Meanwhile, as governments develop specific hydrogen strategies, growing industry associations provide further evidence that something truly different is happening with hydrogen. More industry players are recognising hydrogen's versatility and falling cost, enabling investments in a growing range of sectors. One such global initiative, the Hydrogen Council, has seen its membership grow to 60 companies. This is up from 13 at its founding in 2017, representing a combined market cap of USD 1.7 trillion with combined revenues of over USD 2.6 trillion and close to 4.2 million jobs around the world.

Over the same period, stakeholders have proposed more than 30 major investments globally in segments such as heavy-duty trucking, rail, and steel production from low-carbon or renewable hydrogen. Exhibit 1 lists all the drivers and indicators for hydrogen's growing momentum.

Exhibit 1 | Drivers and indicators of hydrogen's momentum

Drivers of renewed interest in hydrogen

Stronger push to limit carbon emissions

10
Years remaining in the global carbon budget to achieve the 1.5°C goal

66
Countries that have announced net-zero emissions as a target by 2050

Falling costs of renewables and hydrogen technologies

80%
Decrease in global average renewable energy prices since 2010

55x
Growth in electrolysis capacity by 2025 vs. 2015

Indicators of hydrogen's growing momentum

Strategic push in national roadmaps

70%
Share of global GDP linked to hydrogen country roadmaps to date[1]

10 m
2030 target deployment of FCEVs announced at the Energy Ministerial in Japan

Industry alliances and momentum growing

60
Members of the Hydrogen Council today, up from 13 members in 2017

30+
Major investments announced[2] globally since 2017, in new segments, e.g. heavy duty and rail

1. Based on 18 country roadmaps announced as of publication
2. Not exhaustive

The need for a hydrogen cost perspective

The Hydrogen Council's previous report, 'Hydrogen Scaling Up', showed the critical role hydrogen could play in global industrial decarbonisation. While interest in hydrogen has been rising since then, it has not led to the required investments along the value chain. New projects have been announced, but most are not yet sanctioned, likely due to the lack of suitable policy and regulatory frameworks. There are relatively few hydrogen projects already at scale from which stakeholders can gauge hydrogen's near- and long-term economic viability, and industry readiness varies significantly by sub-segment, company and region. Visibility on further cost reduction, hydrogen competitiveness and the scale of required investments – the 'economic gap' that must be bridged in order to reach the scale at which hydrogen is competitive – remain unclear to many.

This report aims to address this information gap by providing the first industry-derived, holistic view of hydrogen's cost base and its path to competitiveness across all scalable applications. It provides an evidence base on the path to cost competitiveness for 40 hydrogen technologies used in 35 applications. For policymakers, such a perspective provides firm ground on which to base priority investments and non-financial support that will unlock the economic value of hydrogen. For decision-makers in industry, it offers a holistic picture of value chain cost dynamics and inter-relationships, allowing them to put their own efforts into a broader perspective.

The report is divided in four parts: Chapter 1 presents an overview of hydrogen's path to competitiveness, including key cost-reduction drivers across a wide range of applications as compared to alternative low-carbon and conventional technologies. The assessment reflects 25,000 data points from over 30 global companies in and close to the Hydrogen Council (listed in Exhibit 2), aggregated and processed using a rigorous clean team approach and covering more than 40 elements along hydrogen value chains, from production to conversion to distribution and end use.

Exhibit 2 | Report contributors

Hydrogen Council Steering Group

Analytical support

McKinsey & Company

For selected technical areas:

Hydrogen Council Supporting Members

Chapter 2 details the role hydrogen production and distribution costs play in hydrogen's competitiveness across applications. Cost trajectories for various technologies were estimated for key regions, including Europe, the US, China, Japan, and Korea.

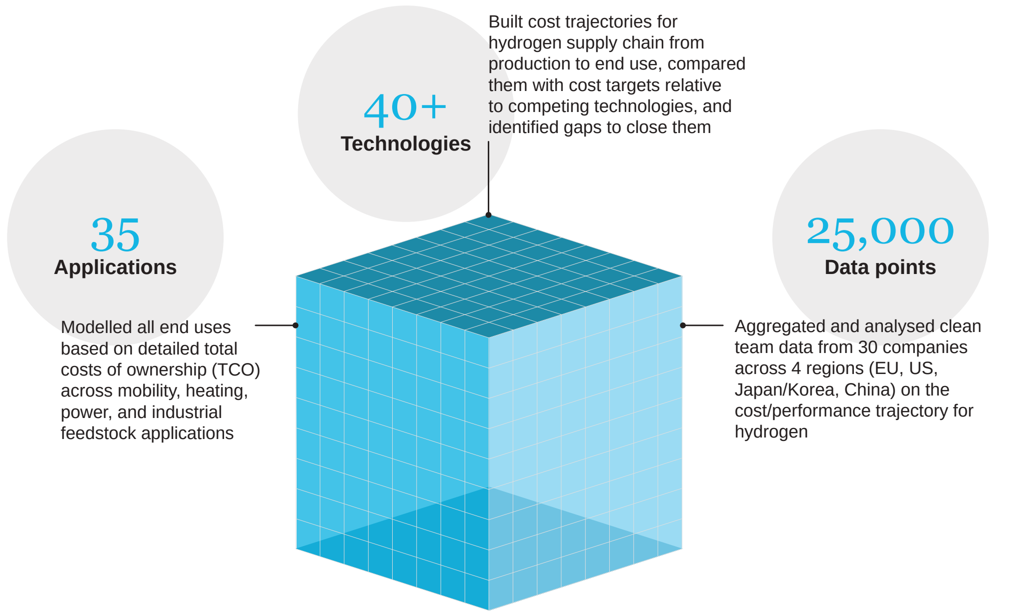
Chapter 3 examines the TCO trajectories and requisite deployed volumes required to achieve the expected cost reductions for several applications in each end-use segment: transportation, heating and power, and industry feedstock. It provides insights into the decision criteria, fundamental competitiveness, and trade-offs for deploying hydrogen over competing technologies. While the report focuses on assessing cost competitiveness, there may be other non-economic factors that stakeholders will consider when comparing technologies, such as the decarbonisation potential and interdependencies between applications.

Chapter 4 explores the implications of the findings on the different cost trajectories. Scaling up existing hydrogen technologies will deliver competitive low-carbon solutions across a wide range of applications by 2030. Yet, to reach this scale, there is a need for investment, policy alignment and demand. The report estimates the economic gap that must be bridged for hydrogen to break even with competing technologies. It goes on to provide recommendations on critical policy areas and lastly, offers five insights for government, industry, and investors to create a hydrogen market.

Methodology for evaluating hydrogen's cost competitiveness

Before presenting the results, some explanation of the methodological approach to the analysis is provided. The report's analysis compares the TCO of low-carbon and renewable hydrogen applications against specific low-carbon and conventional alternatives, e.g. fuel cell electric vehicles versus battery electric vehicles (BEVs) and diesel vehicles. In evaluating applications on which to focus, any hydrogen and other low-carbon solutions that are not realistically scalable were excluded. Exhibit 3 shows the key metrics used in the analysis to highlight the main building blocks of the approach.

Exhibit 3 | Approach to building hydrogen costs perspective



To start, 35 applications were selected across four segments where hydrogen could play a role – in transportation, heat and power for buildings, heat and power for industry, and industry feedstock. Within each of these applications, specific, representative use cases were identified for analysis – such as hydrogen boilers for existing residential properties in Europe – to assess the cases in which hydrogen is competitive and understand what drives its competitiveness. Additionally, more than 40 technologies for hydrogen production and distribution were modelled, covering a range of production methods, conversion steps (e.g. compression, liquefaction), and distribution pathways.

For each hydrogen application and its competing alternatives, a comprehensive TCO trajectory was developed to detail the relevant cost components, cost-reduction drivers were determined, and the break-even point was identified between competing solutions. This was done via an independent third-party clean team who collected, aggregated and processed data from participating Hydrogen Council members, producing anonymised cost estimates by application. In a limited number of use cases where insufficient internal data were available, such as in developing the cost trajectory for aviation synfuels, external projections were used. The findings were then tested with insights from an independent group of experts in government and academia, including Dr. Alan Finkel, Australia's Chief Scientist; Dr. Timur Gül, Head Energy Technology Policy Division at the International Energy Agency; Tom Heller, Chairman of the Climate Policy Initiative; Dr. Noé van Hulst, Hydrogen Envoy at the Netherlands Ministry of Economic Affairs & Climate Policy; and Lord Turner, Chair of the Energy Transitions Commission.

In order to ensure consistent cost projections by the participating companies, we provided specific volume ramp-ups by technology and application as an input. We broadly used the volume ramp-ups from our 2017 'Hydrogen Scaling Up' report but adjusted for certain applications, e.g. passenger vehicles, to arrive at more probable cost trajectories. The scale up assumptions do not represent a forecast of actual volumes, but the trajectory for road transport is supported by promising signs of an ambitious deployment as addressed in the "Ramp-up of hydrogen transportation globally" sidebar. The assumptions are based on the required low-carbon and renewable hydrogen production volume scales to meet 18 per cent of global final energy demand by 2050, to help limit the rise in global temperatures to well below 2°C.

Ramp-up of hydrogen transportation globally

The ramp-up curve for hydrogen applications is still uncertain, and it remains to be seen how volumes will develop. However, the situation is promising as illustrated by hydrogen transport applications: 18 countries have announced ambitious roadmaps and a number of private sector players are working on developing the hydrogen economy through initiatives such as H2 Mobility Germany or H2 Mobility Japan.

The roll-out of HRS networks has started and globally there are more than 400 stations operating, with approximately 200 more planned in 2020. Countries such as Germany have set ambitious targets announcing that 400 stations will be built until 2023, while South Korea has announced 310 stations by 2022.

The Energy Ministerial in 2019 launched a target of 10 million fuel cell vehicles, 10 thousand refuelling stations, in the 10 years until 2030 – the "10-10-10" target. This is in line with the required vehicle fleet volume to reach the 2-degree Celsius target as described in our 'Scaling Up' report, where we found that approximately 3 per cent of global vehicle sales in 2030 should be hydrogen-fuelled, and as much as 36 per cent in 2050.

To reach this target, fuel cell vehicle production will need to increase radically. We find that reaching a production level of approximately 1 million vehicles per annum would bring the majority of vehicle segments to competitiveness, paving the way towards a cost-competitive low-carbon vehicle park as well as the "10-10-10" target.

In general, hydrogen costs were estimated on the basis of an average of natural gas reforming and CCS and renewable hydrogen from renewable power generation and electrolysis. However, for several applications, a specific production method was assumed in order to better understand likely variations between regions, i.e. the EU, the US, Japan, and China. For carbon-emitting applications, the implicit cost of carbon was assumed to increase from USD 30 per ton in 2020 to USD 50 per ton in 2030. These are applied throughout the analyses, except where a carbon cost sensitivity analysis was performed. All financial figures are in US dollars (USD) and refer to global averages unless otherwise indicated.

Hydrogen cost **competitiveness is closer** than previously thought

22

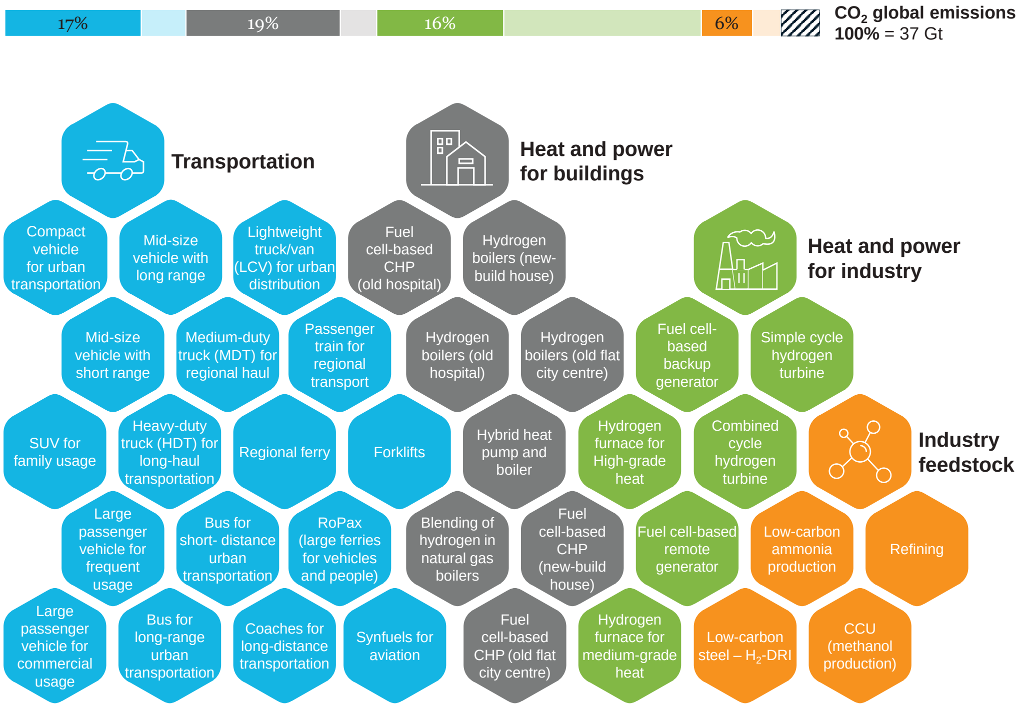
Hydrogen applications may become the most cost-competitive low-carbon solution in 2030

1 | Cost perspective: hydrogen is already surprisingly competitive as a low-carbon option

Overview of cost-competitiveness by application

This report's key finding is that a hydrogen supply and distribution system at scale will unlock hydrogen's competitiveness in many applications sooner than previously anticipated. This report covers 35 hydrogen applications in transport, buildings, industry heat and industry feedstock (Exhibit 4). It includes both new and existing applications currently responsible for 60 per cent of the world's energy- and process-related emissions. Our scope focuses on applications for which hydrogen is best suited, although this analysis does not include all of such applications.

Exhibit 4 | Overview of hydrogen applications



In addition, hydrogen can also be used in, e.g.

Mobility: Container ships, tankers, tractors, container ships, motorbikes, tractors, off-road applications, fuel cell airplanes.

Other: Auxiliary power units, large scale CHP for industry, mining equipment, metals processing (non-DRI steel), etc..

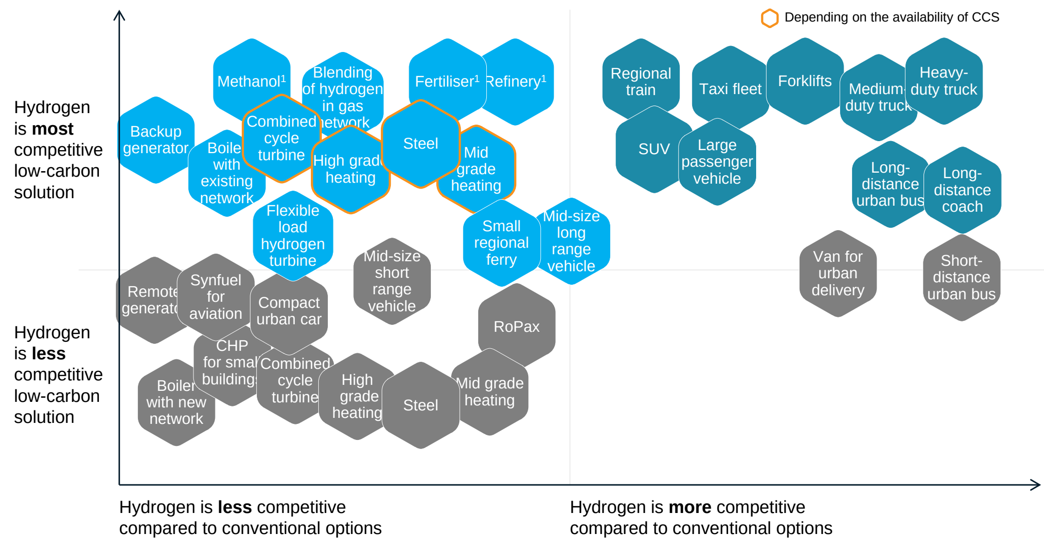
For each application, we assessed the TCO for a low-carbon hydrogen solution from 2020 to 2050. For most applications, we then compared these costs with other low-carbon solutions (e.g. battery vehicles, heat pumps) and conventional technologies (e.g. diesel-powered vehicles, gas boilers). In some applications, hydrogen is practically the only low-carbon solution – for example, in feedstock applications such as ammonia production and hydrocracking in refining, low-carbon and renewable hydrogen competes with ‘grey’ hydrogen produced from unabated fossil resources. In such cases, we only compared to conventional alternatives and between different hydrogen sources.

We identified 22 applications where hydrogen can become a cost-competitive low-carbon solution before 2030 under the right conditions (Exhibit 5) and assumed scale-up cited before. Examples of these include long-distance transport applications and regional trains, which are highly competitive with low-carbon alternatives, as indicated by their position high on the y-axis of Exhibit 5. These 22 hydrogen applications are material: in total, they account for up to 15 per cent of global energy consumption (17,500 TWh). This does not imply that hydrogen will satisfy all this energy demand by 2030, but it does showcase that hydrogen is expected to have a significant role to play as a clean energy vector in the future energy mix.

In four of the reviewed applications, the competitiveness of hydrogen depends on the availability of CCS. If CCS resources for those applications are not available, hydrogen offers the only way to decarbonise the application. Examples include combined cycle turbines, steel production, high-grade heating for cement and medium-grade heating for plastics production.

Compared with conventional alternatives, we find several applications to be highly competitive at scale to both low-carbon and conventional alternatives, requiring zero- or low-carbon prices for hydrogen to break even, as indicated by their position at the right of the x-axis in Exhibit 5. This is true for nine applications, including trucks, trains, long-range passenger vehicles, and long-distance buses. Conversely, for several other applications, including use in turbines, industry feedstock, or synthetic fuel for aviation, a carbon tax of at least USD 100 per ton of carbon dioxide equivalent (CO_2e) would be required to make hydrogen competitive with conventional fuels.

Exhibit 5 | Competitiveness of hydrogen applications versus low-carbon and conventional alternatives



1. Hydrogen is the only alternative and low-carbon/renewable hydrogen competing with grey (optimal renewable or low-carbon shown)

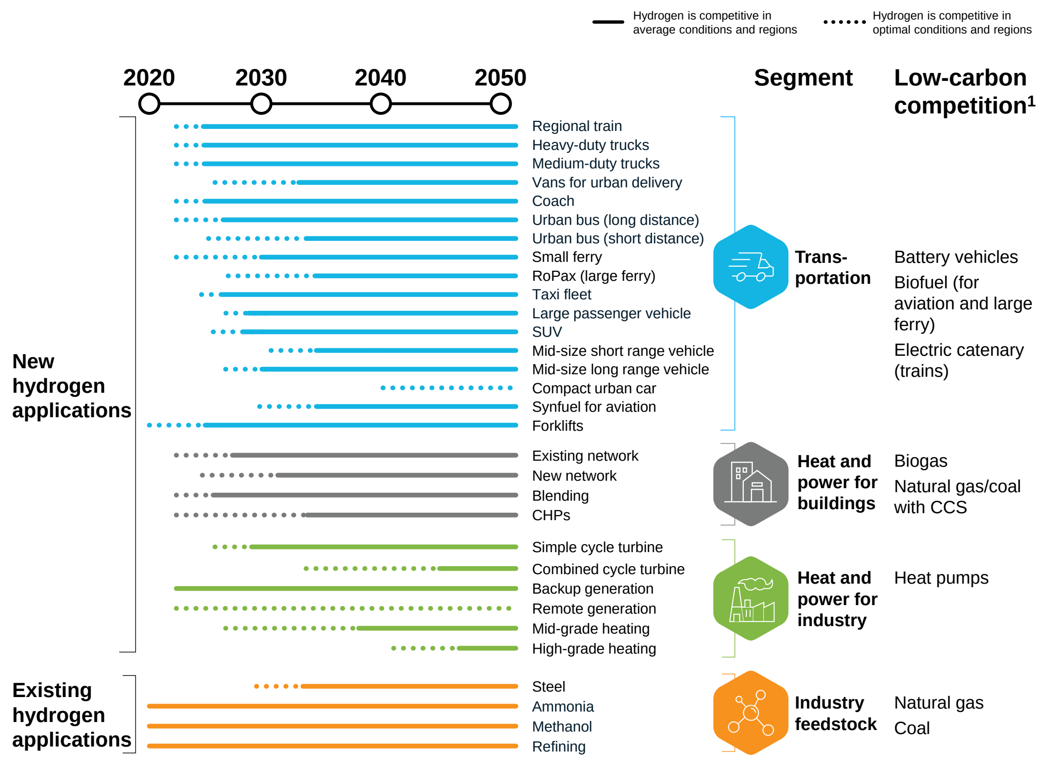
Timeline for cost competitiveness

Exhibit 5 provides a static view of the industry in 2030, but the cost competitiveness of hydrogen applications will improve with scale over time. The timeline in Exhibit 6 builds on the hydrogen deployment scenario presented in our 2017 'Hydrogen Scaling Up' study. It shows the point at which hydrogen becomes the most cost-competitive low-carbon solution for each application. For industry feedstock applications, the logical conclusion is that industry has already passed the break-even point, since no other low-carbon alternative to using low-carbon or renewable hydrogen exists.

The break-even timing depends heavily on the region, each of which has its own energy prices, infrastructure readiness, and available policy framework to support scale-up and regulation. The dashes in the exhibit show when an application becomes cost competitive in all regions analyzed – for example, taxi fleets first become competitive with full BEV fleets around 2023, assuming optimal hydrogen costs, but reach cost parity within two to three years later across all regions.

We compared the hydrogen applications with at least one low-carbon alternative. For example, for road transport applications, we assessed BEVs, while for space heating we considered heat pumps as the low-carbon alternative. The competing low-carbon solutions selected must qualify as fully low-carbon, but may include CCS where relevant (assuming a capture rate of 90 per cent or higher). They must also be scalable and able to achieve full decarbonisation of a segment. Other solutions that qualify as partially low-carbon are not considered as alternatives. For example, using a hybrid heat pump and a natural gas boiler can support the pathway to decarbonisation, but is not considered here as it is not fully low carbon.

Exhibit 6 | Cost competitiveness trajectories of hydrogen applications



1. In some cases hydrogen may be the only realistic alternative, e.g. for long-range heavy-duty transport and industrial zones without access to CCS

From 2020 to 2025. In the short term, hydrogen could become competitive in transportation, particularly for large vehicles with long ranges (i.e. trains, trucks, coaches, and taxi fleets) and forklifts. For these applications, the competing technologies, namely BEVs, are too costly to be viable alternatives for real economic use cases. Heating with hydrogen can become more prevalent when it co-opts existing gas networks. Hydrogen is by default the most competitive alternative to decarbonise industry feedstock, as these processes require hydrogen. All applications will struggle to compete against conventional alternatives on a cost basis in the short term, given the current higher cost of hydrogen technology and limited infrastructure and scale.

By 2030. With the costs of hydrogen production and distribution falling, many more applications should become competitive against low-carbon alternatives by 2030. Examples include most road transport applications except short-range use cases (e.g. compact cars and short-distance buses), simple cycle hydrogen turbines for peak power, hydrogen boilers, and industry heating.

Long term. By 2050, most of the assessed hydrogen applications considered can become competitive against low-carbon alternatives. In our 2-degree Celsius scenario, total world CO_2 emissions will need to be more than 90 per cent lower than today by 2050 – an outcome only achievable by applying low-carbon hydrogen solutions in tandem with other solutions, such as electrification and carbon sequestration.

Hydrogen competitiveness depends greatly on the region. It will play a critical role in decarbonising hard-to-abate industry segments, especially when no nearby direct use clean power alternatives or CCS are available, or prove more expensive. These segments may include long-haul transport, industrial feedstock, power generation from turbines, and industrial heating. Where low-carbon options exist for these segments, they typically require either availability of CO_2 storage or significant amounts of biomass.

Local conditions will influence competitiveness rankings. Regions with access to abundant low-cost clean power, biomass or CO_2 storage will present tougher conditions for hydrogen, especially where direct electrification is an option. For example, heat pumps may work better in some locations compared to building a full hydrogen pipeline network if there is a strong electricity grid, good access to clean electricity and an absence of an existing natural gas network. The same applies to remote power generation where abundant local renewable energy may be preferred over hydrogen generators. In regions with easy access to carbon storage, hydrogen will also face tough competition whenever fossil fuels with CCS are the alternative, like industrial heating or steel production.