low-carbon hydrogen in the long-term**. This market will see significant development in the future, as more projects come online.

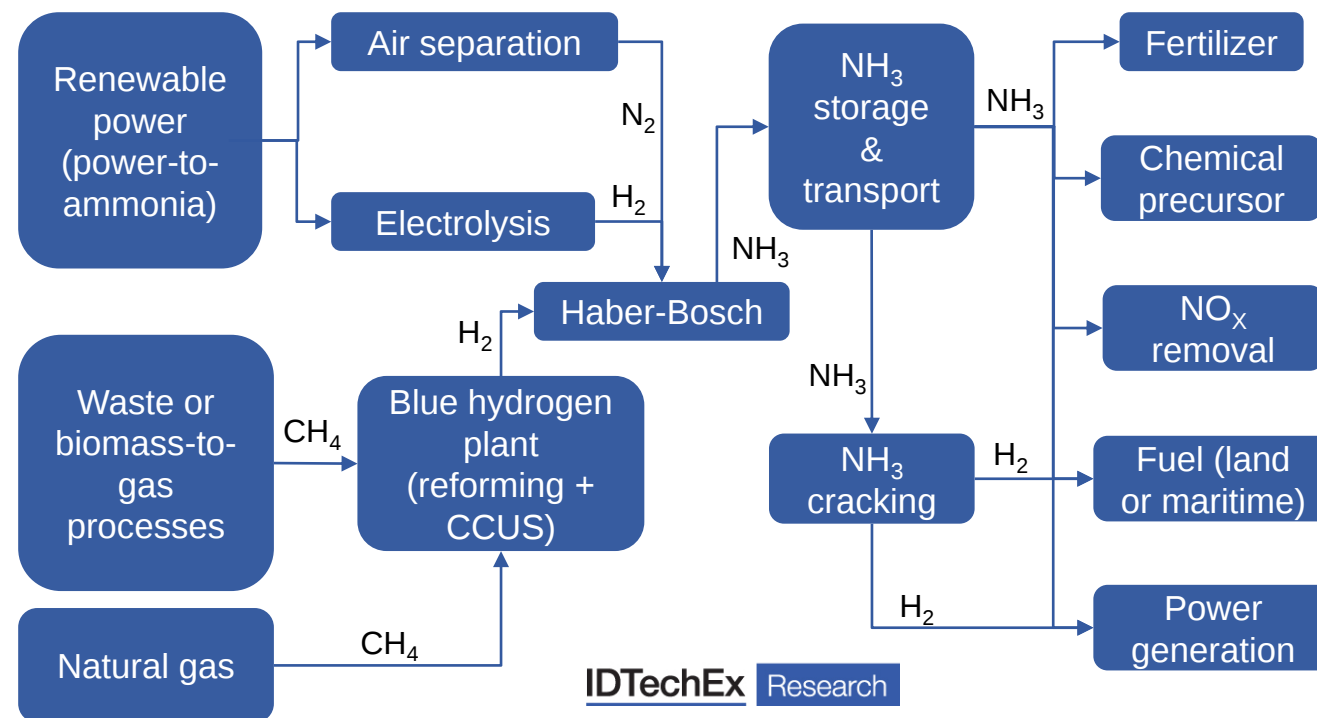
Decarbonizing ammonia production is key to reducing CO₂ emissions in the fertilizer and chemical sectors, where ammonia is a key feedstock. Other more emerging applications for ammonia include its use as a hydrogen carrier or fuel (primarily in power stations or the marine sector).

The traditional Haber-Bosch (HB) process can be modified to produce low-carbon ammonia either by using green hydrogen from electrolysis or blue hydrogen by modifying the traditional process with carbon capture, utilization and storage (CCUS). The major changes are only in the hydrogen production as the downstream HB loop remains mostly the same. Some companies developing green ammonia processes are proposing **more modularized designs for adjusting the scale of production**.

Producing green ammonia is currently very expensive as most of the cost depends on the cost of green hydrogen production. By some estimates, blue ammonia is expected to cost US\$210-490 per tonne of NH₃, while green ammonia would cost US\$ 720-1400 per tonne. Significant government subsidies are needed to enable this transition.

The following will be the **key market drivers for the green ammonia market**: environmental regulations, government incentives, corporate sustainability initiatives, geopolitical factors related to NH₃ and fertilizer (e.g. Russia-Ukraine war) and market demand for more sustainable fertilizer.

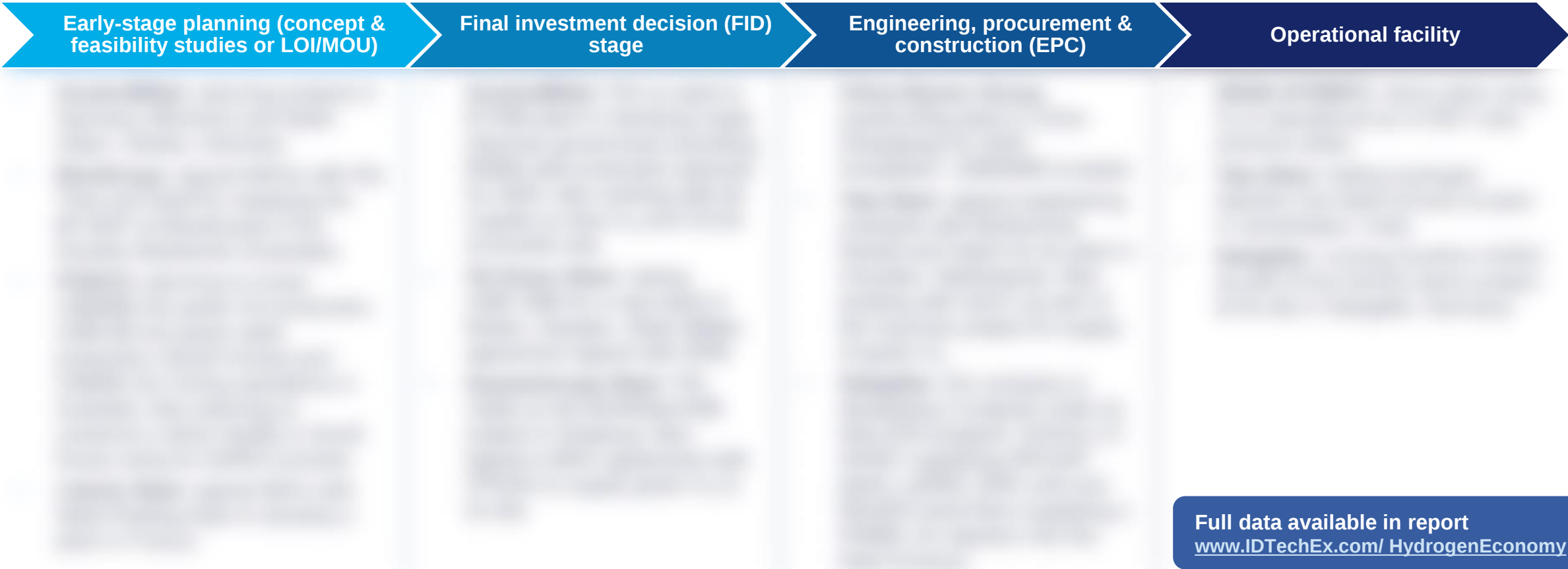
There are many companies aiming to produce low-carbon ammonia. These include fertilizer producers (e.g. Yara International, Nutrien, CF Industries), industrial gases companies (e.g. Air Products), petrochemical companies (e.g. ADNOC) and others.



Drivers for capacity growth for low-carbon hydrogen in the refining industry include:

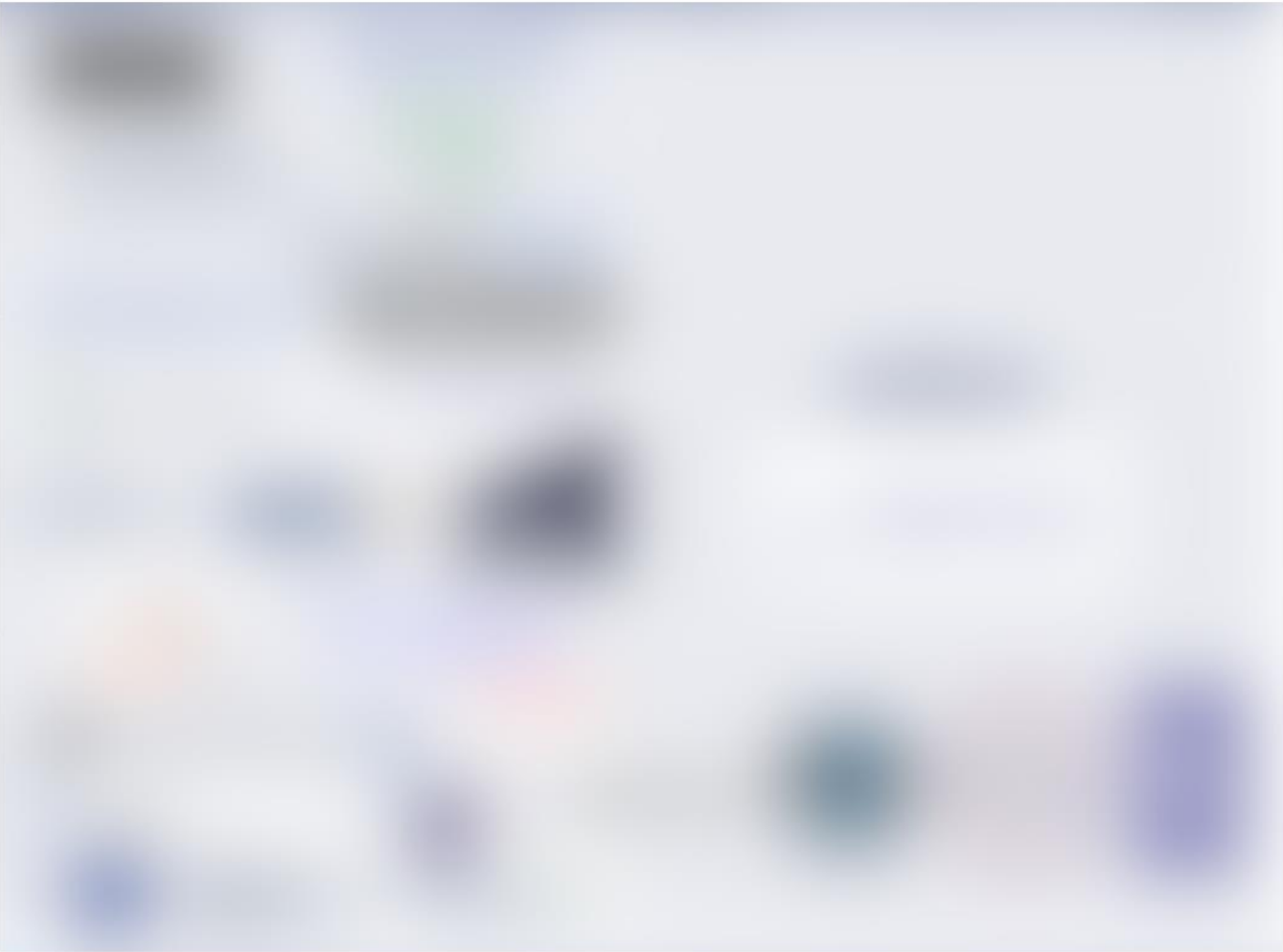
Driver	Potential impact	Notes
Rising global consumption	Largest	Global consumption of crude oil is rising steadily. The IEA forecasts global oil consumption to increase to 104 million barrels per day by 2026.
Processing of heavier and sour crude oils	Large	- An increasing proportion of heavy and sour crude oils is being refined worldwide. - Such oils will consume more hydrogen due to increased use of hydrocracking and hydrotreatment processes.
More stringent environmental regulations	Medium	- Most crude oil and its various fractions contain vast amounts of sulfur that must be removed prior to further processing or use of the product. - Combustion of hydrocarbons containing sulfur emits SO_x into the atmosphere. - More stringent environmental regulations will lead to higher use of hydrodesulfurization processes.
Rising demand for high-quality petroleum products	Medium	- Demand for low-sulfur, high-performance, high-octane gasoline and diesel fuels is increasing. - Refineries prioritizing these markets will consume more H₂ through previously mentioned processes.
Decarbonization of H ₂ feedstock	Medium	- Refineries will require new sources of H₂ feedstock to decarbonize. - This presents a significant growth opportunity for blue and green H₂.
Decarbonization of the refinery heating	Low-medium	- Refineries require a significant amount of heat and power for various processes. - Hydrogen can be combusted in furnaces, boilers and gas turbines at refineries. - Low potential in the medium term since technologies are unlikely to be replaced quickly.

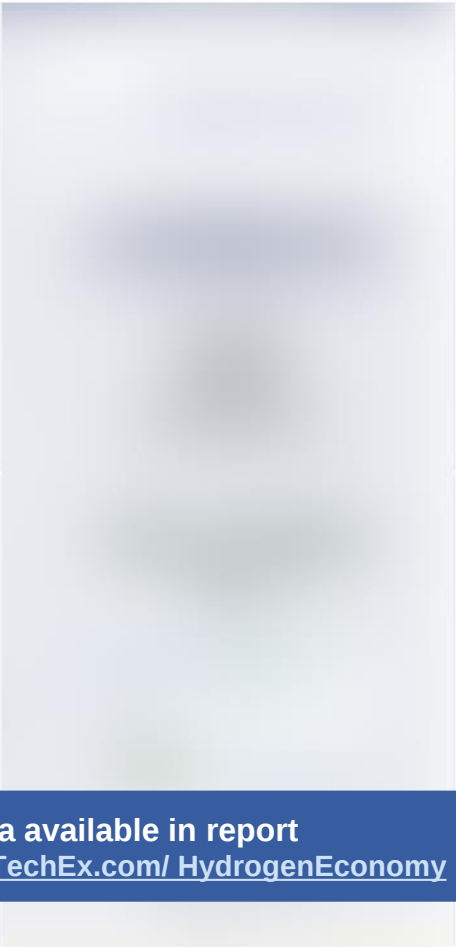
There are many steel producers aiming to develop new H₂-DRI-EAF projects or convert existing facilities to this production method. Below is a selection of some notable projects and initiatives from around the world.



LOI = letter of intent; MOU = memorandum of understanding; PEMEL = proton exchange membrane electrolyzer; SOEC = solid oxide electrolyzer



	Hydrogen fuel cells	Hydrogen combustion
Small aircraft (eVTOL, drones)		
Aircraft / powertrain		
Component / system suppliers		

	Sustainable aviation fuel (SAF)
Use	
Production	

Full data available in report
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From 2023-2033, **refining and ammonia will continue to dominate** the market for hydrogen end-uses. However, these markets will experience less substantial growth relative to current levels of consumption (i.e., compound annual growth rate, CAGR).

In comparison, methanol, DRI, fuel cells mobility and other emerging end-uses **will experience more significant growth**.

Overall, hydrogen use will **mainly be confined to industrial applications** with more emerging applications occupying small market shares in 2033.

See the report for analysis of CAGR, market shares and major growth drivers.

■ Bio- & synfuels
■ CHP
■ FC Mobility
■ Iron & steel (DRI)
■ Methanol
■ Ammonia
■ Refining
Total

Cumulative H₂ Demand by End-Use (Mtpa H₂)

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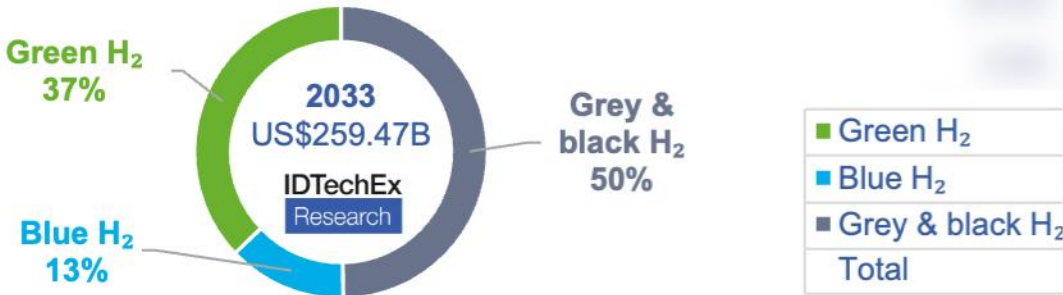


The expected hydrogen market can be calculated from the LCOH values in the previous slide and the applied to the cumulative capacity of H₂ production in Mtpa. The low-carbon H₂ market will grow at a CAGR of 40.7% to US\$130B by 2033. The total H₂ market will grow at a CAGR of 4.9% from 2023-2033, reaching ~US\$260B in 2033.

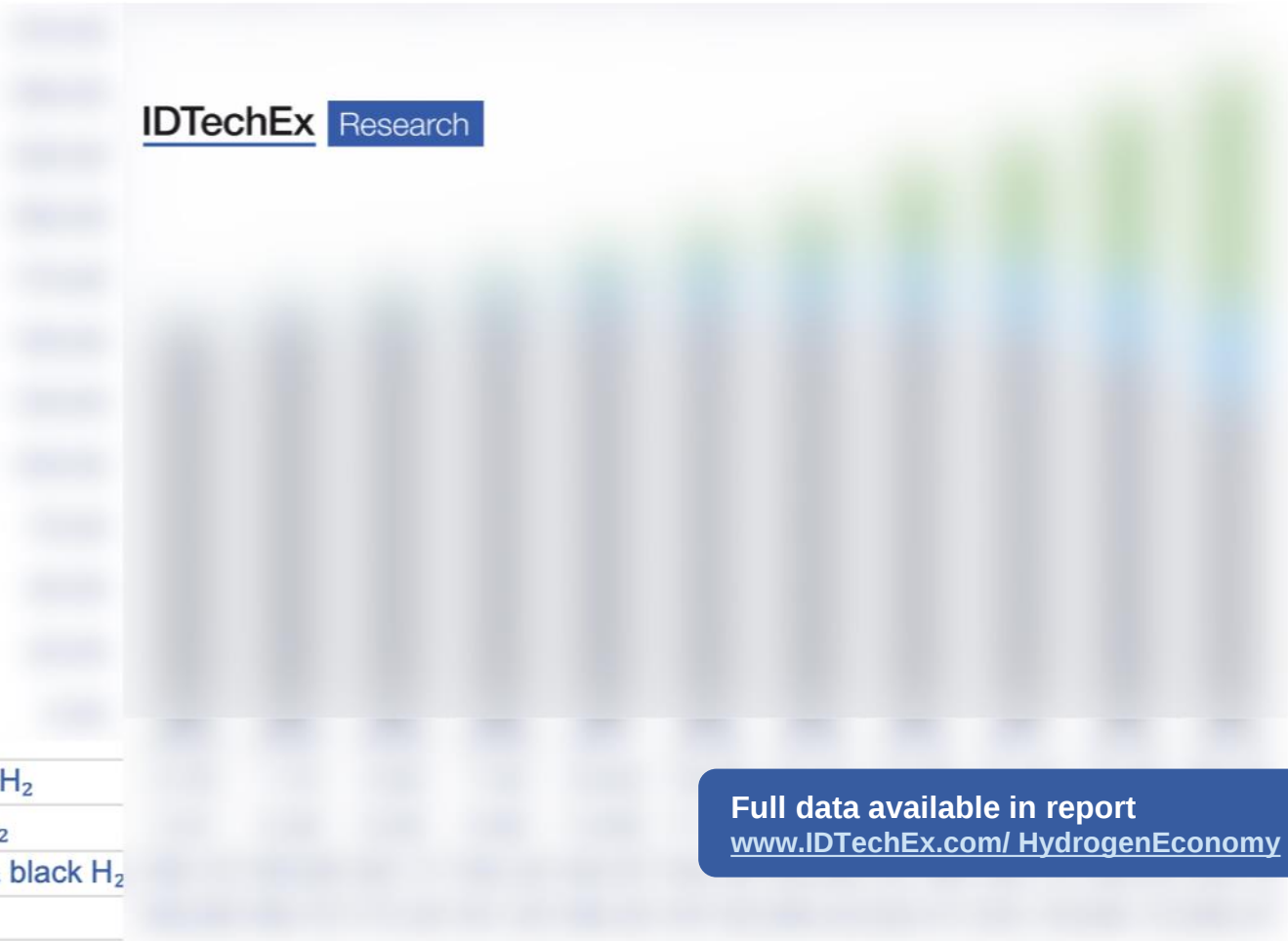
Blue and green H₂ markets will experience the most significant growth, with the green H₂ market being 2.8 times larger than that of blue in 2033.

By contrast, the grey and black H₂ market will decline by US\$27.6B from 2023-2033 due to the reduction in global production capacity.

H ₂ type	CAGR
Grey & black H ₂	-1.9%
Blue H ₂	25.5%
Green H ₂	62.3%
Total	4.9%



Cumulative Value of H₂ Production (Annual US\$B)



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