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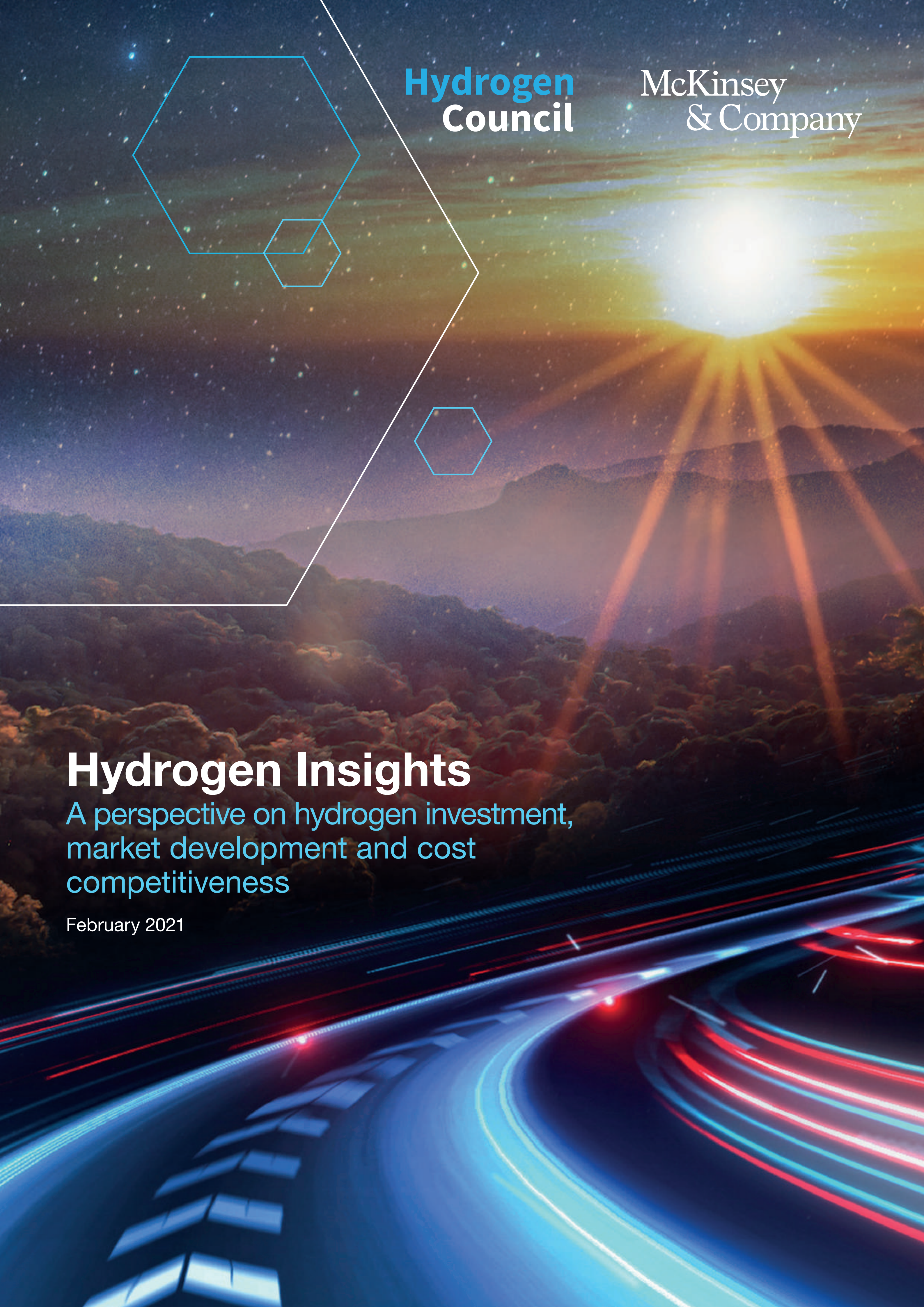

Hydrogen Insights

A perspective on hydrogen investment, market development and cost competitiveness

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Contents

Executive summary

Hydrogen is gathering strong momentum as a key energy transition pillar

Underpinned by a global shift of regulators, investors, and consumers toward decarbonization, hydrogen (H_2) is receiving unprecedented interest and investments. At the beginning of 2021, over 30 countries have released hydrogen roadmaps, the industry has announced more than 200 hydrogen projects and ambitious investment plans, and governments worldwide have committed more than USD 70 billion in public funding. This momentum exists along the entire value chain and is accelerating cost reductions for hydrogen production, transmission, distribution, retail, and end applications.

Similarly, having grown from 60 to over 100 members since 2020, the Hydrogen Council now represents more than 6.6 trillion in market capitalization and more than 6.5 million employees globally.

This report provides an overview of these developments in the hydrogen ecosystem. It tracks deployments of hydrogen solutions, associated investments and the cost competitiveness of hydrogen technologies and end applications. Developed collaboratively by the Hydrogen Council and McKinsey & Company, it offers a fact-based, holistic, quantitative perspective based on real industry data. Along with the report, the Hydrogen Council is launching Hydrogen Insights - a subscription service that provides granular insights and data about the hydrogen ecosystem and its development.

Deployment and investments: Announced hydrogen investments have accelerated rapidly in response to government commitments to deep decarbonization

More than 200 hydrogen projects now exist across the value chain, with 85% of global projects originating in Europe, Asia, and Australia, and activity in the Americas, the Middle East and North Africa accelerating as well.

If all projects come to fruition, total investments will exceed USD 300 billion in hydrogen spending through 2030 – the equivalent of 1.4% of global energy funding. However, only USD 80 billion of this investment can currently be considered "mature," meaning that the investment is either in a planning stage, has passed a final investment decision (FID), or is associated with a project under construction, already commissioned or operational.

On a company level, members in the Hydrogen Council are planning a sixfold increase in their total hydrogen investments through 2025 and a 16-fold increase through 2030. They plan to direct most of this investment toward capital expenditures (capex), followed by spending on merger and acquisition (M&A) and research and development (R&D) activities.

The global shift toward decarbonization backed by government financial support and regulation is supporting this momentum. For instance, 75 countries representing over half the world's GDP have net zero carbon ambitions and more than 30 have hydrogen-specific strategies. Governments have already pledged more than USD 70 billion and included new capacity targets and sector level regulation to support these hydrogen initiatives. For example, the EU has announced a 40-gigawatt (GW) electrolyzer capacity target for 2030 (up from less than 0.1 GW today) and more than 20 countries have announced sales bans on internal combustion engine (ICE) vehicles before 2035. In the US, where federal emission standards for new vehicles have lagged behind those in the EU, state-level initiatives in California and 15 other states have set ambitious targets to transition not only passenger cars but also trucks to zero-emission status by 2035. In China, the 2021-24 fuel cell support program will see the equivalent of USD 5 billion spent on fuel cell vehicle deployment, with a strong emphasis on the development of local supply chains.

Supply: If scaled up with the right regulatory framework, clean hydrogen costs can fall faster than expected

With the advent of hydrogen giga-scale projects, hydrogen production costs can continue to fall. For renewable hydrogen, the biggest driver is a quicker decline in renewables costs than previously expected, driven by at-scale deployment and low financing costs. 2030 renewable costs could be as much as 15% lower than estimated just a year ago. The strongest reductions are expected in locations with optimal resources such as Australia, Chile, North Africa and the Middle East.

But lower renewable costs are not enough: for low-cost clean hydrogen production, value chains for electrolysis and carbon management need to be scaled up. This will not happen on its own: a further step-up of public support is required to bridge the cost gap, develop low-cost renewable capacities and scale-up carbon transportation and storage sites. For the cost projections in this report, we assume an ambitious development of the use of hydrogen in line with the Hydrogen Council vision. For electrolysis, for example, we assume 90 GW deployment by 2030.

Such a scale-up will lead to a rapid industrialization of the electrolyzer value chain. The industry has already announced electrolyzer capacity increases to over approximately 3 GW per year, and will need to scale rapidly beyond that. This scaling can translate into system costs falling faster than previously estimated, hitting USD 480-620 per kilowatt (kW) by 2025 and USD 230-380 per KW by 2030. System costs include stack and balance of plant but exclude transportation, installation and assembly, costs of building and any indirect costs.

At-scale deployment of renewable hydrogen will require the development of giga-scale hydrogen production projects. Such projects with purpose-built renewables can boost utilization by merging multiple renewable sources, such as a combined supply from onshore wind and solar photovoltaics (PV), and by overbuilding renewables supply versus electrolyzer capacity.

In combination, projections show that renewable hydrogen production costs could decline to USD 1.4 to 2.3 per kilogram (kg) by 2030 (the range results from differences between optimal and average regions).[1] This means new renewable and gray hydrogen supply could hit cost parity in the best regions by 2028, and between 2032 and 2034 in average regions.

In parallel to renewable hydrogen production, low-carbon hydrogen production from natural gas has continued to evolve technologically. With higher CO_2 capture rates and lower capex requirements, low-carbon hydrogen production is a strong complementary production pathway. If carbon transportation and storage sites are developed at scale, low-carbon hydrogen could break even with gray hydrogen by the end of the decade at a cost of about USD 35-50 per ton (t) of carbon dioxide equivalent (CO_2e)[1].

Distribution: Cost-efficient transmission and distribution required to unlock hydrogen applications

With hydrogen production costs falling, transmission and distribution costs are the next frontier when it comes to reducing delivered hydrogen costs. Longer-term, a hydrogen pipeline network offers the most cost-efficient means of distribution. For example, pipelines can transmit 10 times the energy at one-eighth the costs associated with electricity transmission lines and have capex costs similar to those for natural gas. The industry can partially reuse existing gas infrastructure, but even newly constructed pipelines would not be cost prohibitive (assuming leakage and other safety risks are properly addressed). For example, we estimate the cost to transport hydrogen from North Africa

[1] These costs reflect pure production costs and assume a dedicated renewable and electrolysis system for renewable hydrogen. They do not include costs required for baseload supply of hydrogen (e.g., storage and buffers), costs for redundancies, services and margins; they also do not include any cost for hydrogen transportation and distribution.

to central Germany via pipeline could amount to about USD 0.5 per kg of H_2 – less than the cost difference of domestic renewable hydrogen production in these two regions.

In the short- to medium-term, the most competitive setup for large-scale clean hydrogen applications involves co-locating hydrogen production on- or near-site. The industry can then use this scaled production to supply the fuel to other hydrogen users in the vicinity, such as refueling stations for trucks and trains, and smaller industrial users. Trucking the fuel to such users typically offers the most competitive form of distribution, with costs below USD 1 per kg of H_2.

For longer-distance transport by ship, hydrogen needs to be converted to increase its energy density. While several potential hydrogen carrier approaches exist, three carbon-neutral carriers – liquid hydrogen (LH_2), liquid organic hydrogen carriers (LOHC) and ammonia (NH_3) – are gaining most traction.[2] The cost-optimal solution depends on the targeted end-use, with deciding factors including central versus distributed fueling, the need for reconversion, and purity requirements.

At-scale, international distribution could arrive by 2030 at total costs of USD 2-3/kg (excluding cost of production), with the lion´s share of costs needed for conversion and reconversion. For example, if the targeted end application is ammonia, shipping costs add only USD 0.3-0.5/kg to the total cost. If the targeted end application is for liquid hydrogen or hydrogen with a high purity requirement, shipping as liquid hydrogen might add only USD 1.0-1.2/kg, with additional benefits for further distribution from port. These cost levels would enable global trade in hydrogen, connecting future major demand centers such as Japan, South Korea, and the EU to regions of abundant low-cost hydrogen production means like the Middle East and North Africa (MENA), South America or Australia. Like hydrogen production, carriers need substantial initial investments, and the right regulatory framework to bridge the cost delta in the first decade.

End applications: Falling clean hydrogen costs and application-specific cost drivers improve the cost competitiveness of hydrogen applications

From a total cost of ownership (TCO) perspective (including hydrogen production, distribution and retail costs) hydrogen can be the most competitive low-carbon solution for 22 end applications, including long haul trucking, shipping and steel. However, pure TCO is not the only driver of application adoption: future expectations on environmental regulations, demands from customers and associated "green premiums," as well as the lower cost of capital for ESG-compliant investments will all influence investment and purchase decisions.

In industry, lower hydrogen production and distribution costs are particularly important for cost competitiveness as they represent a large share of total costs. Refining is expected to switch to low-carbon hydrogen over the next decade. For fertilizer production, green ammonia produced with optimized renewables should be cost competitive by 2030 against gray ammonia produced in Europe at a cost of less than USD 50 per ton of CO_2e. Steel, one of the largest industrial CO_2 emitters, could become one of the least-cost decarbonization applications. With an optimized setup using scrap and hydrogen-based direct reduced iron (DRI), green steel could cost as little as USD 515 ton of crude steel, or a premium of USD 45 per ton of CO_2e by 2030.

In transport, lower hydrogen supply costs will make most road transportation segments competitive with conventional options by 2030 without a carbon cost. While battery technology has advanced rapidly, fuel cell electric vehicles (FCEVs) are emerging as a complementary solution, in particular for heavy-duty trucks and long-range segments. In heavy-duty long-haul transport, the FCEV option can achieve breakeven with diesel in 2028 if hydrogen can be made available for USD 4.5 per kg at the

[2] Synthetic methane produced from biogenic or air-captured CO_2 represents a potential fourth candidate to be studied further.

pump (including hydrogen production, distribution and refueling station costs). Furthermore, hydrogen combustion (H_2 ICE) offers a viable alternative in segments with very high power and uptime requirements, including heavy mining trucks.

Hydrogen is likewise advancing in trains, shipping, and aviation. Clean ammonia as a shipping fuel will be the most cost-efficient way to decarbonize container shipping by 2030, breaking even with heavy fuel oil (HFO) at a cost of about USD 85 per ton of CO_2e.[3] Aviation can achieve competitive decarbonization via hydrogen and hydrogen-based fuels. The aviation industry can decarbonize short- to medium-range aircrafts most competitively through LH_2 directly, at a cost of USD 90-150 per ton of CO_2e. Long-range aircrafts can be decarbonized most competitively using synfuels, at a cost of about USD 200-250 per ton of CO_2e, depending on the CO_2 feedstock chosen.

Other end-applications such as buildings and power will require a higher carbon cost to become cost competitive. However, as large-scale and long-term solutions to decarbonize the gas grid, they will still see strong momentum. In the United Kingdom, for example, multiple landmark projects are piloting the blending of hydrogen into natural gas grids for residential heating. Hydrogen as a backup power solution, especially for high power applications like data centers, is also gaining traction.

Implementation: Capturing the promise of hydrogen

Strong government commitment to deep decarbonization, backed by financial support, regulation and clear hydrogen strategies and targets, has triggered unprecedented momentum in the hydrogen industry. This momentum now needs to be sustained and the long-term regulatory framework set.

These ambitious strategies must now be translated into concrete measures. Governments, with input from businesses and investors, should set sector-level strategies (e.g., for the decarbonization of steel) with long-term targets, short-term milestones, and the necessary regulatory framework to enable the transition. The industry must set up value chains for equipment, scale up manufacturing, attract talent, build capabilities, and accelerate product and solution development. This scale up will require capital, and investors will play an outsized role in developing and pushing at-scale operations. All this will require new partnerships and ecosystem building, with both businesses and governments playing important roles.

To get things started, strategies should aim at the critical “unlocks,” like reducing the cost of hydrogen production and distribution. We estimate roughly 65 GW of electrolysis are required to bring costs down to a break-even with gray hydrogen under ideal conditions, which implies a funding gap of about USD 50 billion for these assets. Support is also required to scale up carbon transport and storage; hydrogen shipping, distribution and retail infrastructure; and the take up of end applications.

One place to support deployment is the development of clusters with large-scale hydrogen offtakers at their core. These will drive scale through the equipment value chain and reduce the cost of hydrogen production. By combining multiple offtakers, suppliers can share both investments and risks while establishing positive reinforcing loops. Other smaller hydrogen offtakers in the vicinity of such clusters can then piggy-back on the lower-cost hydrogen supply, making their operations breakeven faster.

We see several cluster types gaining traction, including:

- **Port areas** for fuel bunkering, port logistics, and transportation
- **Industrial centers** that support refining, power generation, and fertilizer and steel production
- **Export hubs** in resource-rich countries

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3 Alternatives such as synthetic methane from biogenic or air-captured CO_2 in current liquefied natural gas (LNG) vessels were not in the scope of this report and require further study.

Successful clusters will likely involve players along the entire value chain to optimize costs, tap into multiple revenue streams and maximize the utilization of shared assets. They should be open to additional players and infrastructure should allow for ready access where possible.

The next few years will be decisive for the development of the hydrogen ecosystem, for achieving the energy transition and for attaining the decarbonization objective. As this report shows, progress over the past year has been impressive, with unprecedented momentum. But much lies ahead. The companies in the Hydrogen Council are committed to deploying hydrogen as a critical part of the solution to the climate challenge and *Hydrogen Insights* will provide a regularly updated, objective and global perspective on the progress achieved and the challenges ahead.

Hydrogen Insights draws upon the **collective knowledge** of Hydrogen Council members

109 companies

>6.8 tm market cap

>6.5 mn employees