Hydrogen Council

McKinsey & Company

Hydrogen for Net-Zero

A critical cost-competitive energy vector

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Executive summary

Hydrogen is central to reaching net zero emissions because it can abate 80 gigatons of CO_2 by 2050

Hydrogen has a central role in helping the world reach net-zero emissions by 2050 and limit global warming to 1.5 degrees Celsius. Complementing other decarbonization technologies like renewable power, biofuels, or energy efficiency improvements, clean hydrogen (both renewable and low carbon) offers the only long-term, scalable, and cost-effective option for deep decarbonization in sectors such as steel, maritime, aviation, and ammonia. From now through 2050, hydrogen can avoid 80 gigatons (GT) of cumulative CO_2 emissions. With annual abatement potential of 7 GT in 2050, hydrogen can contribute 20% of the total abatement needed in 2050.[a] This requires the use of 660 million metric tons (MT) of renewable and low-carbon hydrogen in 2050, equivalent to 22%[b] of global final energy demand.

Hydrogen is critical in enabling a decarbonized energy system. It facilitates the integration of renewably produced energy because hydrogen can store energy, provide resilience, and transport high volumes of energy over long distances via pipelines and ships. Hydrogen allows energy companies to tap extremely competitive, but otherwise “stranded” renewable energy in remote locations. This accelerates the energy transition as it allows more renewables to be built. Finally, because hydrogen can be produced from electricity and used as, or converted into, fuels, chemicals, and power, the production of hydrogen from electricity will connect and fundamentally reshape current power, gas, chemicals, and fuel markets.

In terms of end uses, hydrogen is critical for decarbonizing industry (e.g., as feedstock for steel and fertilizers), long-range ground mobility (e.g., as fuel in heavy-duty trucks, coaches, long-range passenger vehicles, and trains), international travel (e.g., to produce synthetic fuels for maritime vessels and aviation), heating applications (e.g., as high-grade industrial heat), and power generation (e.g., as dispatchable power generation and backup power).

China, followed by Europe and North America, will be the largest hydrogen markets in 2050, together accounting for about 60% of global demand. Fulfilling this decarbonization role will require a large scale-up of clean hydrogen production in the coming decades. Supplying 660 MT to end-uses will require 3 to 4 terawatts (TW) of electrolysis capacity and about 4.5 to 6.5 TW of renewable generation capacity, as well as 140 to 280 MT of reforming capacity for low-carbon hydrogen production and associated infrastructure to store about 1 to 2.5 GT of CO_2 a year. In such a supply scenario, renewable energy for hydrogen will account for roughly 15% to 25% of the 27 TW of total new renewable energy required by 2050[c] to reach net zero – a 10x increase over the 2.8 TW installed today.

Scaling through 2030 is critical for meeting long-term targets and unlocking cost-efficient decarbonization opportunities

Setting our energy system on a trajectory to net-zero requires firm commitment and rapid acceleration. We estimate the deployment of 75 MT clean hydrogen is needed by 2030 – an ambitious, yet achievable target. This supply of clean hydrogen can replace 25 MT of grey hydrogen in ammonia, methanol, and refining; 50 billion liters of diesel in ground mobility; and 60 MT of coal used for steel production. Early growth in clean hydrogen deployment will likely center on Europe, Japan, and Korea, which will account for about 30% of new clean demand. China and North America – significantly larger hydrogen markets today – will follow closely with about 20% of demand for clean hydrogen each.

To supply this demand in a cost-optimal way, a mix of both renewable and low-carbon hydrogen supply would require 200 to 250 gigawatts (GW) of electrolyzer capacity and 300 to 400 GW of new renewables, as well as 45 to 55 MT of low-carbon hydrogen production capacity and associated carbon infrastructure to store 350 to 450 MT of CO_2 a year. This will create the need to step up the deployment of renewables: in 2020, 260 GW of capacity was commissioned. A further acceleration is required to meet rising electrification demand.

This deployment of clean hydrogen will not happen without the right regulatory framework – both governments and businesses need to act. Requirements include a set of suitable policies such as mandates and robust carbon pricing, the development of large-scale infrastructure, and targeted support and de-risking of large initial investments.

These investments will pay off; scaling hydrogen is the key to reducing costs through economies of scale, making hydrogen available to end-users through the necessary infrastructure, and ultimately making hydrogen a competitive, available, cost-efficient decarbonization vector. In this report, the use of clean hydrogen would abate as much as 730 MT of CO_2 annually in 2030, the equivalent to more than the annual CO_2 emissions in 2019 of the UK, France, and Belgium combined. The decarbonization contribution from clean hydrogen use will differ per end-use segment:

Current industrial uses: A large share of the decarbonization will come from current industrial uses of hydrogen with 270 MT of CO_2 avoided a year, particularly from the decarbonization of refining and ammonia synthesis. These applications are among the most attractive uses for early deliverable low-carbon hydrogen, at carbon abatement costs for high-purity emission streams of USD 50 to 100 a ton in most regions.

Ground mobility: In the ground mobility sector hydrogen could avoid about 90 MT of CO_2 emissions in 2030. By about 2030, hydrogen-powered vehicles (e.g., heavy-duty trucks, coaches, long-range passenger vehicles, and rail) could achieve cost parity with internal combustion engine (ICE) vehicles, leading to a significant scale-up. Given heavy payloads and long distances traveled, trucks account for the biggest share of the abatement. With a share of about 11% of global heavy-duty truck sales in 2030, emissions of about 60 MT of annual CO_2 emissions would be avoided – as much as 22 million battery-electric passenger vehicles.

Hydrogen-based fuels: Fuels based on hydrogen, e.g., ammonia, methanol, e-methane, e-kerosene, or liquid hydrogen, are the most promising scalable alternatives to decarbonize aviation and maritime applications above and beyond biofuels where feedstock availability is limited. The early adoption of hydrogen in these sectors will be driven by regulators and industry commitments, and while hydrogen adoption in 2030 will be relatively low in these segments at about 1% and 6%, it lays the foundation to decarbonize these sectors longer-term by up to 60% by 2050.

Steel: While requiring larger initial investments, the use of hydrogen in steel represents a large, cost-effective decarbonization lever for 2030, with 880 MT of CO_2 abated by then. A carbon cost of less than USD 50 to 100 a ton can make hydrogen-based steel production competitive in many locations due to the significant emissions of 1.85 tons of CO_2 per ton of steel produced from coking coal. Steel could account for about 4% of hydrogen demand in 2030 while driving nearly 20% of emissions reductions that year.

Power: Hydrogen will enable early decarbonization of current fossil-fueled power generation assets through blending in natural gas, displacing fossil fuels such as coal and natural gas.

Strong momentum, but a USD 540 billion capital gap remains until 2030

The hydrogen industry shows strong momentum around the globe, with more than 520 projects announced in 2021, up 100% compared to 2020. These announced projects will translate into 18 MT of clean hydrogen supply (accounting for USD 95 billion) as well as infrastructure (USD 20 billion) and end-uses (USD 45 billion). Considering investments to achieve government targets and support equipment value chains, the total sum of estimated spending will grow to more than USD 600 billion by 2030.

Although the pipeline of projects is strong, a significant gap to the net zero scenario remains, and the right regulatory framework is required to turn projects from concepts into actual investments. Out of the currently announced direct investments, only USD 20 billion (13%) have passed the final investment decision (FID) so far, with another USD 64 billion (40%) in the feasibility or front-end engineering and design (FEED) stage. This means many proposals are on the table awaiting the right regulatory framework to unlock demand and investments.

In terms of additional investments, the currently announced projects (USD 160 billion) cover nearly 25% of the required USD 700 billion to achieve the deployment laid out in this report, out of which USD 300 billion is required for hydrogen production, 200 billion for infrastructure, and 200 billion for hydrogen end-uses. This leaves a gap of USD 540 billion. While significant, these investment levels appear possible: The USD 700 billion required equates to about a third of the investments made in renewable energy from 2010 through 2019[d], or less than 15% of cumulative investments in upstream oil and gas in the same timeframe[e].

Call to action

A tremendous acceleration has taken place over the past year with strong growth in the number of projects being launched, demonstrating hydrogen's many potential uses are recognized in the industry. However, a five-fold increase in announcements is required to enable the full abatement potential of hydrogen. The conversion of this momentum into real deployment and scale-up now critically depends on the right regulatory framework, which will create demand, enable supply, and reduce investment risks.

Hydrogen's full potential can only be realized if action is taken across three fronts to: stimulate demand, enable access through infrastructure, and create scale to bring down costs and close the economic gap of hydrogen decarbonization solutions versus conventional alternatives. While the overall investment required is large, it is well within the order of magnitude of current financial flows into the energy sector.

a. Abatement of 7 GT CO_2 from use of clean hydrogen is equivalent to about 20% of CO_2 emissions in 2050, assuming annual emissions would be 35 gigaton CO_2.

b. Assumes 340 EJ final energy demand in 2050 (IEA Net Zero by 2050), considers hydrogen demand excluding power sector

c. 27 TW new renewable generation capacity required until 2050 according to 'Net Zero by 2050' by the IEA

d. Global investments into renewable energy from 2010 to 2019 amounted to about USD 2.6 trillion according to UN Environment Programme (UNEP)

e. Global investment into upstream oil and gas from 2010 to 2019 amounted to about USD 5.7 according to IEA World Energy Investment

Introduction

93

countries have adopted net-zero targets

39

countries have adopted hydrogen strategies

Growing awareness of the need for decarbonization

With climate urgency now pressing, stakeholders are making commitments to rapidly curb emissions, demonstrating a significant shift in sentiment and sense of urgency. Ninety-three countries have introduced net-zero targets[1], and 55 countries have carbon trading schemes. More than 1,300 corporations have committed to the Science-Based Targets[2] as of the first quarter of 2021, including commitments from more than 20% of the world's 2,000 largest corporations. Increasingly, stakeholders such as governments, industries, and consumers are recognizing that hydrogen could and should play a central role in meeting climate targets. A growing number of countries have set pathways to tap hydrogen's decarbonization potential. Thirty-nine countries are covered by government-backed hydrogen strategies, including the EU and another 12 countries outside the EU[3], while several others are developing strategies or considering doing so. The Hydrogen Council now counts 129 members, up from 60 in 2020, representing USD 7.6 trillion in market capitalization, 6.9 million employees globally[4], and revenues of USD 4.5 trillion in 2020.[5]

Urgent near-term actions must be taken to meet climate objectives and prevent out-of-control global warming. The world is currently not on a path toward net-zero in 2050, and humanity is at a pivotal point in its history. At the current emission rate of about 43 GT of CO_2 emitted in 2019, with a COVID-19 induced dip in 2020 to about 40 GT, the remaining carbon budget of 420 GT of carbon dioxide (CO_2) through 2050[6] – consistent with a 1.5-degree scenario – will be exhausted by 2030 unless drastic emission reductions are initiated in the coming decade. The solution requires the full arsenal of decarbonization solutions, including energy efficiency, the electrification of transport, industrial uses, and applications in buildings, biofuels, carbon capture and storage – and clean hydrogen. The time to act and address this unprecedented challenge of global warming is now and the coming decade will play a critical role in making it possible. Clean hydrogen is one of the most versatile and cost-efficient decarbonization vectors. Its systemic role is critical if the world is to achieve the decarbonization of hard-to-abate sectors and enable the wider uptake of complementary decarbonization efforts.

Building a hydrogen demand, abatement, and investment perspective

The Hydrogen Council's report from January 2020, "Path to Hydrogen Competitiveness," demonstrated hydrogen could become a cost-competitive decarbonization solution across many sectors in the coming decade. The more recent "Hydrogen Insights" publications show a continued acceleration in momentum for hydrogen. However, while interest in hydrogen in its many configurations and uses is strong, a significant step-up in investments, commitments, and supportive regulatory frameworks must happen to achieve success.

While the role hydrogen could play is clear to many, significant uncertainty remains regarding the magnitude of the investments required in the coming decade to enable a clean hydrogen economy to contribute to the net-zero emission targets.

1 Includes 14 EU member states that have not announced targets but fall under EU's overarching net zero target by 2050. Alliance of Small Island States (AOSIS) has on behalf of its 37 member states (as defined by the UN) committed to net zero by 2050.
2 As of first Q1 2021, up from 1,009 at the end of year 2020.
3 Countries with a government-backed hydrogen strategy: Australia, Canada, Chile, China, the EU (covering 27 member states), Japan, New Zealand, Norway, South Africa, South Korea, United Kingdom, United States, and Uzbekistan.
4 As of October 2021.
5 2020 revenues.
6 The carbon budget includes all anthropogenic CO_2 emissions.

Exhibit 1 – Framing for 'Hydrogen for Net-Zero'

Focus

Hydrogen for Net Zero…

- Hydrogen demand and CO_2 abatement
- Current momentum
- Investments required & gap

Perspective on the role hydrogen can play in a Net Zero world 2050, and **highlight** (realistic) **steps that must be taken in the coming decade**

… is developing a ambitious, yet realistic, path to Net Zero in 2050

Current trajectory (BAU)	Hydrogen for Net Zero	Net Zero (Unconstrained)
Continuation of current trajectory and trends, with limited emission reduction - **we fail to meet the Paris targets**	**Ambitious, yet realistic, perspective** on hydrogen's role on the pathway to Net Zero in 2050 **in line with the Paris Accord**	**Techno-economic optimum** for 'what would need to happen', that is **unconstrained** by policy framework, supply chain limitations, and investments required

This publication lays out an ambitious yet realistic path to net-zero in 2050 (see Exhibit 1) and examines the role clean hydrogen could play in the energy transition from now through 2050. It addresses an information gap by providing an industry-derived, holistic perspective on hydrogen and its critical role as a cost-efficient decarbonization solution. It not only lays out hydrogen's potential long-term role but also describes what must happen in the coming decade to reach the net-zero targets. This perspective provides a unique basis for industry and governments to make informed decisions, prioritize, and initiate the necessary transition. The Hydrogen Council Members (Exhibit 2) and McKinsey & Company co-authored this report.

Exhibit 2 – Hydrogen Council Members

Report structure

The publication explores multiple aspects of the hydrogen economy and is structured in the following four chapters:

Chapter 1 (Demand for hydrogen and its cost- and carbon-cutting role) addresses the 2050 long-term demand potential of clean hydrogen across applications and regions, the clean hydrogen supply mix, CO_2 abatement potential, and hydrogen's systemic role in connecting multiple industries such as chemicals and power.

Chapter 2 (Scaling until 2030 is critical for meeting long-term targets) explores the hydrogen demand growth toward 2030, the required changes to hydrogen supply mix, hydrogen's mid-term abatement potential, as well as which sectors are most likely to reach scale first, thus enabling the full hydrogen economy across a broader set of end-use applications.

Chapter 3 (Hydrogen momentum and required investments) considers current hydrogen momentum in terms of announced projects and investments, comparing it to the investments across the value chain and regions required to scale hydrogen. It identifies the investment gap, which is the difference between announced and required investments.

Chapter 4 (Action is required) describes the role hydrogen should play in the energy transition, what is needed to unlock clean hydrogen at scale, and gives a call to action to regulators and the industry.

The focus is on Europe, North America, China, Japan and Korea together, and the rest of the world. The report considers 39 sub-sectors across the existing hydrogen industry, new industry uses (e.g., steel), mobility, heating, and power.

A description of the analytical methodology underlying the report can be found in the appendix.

1

Demand for hydrogen and its cost- and carbon-cutting role

660 MT

p.a. clean hydrogen required in 2050 to reach net-zero – up from 90 MT today

22%

of CO_2 abatement required in the year 2050

The role hydrogen can – and should – play in achieving net-zero targets has become increasingly clear to regulators, industry leaders, and end-consumers. The world needs rapid emissions reductions and clean hydrogen has a crucial role to play, particularly in hard-to-abate sectors.

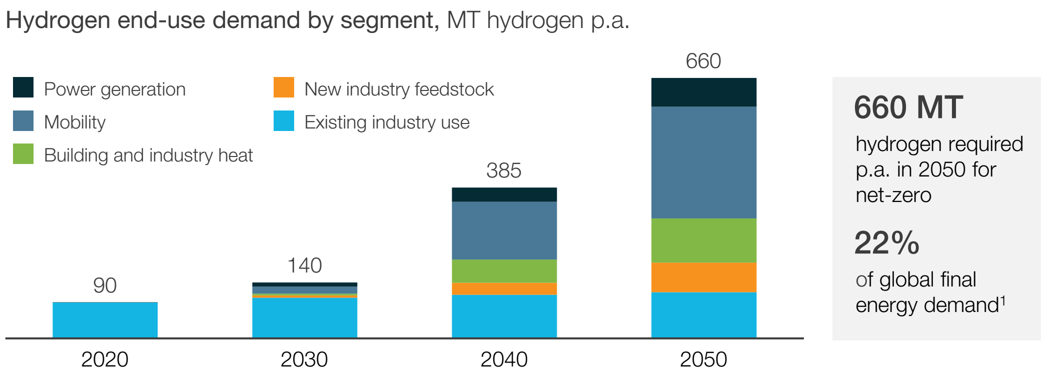
This chapter provides a perspective on hydrogen's long-term role in the energy system through 2050 and its broader role in enabling access to attractive renewable resources and in coupling sectors. It describes the long-term potential of clean hydrogen demand across segments and regions, the clean hydrogen supply scale-up required, as well as hydrogen's abatement potential.

Hydrogen is a critical decarbonization vector and can connect and reshape current power, gas, chemicals, and fuel markets

Hydrogen can play a fundamental role in enabling countries and industries to meet their net-zero emission targets by 2050. While not in itself the solution to abate all emissions across sectors, hydrogen uniquely complements and enables other decarbonization pathways such as direct electrification, energy efficiency measures, and biomass-based fuels.

In a net-zero world, demand for clean hydrogen[7] could reach approximately 660 million metric tons (MT) in 2050, making up 22% of the final energy demand globally (Exhibit 3) and avoiding annual emissions of 7 gigatons (GT) of CO_2. This annual abatement potential of 7 GT in 2050 is equivalent to about 20% of the emissions if the world remains on its current global warming trajectory.[8] By 2050, clean hydrogen could abate a cumulative total of 80 GT of CO_2 – about twice the current amount of annual anthropogenic emissions. The 80 GT cumulative CO_2 abatement potential through 2050 constitutes about 11%[9] of the emissions reductions required to stay within the carbon budget of 420 GT needed to limit global warming to 1.5-1.8 degrees Celsius.

Exhibit 3 – Global hydrogen demand by segment until 2050



1. IEA net-zero scenario with 340 EJ final energy demand in 2050. HHV assumed. Excluding power.

[7] Clean hydrogen is in this publication defined as either renewable or low-carbon hydrogen; Renewable hydrogen refers to hydrogen produced from water electrolysis with renewable electricity, while low-carbon hydrogen refers to hydrogen produced from fossil fuel reforming with carbon sequestration.
[8] Assumes 35 GT anthropogenic emissions in 2050 in current trajectory.
[9] Considers the share 80 GT CO_2 abated from hydrogen in terms of cumulative emissions from 2021 to 2050, subtracting the remaining carbon budget of 420 GT.

Hydrogen's primary role in the energy transition is that of a cost-efficient decarbonization vector across many sectors, particularly those less suited for direct electrification. Hydrogen applications include a variety of feedstock uses, such as ammonia synthesis for fertilizer production and iron reduction for steel; fuel for mobility, including the direct use of hydrogen in heavy-duty vehicles and hydrogen-based fuels or liquid hydrogen for use in maritime and aviation applications; heating, including high-grade heat in industry and building heat; and power applications like seasonal balancing, backup generators and blending in existing baseload power plants.

Hydrogen's role in the energy system

Hydrogen also plays a critical role in enabling a higher degree of electrification and a stronger penetration of renewable power generation to build decarbonized energy systems. Hydrogen's versatility enables it to store energy over long periods and provide energy system resiliency by making system balancing possible. It can facilitate the transport of clean energy over long distances via pipelines and shipping, thus unlocking previously untapped "stranded" renewables resources. Furthermore, it can reshape current chemicals, fuels, and metal production sectors and connect them with the power industry. This systemic role of hydrogen makes possible a holistic and hence faster and more cost-effective decarbonization across sectors and regions.

Energy storage: Hydrogen can store large amounts of energy over long periods to be tapped as required, for example, in underground salt caverns. Such uses might include providing heating during unexpectedly cold winters or ensuring steady hydrogen supply at industrial plants. If pipelines are available, hydrogen can be stored through "line packing," i.e., increasing the pressure in the pipelines to store a higher volume of hydrogen and strengthen the security of the energy supply.

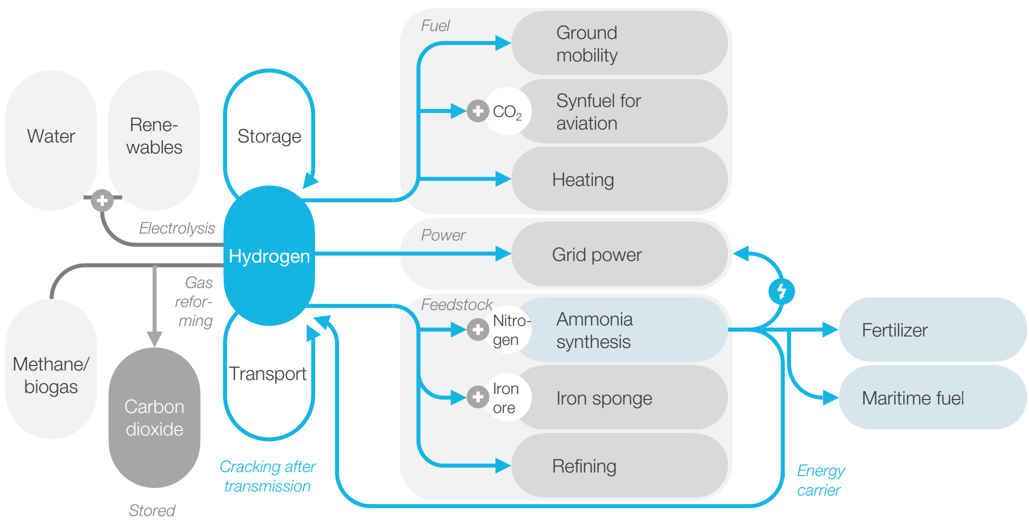
Energy system resiliency: Hydrogen provides energy system resiliency in multiple ways. It enables continuous grid operation by balancing peaks and troughs in demand, storing power when excess low-cost energy is available and releasing it when needed. Furthermore, it supports the diversification of energy resources across geographies, enabling the use of the most attractive cost-effective resources rather than overbuilding locally. It fuels backup generators required to ensure the power supply for essential facilities like data centers and hospitals.

Energy transmission: Hydrogen can move clean energy from areas with attractive energy resources to areas with less attractive domestic resources, enabling both regional and global energy transmission. Within a region, pipelines and trucks can distribute hydrogen. Pipelines can transmit significant amounts of energy, about 10 to 20 times more than electricity transmission grids and ensure the cost-competitive provision of large volumes of energy over long distances. For instance, pipelines could transmit energy from the renewable rich south of Europe to northern demand centers. Pipelines will also be required to supply hydrogen to large-scale industrial users such as steel and ammonia plants where on-site hydrogen supply is not available. Trucks with compressed or liquid hydrogen can cost-competitively supply distributed end-users such as refueling stations, remote generators, construction sites, or smaller industrial customers. For longer distances, hydrogen can be shipped. It can connect low-cost hydrogen production regions like Australia, Latin America, and the Middle East to demand centers such as Europe, the Western US, Japan, and Korea. It can be shipped as either pure liquefied hydrogen or converted into other carriers such as ammonia or liquid organic carriers to be used directly in end-use applications or "cracked" back into pure hydrogen.

Unlocking untapped "stranded renewables": Hydrogen can enable extremely competitive yet otherwise untapped "stranded" renewable energy potential in remote, thinly populated locations. These renewable resources often exist in high volumes and quality (i.e., high load factors and low cost), but have been inaccessible until now because of the infeasibility of building electricity transmission lines to demand centers. Hydrogen enables the energy system to tap into these resources and transmit them to demand centers with less attractive energy resources, ultimately transferring low-cost, clean energy to where it is needed. It can thus accelerate the energy transition and avoid shortages in renewable energy deployment by providing access to previously inaccessible resources.

Sector coupling: Beyond these system functions, hydrogen connects industries in novel ways. Because hydrogen can convert electricity into gas and other end-products, it can connect and ultimately reshape current gas, power, chemicals, and fuel markets, with clean energy at the source of these applications (Exhibit 4). Clean hydrogen used in steel production or fuel for aviation, for example, ultimately originates from renewable energy, natural gas, or biogas with carbon capture. Hydrogen connects the clean power and energy market with the metals, fuels, chemicals, and petrochemical industries, expanding the borders of previously distinctly separate sectors. For instance, ammonia – today used for fertilizer production or other industrial applications – could play a major role as a fuel for maritime or power generation, or as a clean energy carrier for the global transmission of clean electrons in the form of clean molecules.

Exhibit 4 – Hydrogen pathways in the energy system



Clean hydrogen produced from "stranded" renewables used as reductant in steel production - or to fuel ships and trucks
Chemicals and energy sectors are coupled - chemicals become energy carriers or fuels

Note: Selected examples – not exhaustive

To meet net-zero targets, long-term hydrogen demand should reach 660 MT in 2050

The largest end-use segments for hydrogen in 2050 will likely be mobility, industrial uses of hydrogen, including feedstock and heating, and heating for buildings, together accounting for 90% of the total demand of 660 MT. Most of the growth will come from new uses for hydrogen, which will account for more than 540 MT of demand in 2050. There are multiple major sub-sectors:

Mobility. Mobility, accounting for about 19% of global emissions today, will be the largest single hydrogen end-use segment with 285 MT of hydrogen demand in 2050. The sector includes hydrogen applications within ground mobility, maritime, and aviation. Some mobility end-uses, such as long-range flights and containerships, are among the most challenging sectors to decarbonize, and hydrogen in combination with biofuels offers the only scalable pathway to fully decarbonize these.

Within **ground mobility**, hydrogen has an important role to play. Ground mobility contributes about 15% of global emissions today, including those from heavy trucks, regional trains, long-range passenger vehicles, and coaches. Hydrogen complements direct electrification through batteries in use cases that require long ranges, high uptime, and swift refueling. Heavy-duty trucks are expected to be the largest consumer of hydrogen long-term due to their high mileage and power characteristics, requiring 110 MT of hydrogen in 2050 to abate 13 GT of CO_2.

Maritime and aviation, which generate about 4% of global emissions today, are both high-power, long-range end-uses and will partly rely on hydrogen-based fuels to decarbonize cost-efficiently. Liquid hydrogen or hydrogen-based fuels such as ammonia, methanol, or e-methane are the most promising clean fuels for full decarbonization of the maritime sector. Aviation will become a major consumer of synthetic fuels (e-kerosene), based on hydrogen combined with CO_2 from biogenic sources or directly captured from the air, as well as liquid hydrogen for short-range intracontinental flights. Together, these two end-uses will account for 110 MT of hydrogen demand, abating 13 GT of CO_2 through 2050.

Existing feedstocks. Hydrogen today plays an integral role in feedstock applications like ammonia, methanol, and refining, and clean hydrogen is required for decarbonization. Together, these uses comprise about 2% to 3% of global emissions. Clean hydrogen to decarbonize these applications will account for about 15% of demand in 2050 (about 105 MT), down from more than 90% today.

Steel. Steel is one of the world's highest CO_2-emitting industries, accounting for about 8% of global annual emissions due to the use of coking coal in the blast furnace process. Steelmaking is one of the most challenging sectors to abate due to few alternative decarbonization pathways and relies on hydrogen for full decarbonization. Steel decarbonization requires 35 MT of demand for hydrogen in 2050, resulting in 12 GT of emissions avoided through 2050.

Power. Power accounted for about 30% of global emissions in 2019. The key decarbonization solution within power generation is expanding renewable energy generation capacity. However, solar and wind power is inherently volatile, and the energy system will require both short- and long-duration balancing. Hydrogen has a crucial role in decarbonizing the final 1% to 3% of demand in a fully decarbonized grid, because it can provide long-duration and seasonal storage, as well as peak shaving, and will be critical for stabilizing the grid. In 2050, hydrogen for grid power generation could account for 65 MT of clean hydrogen.

Aromatics. The decarbonization of BTX (benzene, toluene, and xylene) production is currently at a very early stage. Hydrogen-based aromatics production routes, such as methanol-to-aromatics, which combines clean hydrogen with CO_2 from biogenic sources or captured from the air, are currently under development and testing. Industry players expect aromatics will decarbonize in line with the rest of the economy, accelerating after 2030 when technology reaches commercial scale. In 2050, hydrogen demand for methanol-to-aromatics could account for about 40 MT, although this is highly uncertain. If used for plastics production (e.g., nylon), BTX can act as a carbon sink by storing captured CO_2 for long-duration storage. If biogenic or air-captured CO_2 is used and the plastic is not incinerated, low-carbon BTX can contribute to negative carbon dioxide emissions.

>7x

growth in hydrogen demand until 2050

Industry heat. Industrial heating accounts for significant emissions today due to the extensive use of coal and natural gas, particularly for high-grade heat supply. Multiple decarbonization pathways exist, including biomass, direct electrification, post-combustion carbon capture and storage, and hydrogen combustion. Hydrogen has a key role to play in decarbonizing industry heat, in particular for high-grade heat (temperatures above 400 degrees Celsius) applications such as cement plants, glassmaking, and aluminum remelting. In 2050, demand for hydrogen in industrial heat could account for about 70 MT, mainly in high-grade heating applications.

Building heat. Heating for residential and commercial buildings accounts for about 5% of global emissions and is one of the last hydrogen end-uses to scale due to the significant infrastructure investments needed, as it will require a hydrogen pipeline distribution network. Blending hydrogen in existing natural gas grids could develop as an early step toward fully hydrogen-ready pipeline networks. In 2050, building heat could account for 40 MT, mainly in regions that today use natural gas for heat like Europe, parts of China, and the US. However, significant uncertainties remain regarding the role of hydrogen solutions in this sector and cost competitiveness versus electrified solutions such as heat pumps.

China likely the largest single market for clean hydrogen in 2050

Across regions, China, Europe, and North America will be the largest consumers of hydrogen globally (Exhibit 5). In 2050, hydrogen will be a major part of energy markets across geographies, enabling some countries to exploit their natural resources and reduce their reliance on imported oil and gas while decarbonizing various sectors. Australia, Latin America, and the Middle East will likely become major exporters.

China, the world's largest consumer of primary energy, should become the largest single market for clean hydrogen in 2050, with about 200 MT of demand. Europe and North America will follow, accounting for 95 MT of clean hydrogen each.

Europe has significant decarbonization momentum across industries. Hydrogen should play a major role in meeting the targets across feedstock, industry energy, mobility, and power. In Europe, clean hydrogen demand is expected to be partially supplied by imports and scale-up proportionally earlier than in other geographies.

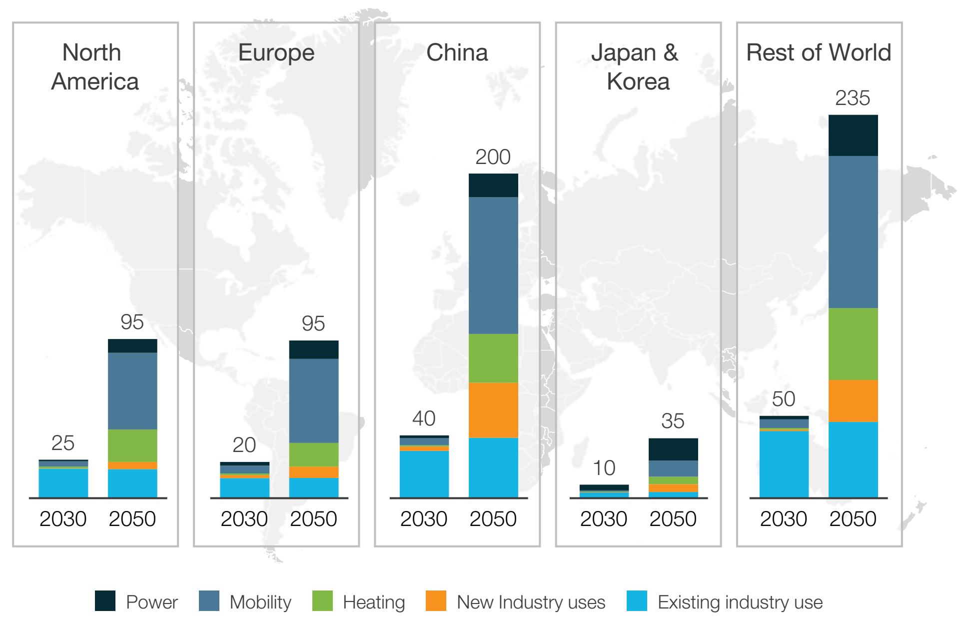
In North America, the world's second-largest consumer of energy, hydrogen will play a major role in ensuring a low-carbon domestic energy supply, building on attractive resources for renewable power production as well as low-cost natural gas and abundant carbon storage sites.

Japan and Korea will require about 35 MT of hydrogen in 2050, the majority of which will be imported renewable or low-carbon hydrogen. Although many consider these markets hydrogen front-runners and the countries themselves view hydrogen as a core part of their energy strategies, these will be relatively small markets compared to China, Europe, and North America.

Other regions like South-East Asia, Oceania, Middle East, and Latin America will account for about 235 MT hydrogen demand in 2050. While many of these markets have been slower to adopt hydrogen at scale in new end-uses compared with frontrunners such as Europe, Japan, and Korea, they have already seen activity on this front. Several countries within these regions have developed hydrogen strategies or are in the process of developing such plans. There have also been moves to develop their export potential by leveraging attractive renewable and low-carbon energy resources to produce low-cost hydrogen.

Exhibit 5 – Hydrogen demand by region in 2030 and 2050

Hydrogen end-use demand by region, MT hydrogen p.a.



Clean supply is critical to fulfilling hydrogen's role as a decarbonization vector

Fulfilling hydrogen's role as a decarbonization vector will require a significant scale-up of clean hydrogen supply through 2050 to meet the net-zero targets. The industry needs 690 MT of low-carbon and renewable hydrogen supply to meet hydrogen demand of 660 MT in 2050 due to losses in the supply chain, such as those from conversions to or from carriers, leakage in pipelines, or boil-off from liquid hydrogen storage or distribution.

Today, most hydrogen is fossil-based (grey); over the longer term, this capacity will either be decommissioned or converted into renewable or low-carbon hydrogen (Exhibit 6). Low-carbon hydrogen will be the most cost-competitive mid-term solution in multiple regions, and most of the capacity built during the coming 10 to 15 years will be low-carbon hydrogen. Longer-term, renewable power generation capacity will have expanded, and renewable hydrogen will become the most competitive source of hydrogen in most regions. In the decade between 2040 and 2050, renewable hydrogen will likely account for the largest share of capacity.

Low-carbon hydrogen will account for about 20 to 40% of supply in 2050, the equivalent of 140 to 280 MT of hydrogen supply. This amounts to about two to three times today's grey capacity and would require infrastructure to store about 1 to 2.5 GT of CO_2 a year.

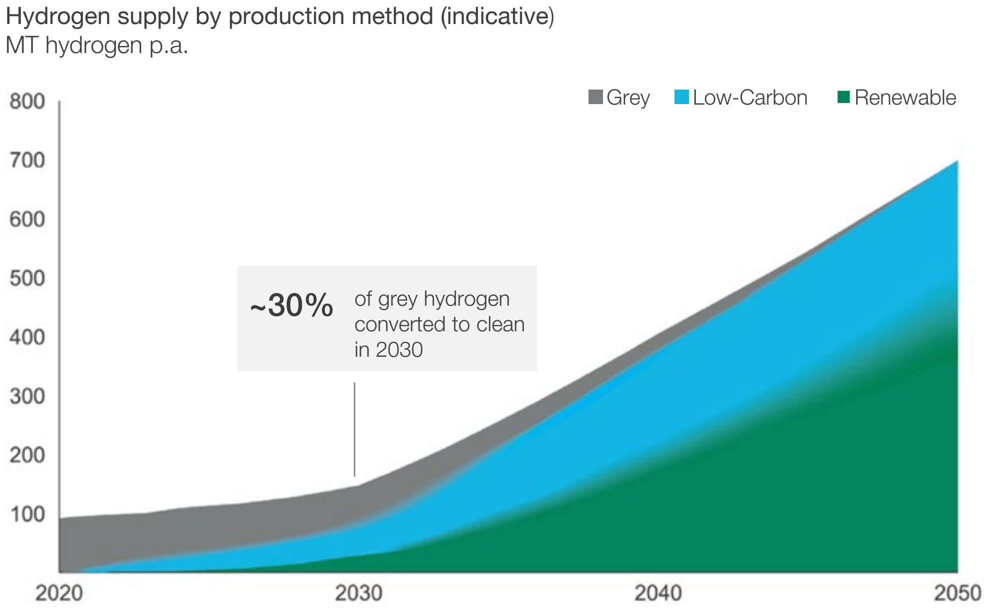
Renewable hydrogen will account for 60% to 80% of supply or 400 to 550 MT of hydrogen. Such a volume of renewable hydrogen will require 3 to 4 TW of electrolysis capacity and about 4.5 to 6.5 TW of renewable capacity dedicated to hydrogen production. In comparison, this is about two times the total renewable generation capacity of 2.8 TW installed through 2020. A step-up in renewable generation installations is required not only for hydrogen production but also for the broader electrification of society. About 27 TW of renewable power would be required in a net-zero economy in 2050 – the estimated electrolyzer buildout would require about 20% of this capacity.

Renewable and low-carbon hydrogen are complementary. Building out both supply pathways will enable the use of the most attractive resources to decarbonize cost-efficiently and rapidly across sectors and regions. If all the hydrogen were to come from renewable power, about 5.5 TW electrolysis would be required, with about 8 GW of renewables. Similarly, supplying the demand with only low-carbon hydrogen, about 5.5 GT of annual carbon storage capacity would be required. Combining the two sources will lead to lower energy system costs overall and a faster transition. Relying on a single pathway for clean hydrogen supply may slow the necessary scale-up as it requires an even swifter ramp-up of value chains and project developments, hindering the necessary decarbonization to reach the net-zero targets.

Zero grey

hydrogen in 2050

Exhibit 6 – Hydrogen supply mix over time

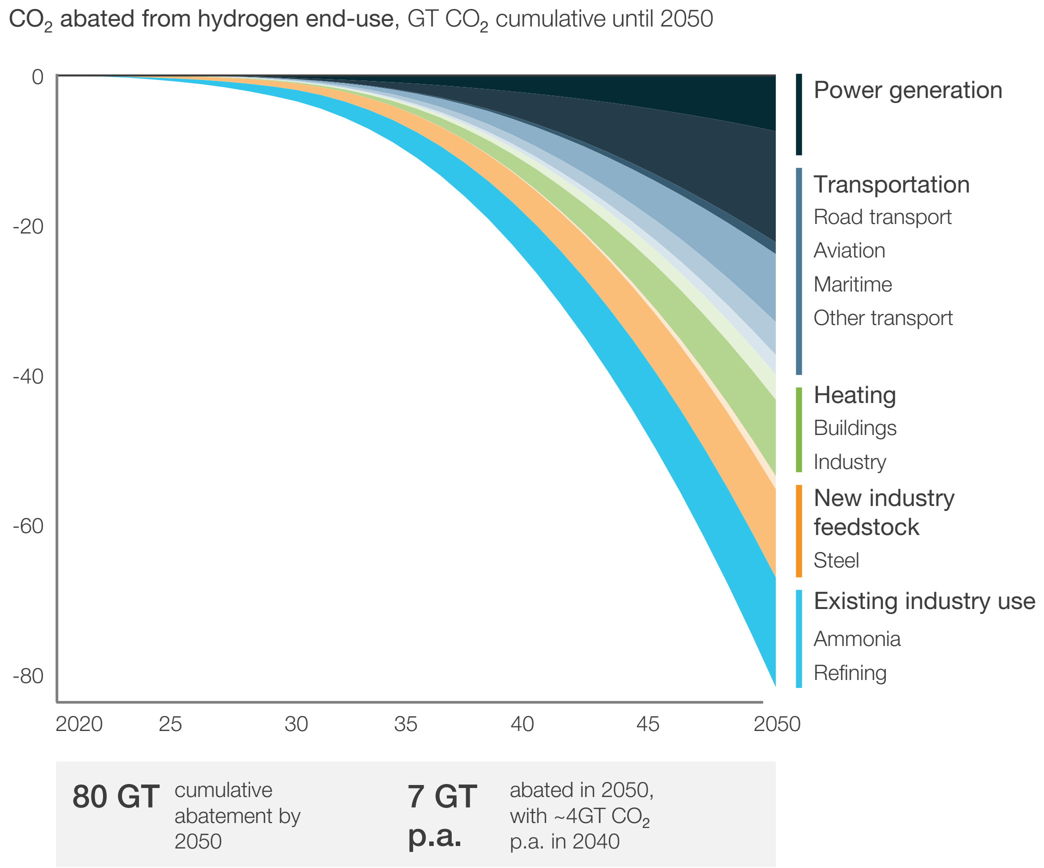


Clean hydrogen has significant abatement potential through 2050

From now through 2050, hydrogen could prevent 80 gigatons (GT) of cumulative CO_2 emissions, as much as eight times what China emitted in 2019 or equivalent to about 11% of the abatement required to limit global warming to 1.5-1.8 degrees Celsius (Exhibit 7). The annual carbon abated from the use of clean hydrogen annually in 2050 could be around 7 GT, or about 20% of annual anthropogenic emissions if the world remains on its current trajectory. Abating 7 GT of CO_2 emissions equals removing all passenger vehicles, trucks, and buses from the road and removing all aviation industry, or abating net emissions from the US, Japan, and Germany in 2019.

Industry and mobility will account for most of this potential with over 6 GT of CO_2 abated in 2050, or cumulative abatement of 70 GT CO_2 through 2050. For aviation and maritime sectors, hydrogen-based fuels are the only viable at-scale decarbonization option, with significant potential for hydrogen to abate 13 GT of CO_2 by 2050. Chemicals and steel will provide another third of total hydrogen abatement potential through 2050, decarbonizing respectively 20% and 35% of emitted CO_2 in 2050 in the current trajectory.[10]

Exhibit 7 – Global emissions abated by hydrogen until 2050



[10] Assumes 35 GT of anthropogenic emissions in 2050 on the current trajectory.

2

Scaling through 2030 is critical for meeting long-term targets

75 MT

p.a. clean hydrogen needed in 2030 to be on track to net-zero – approximating grey hydrogen production today

30%

of grey hydrogen capacity phased out until 2030

The potential for hydrogen as a significant decarbonization lever is clear. However, positioning hydrogen to avoid 80 GT of CO_2 emissions by 2050 will require action today. Foundational investments are needed rapidly to scale up the value chain to realize hydrogen's long-term potential, as are clear regulatory frameworks that enable the transition. Industry must also be willing to invest in the coming decade to achieve the targets.

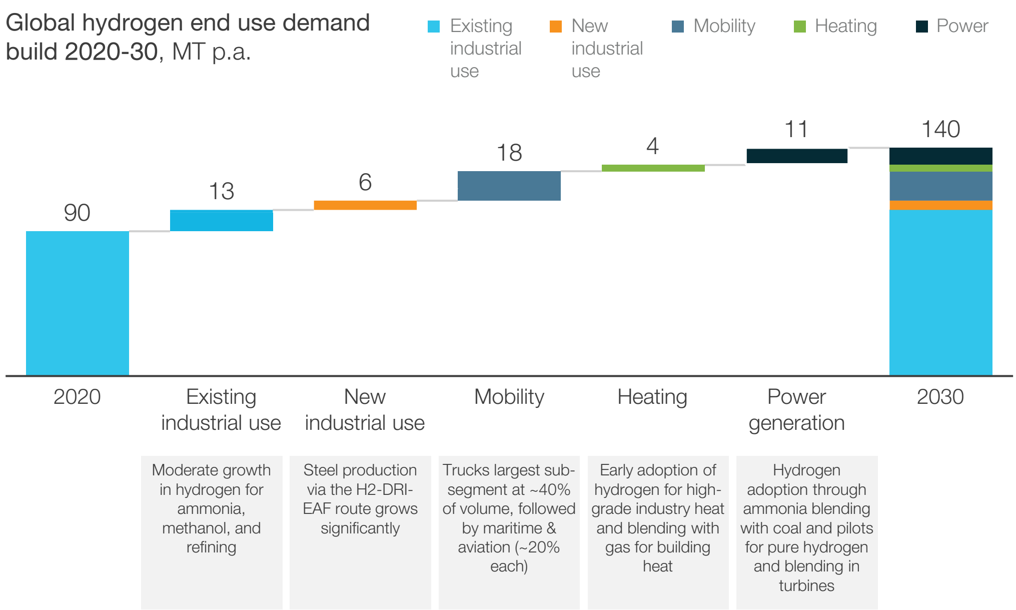
This chapter describes where stakeholders need to scale up hydrogen demand and supply through 2030 to enable its full CO_2 reduction potential and achieve net-zero emissions in 2050. It describes a pathway for growth in clean hydrogen demand across sectors and regions. Furthermore, it considers the required supply mix of low-carbon and renewable hydrogen, including the phase-out of grey hydrogen, as well as hydrogen's abatement potential through 2030.

Needed: 75 MT of clean hydrogen by 2030 for a net-zero 2050

In this net-zero vision, demand for hydrogen would reach 140 MT in 2030 (an increase of 50 MT in the coming decade) of which 75 MT would be clean hydrogen (Exhibit 8). Although this is ambitious, it is both achievable and necessary. Growth in hydrogen demand must accelerate in multiple sub-sectors and regions to reach the required clean hydrogen deployment. By scaling up in multiple sectors and growing demand in new hydrogen end-uses, the cost of hydrogen supply will decline, and supporting infrastructure will proliferate. This development is necessary to enable further uptake of clean hydrogen in applications that are less competitive today.

Clean hydrogen demand growth through 2030 will differ across end-use segments, with the largest contribution from applications within existing feedstocks (13 MT of new demand, and 25 MT of grey capacity converted to green), mobility (18 MT), power (11 MT), and steel (6 MT). Within existing feedstocks and industry uses, ammonia, refining, and methanol account for nearly all the absolute growth in demand. In mobility, trucks are expected to contribute roughly 40% of volumes, followed by maritime fuels (about 5 MT), and aviation (about 4 MT). Steelmaking will be one of the single largest sub-segments for clean hydrogen in 2030, with early growth centered in Europe.

Exhibit 8 – Hydrogen demand growth from 2020 to 2030



Early growth will center in Europe, Japan and Korea; China and North America need to follow closely

Early growth in hydrogen will likely center in Europe, Japan, and Korea. Combined, they will represent about 20% of total hydrogen demand in 2030. China and North America, together representing nearly half of grey hydrogen demand today, will follow closely. Combined, these four regions will account for more than 60% of the global hydrogen market in 2030, and 70% of global clean hydrogen demand.

Europe. Europe is currently the region with the most activity in hydrogen, with 50% of announced projects and about 35% of announced investment volume. There is significant momentum across all sectors. Examples include clean steel, where Europe accounts for the majority of all announced capacity, mobility, existing feedstock, and power and heating. The phase-out of grey hydrogen is expected to be the fastest in Europe, with grey capacity representing only 25% of hydrogen production in 2030 due to the elimination of about 50% of grey capacity. Phase-outs of free allowances under ETS, available incentives for reconversions, and the introduction of a carbon border tax adjustment will drive this change.

Japan and Korea. Hydrogen plays a major role in the energy strategies of both Japan and Korea, with an estimated 35 to 40 MT of hydrogen demand in 2050. The countries place a strong focus on imported clean hydrogen from the Middle East and Australia, both regions with attractive energy resources. Hydrogen in power and mobility are central pillars of the strategy, with early plans to blend ammonia with coal for power generation. Analysts also expect the two countries to have the highest shares of fuel-cell vehicle sales.

China. China has set high ambitions to be a leader in hydrogen. Today it is the largest consumer of hydrogen and a front-runner in hydrogen-fueled trucks and buses, with about 40 MT of demand expected in 2030 (up from about 25 MT today). China started developing the clean hydrogen economy after Europe and Japan and Korea but is accelerating fast. The Chinese government considers clean hydrogen a central pillar of its future energy strategy to decarbonize the economy, create jobs, and become a technology leader in equipment for mobility and hydrogen production.

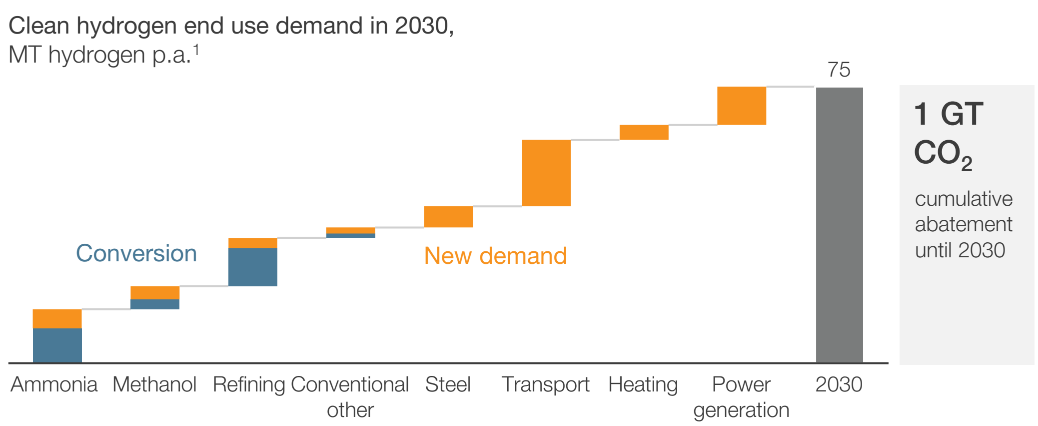
North America. North America is the second-largest consumer of hydrogen today, with strong momentum, particularly in the coastal states. The adoption of clean hydrogen will be lower than in the leading regions, yet significant demand growth is expected, from 17 MT today to about 25 MT in 2030 – growth of 50%. North America is well-positioned to produce both low-cost renewable and low-carbon hydrogen, yet prices of other fuels are low. There are fewer regulatory incentives on the federal level than, for instance, in Europe (although some states have strong incentives, e.g., LCFS[11]), resulting in slower hydrogen adoption.

Rest of world. Demand in countries outside the four main regions is expected to develop slower due to less regulation and momentum around hydrogen. However, many of these markets are expected to be crucial in meeting hydrogen demand in hydrogen hubs such as Europe, Japan and Korea, as evidenced by large hydrogen export projects announced in the Middle East, Latin America, and Oceania.

Low-carbon and renewable hydrogen supply must expand to support the energy transition

Of the 75 MT of clean hydrogen supply required in 2030, about 25 MT should come from converted grey capacity and about 50 MT from newbuilt renewable or low-carbon hydrogen (Exhibit 9). To achieve climate targets, production capacity additions must be clean hydrogen for new demand, with a gradual phase-out of current grey production in existing uses towards 2030.

Exhibit 9 – Clean hydrogen deployment by sector in 2030



1. Grey conversion by 2030 of: 50% (EU), 40% (Japan, Korea), 30% (North America) and 20% (China, Middle East, RoW)

[11] Low Carbon Fuel Standards

Phase-out of grey hydrogen. Existing hydrogen use cases such as ammonia, methanol, and refining will see both a growth in demand of 13 MT of clean hydrogen for new capacity coming online, as well as the conversion of 25 MT of existing grey capacity into clean hydrogen, resulting in a demand for nearly 40 MT of clean hydrogen by 2030. The conversion of existing grey hydrogen capacity in existing plants is a major decarbonization lever and one of the key near-term opportunities to rapidly scale up clean hydrogen supply – in turn lowering costs and making clean hydrogen more competitive. The pace of conversion and phase-out will depend on technical complexity, the cost of switching to clean hydrogen, as well as the regulatory environment and economic incentives. Refining is the easiest to convert from grey to clean since it requires no additional equipment, followed by ammonia synthesis, which needs an air separation unit to ensure nitrogen supply (if renewable hydrogen is used). Methanol is the most complex due to the integrated syngas-based production process.

Cost is a central element of transitioning from grey to clean hydrogen, where the latter carries a premium in the near term in most regions. Regulatory incentives such as carbon prices, tax credits, or blending mandates will contribute to closing the economic gap, and heavily influence the pace of grey hydrogen phase-out in conventional industry feedstock applications. CO_2 prices, if sufficiently high, will act as a primary economic driver. However, expectations suggest that most regions will require additional policies such as blending mandates, for instance, RED II[12] in Europe, to accelerate demand for clean hydrogen. By 2030, regions such as Europe or Japan and Korea are likely to implement a more supportive policy environment for grey hydrogen phase-out, which would result in a larger share of grey phaseout in these markets relative to other markets such as China.

New hydrogen demand. Decarbonization is the main reason for employing hydrogen in new use cases such as mobility and steelmaking, and those should not be met with grey hydrogen. The growth in hydrogen demand – from about 90 MT today to 140 MT in 2030 – will result in large demand for clean hydrogen in these sectors. The growth of new use cases will require nearly 40 MT of clean hydrogen in 2030, equal to about half of total clean hydrogen demand.

Building out 75 MT of clean hydrogen by 2030 will require significant investments in renewable and low-carbon hydrogen production equipment and infrastructure. This analysis expects that renewable hydrogen will account for about 20 to 30 MT in 2030, while low-carbon hydrogen will be about 45 to 55 MT. Both renewable and low-carbon hydrogen must play a role to set the world on track to net-zero in 2050. Clean hydrogen supply is a key ingredient in a hydrogen economy and ensuring ample supply will be critical to reaching goals.

Renewable hydrogen. Supplying about 20 to 30 MT of renewable hydrogen would require 200 to 250 GW of electrolysis capacity, with annual electrolyzer installations reaching about 45 GW in 2030. This is well above the roughly 90 GW cumulative capacity announced today and will require electrolyzer manufacturers to scale up production lines rapidly to be able to meet the demand. The new electrolyzer capacity will require a buildout of renewable energy sources; about 300 to 400 GW of new solar, wind, and hydro capacity dedicated to hydrogen production will be needed by 2030, assuming these sources supply all demand. Considering the projected increase in renewable capacity is 7.3 TW in a net-zero scenario from today until 2030, renewable hydrogen would require about 5% of this capacity. Such a buildout of renewable capacity is ambitious but required to enable broader electrification of society, including sufficient renewable hydrogen supply.

[12] Renewable Energy Directive 2

Low-carbon hydrogen. A volume of 45 to 55 MT low-carbon hydrogen is needed to enable the required uptake of clean hydrogen and the annual abatement potential of 730 MT of CO_2 in 2030. Low-carbon hydrogen enables a more rapid phase-out of grey hydrogen as existing plants can be retrofitted with additional carbon capture equipment, limiting the initial investment needed. The deployment of low-carbon hydrogen requires infrastructure to transmit the captured CO_2 to underground storage sites. Scaling-up low-carbon hydrogen complements renewable hydrogen and allows for renewable power generation capacity buildup – if only renewable hydrogen were deployed, the electrolyzer volume needed would be about 600 GW, supported by about 1 TW renewable generation capacity. Such a scale-up of renewable generation and electrolysis would be extremely challenging and may heavily draw on still-scarce renewable power, thus requiring stronger commitments and an even faster scale-up of supply chains.

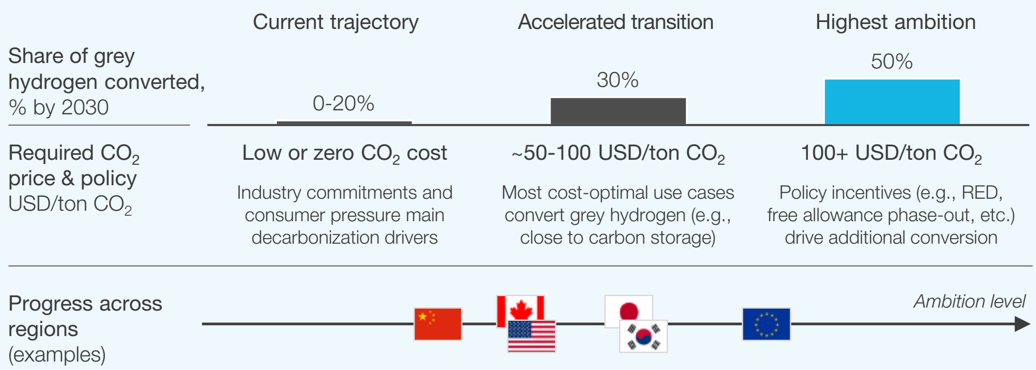
Phase-out of grey hydrogen

The pace of grey hydrogen phase-out depends on the regulatory environment. To rapidly accelerate grey phaseout, a carbon price is required as well as other supporting policies, such as blending mandates for clean fuels or ammonia. Without policies to support grey hydrogen phase-out, industry commitments and consumer pressure will be the main drivers, which will likely not meet the net-zero target.

Current trajectory: Under the current trajectory, some grey hydrogen production capacity will convert to renewable or low-carbon, driven by industry commitments and consumer pressure, resulting in about 10% conversion through 2030.

Accelerated transition: In a world with CO_2 costs of about 50 to 100 USD a ton, about 30% of grey hydrogen would convert to clean, with higher shares in regions where clean hydrogen production costs are lowest and existing plants allow for cost-effective conversion with limited complexity.

Highest ambition: Conversion of 50% of current grey capacity is feasible where sufficiently high carbon prices are combined with selected incentives to decarbonize. Policies such as RED II / RED III in Europe and the LCFS in California are examples of policies that target such uses.



Note: Rapid acceleration of grey phase-out depends to a large extent on carbon price, as most CCS retrofit applications break even at 50-100 USD/ton CO_2. Additional policies required for net-zero, such as RED and swift phase-out of free allowances to convert grey hydrogen in use cases where CO_2 price not sufficient as policy instrument.

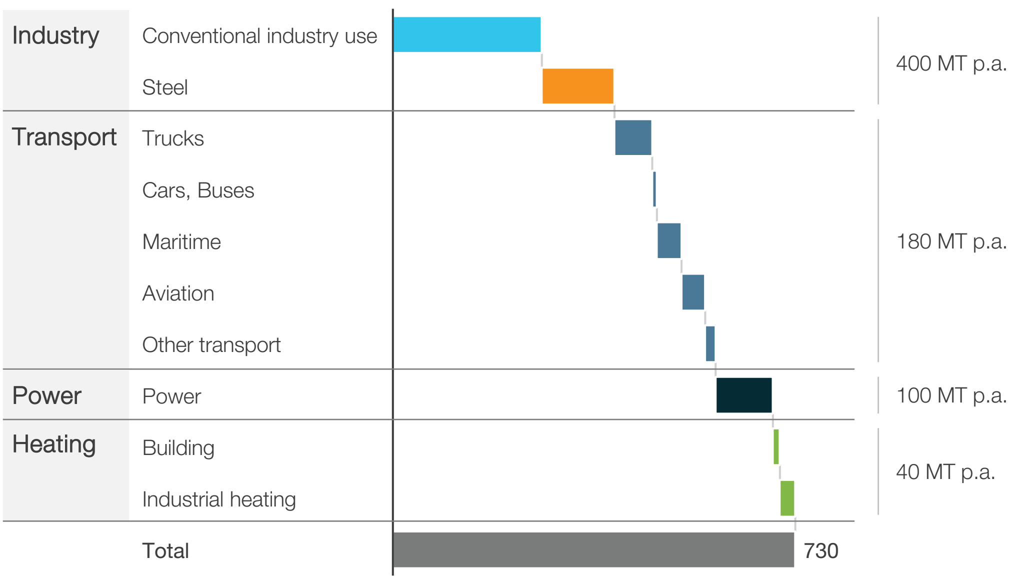
Clean hydrogen has significant abatement potential in 2030

Clean hydrogen can contribute as much as 3.5 GT of CO_2 abatement by 2030. Most of the decarbonization will come from industrial uses in refining and ammonia production, as well as from mobility, primarily from heavy road transport (Exhibit 10). Within existing hydrogen uses, the conversion of grey to clean hydrogen in conventional uses is a critical way to decarbonize feedstock industries, thus avoiding about 1 GT of CO_2 through 2030. It can also help scale up the clean hydrogen supply, making low-cost, clean hydrogen available throughout the hydrogen economy.

The annual abatement potential from clean hydrogen in 2030 is 730 MT of CO_2, or nearly 2% of emissions today. This constitutes more than the emissions in 2019 from the United Kingdom, France, and Belgium combined, or the equivalent of taking about 200 million passenger vehicles off the road. Large parts of this abatement potential in 2030 are from conventional industrial uses (270 MT of CO_2 per annum) and steel (130 MT of CO_2 per annum). Other big contributors to hydrogen's abatement potential in 2030 include mobility (180 MT of CO_2 a year) and power generation (100 MT a year).

Exhibit 10 – Hydrogen abatement in 2030 by segment

CO_2 abatement from clean hydrogen in 2030 by segment, MT CO_2 in 2030



Clean hydrogen must be deployed in new and existing hydrogen applications

Growth in clean hydrogen will come from existing hydrogen industry uses and new hydrogen applications in mobility, power, steelmaking, and heating. The following describes the hydrogen growth required to reach 730 MT of CO_2 abatement in 2030 to be on the track to net-zero in 2050.

Existing conventional feedstock

Ammonia synthesis and refining will likely become the first of the existing uses to convert to clean hydrogen due to a relatively attractive business case and limited complexity in changing hydrogen supply. For ammonia synthesis and hydrogen used in refining, the main cost driver today is the natural gas feedstock, which accounts for about 60% to 70% of the total cost of ammonia. Carbon costs between USD 50 to 100 a ton are sufficient to sequestrate a large share of emissions in most locations. Methanol synthesis will likely take longer to decarbonize due to three main factors. First, the need for a clean source of CO_2 (from either biogenic sources or directly captured from the air), second, the higher complexity of altering the current integrated syngas-based process, and third, the expected large share of capacity in geographies with lower immediate decarbonization pressure (e.g., more than 50% of global methanol demand is supplied from China).

Today, most plants produce the hydrogen on-site or have it delivered by pipeline – a necessity, given the significant volumes required. This is expected to remain common in the industry, however locations of new plants could be influenced by the quality of low-cost renewable or low-carbon energy and carbon storage available. In addition, several plants are expected to be retrofitted to capture the emitted carbon, which will require infrastructure to transmit the CO_2 (e.g., through pipelines) and store it underground. Such infrastructure will develop in areas with easy access to carbon sinks and with concentrations of large emitters that can benefit from it.

Steel production

Hydrogen-based steel production will account for 6 MT hydrogen in 2030, equivalent to about 90 MT of "green steel" produced per annum – or about 5% of global steel production in 2019. Hydrogen is the only scalable zero-carbon alternative for steel decarbonization, and while requiring initial investments to convert to hydrogen-based steelmaking, the use of hydrogen in steel is a highly efficient decarbonization lever. Although steel will only make up about 8% of clean hydrogen demand in 2030 (about 4% of total hydrogen demand), it will account for nearly 20% of emissions avoided. This large abatement potential for hydrogen-based steelmaking stems from the use of coking coal in the conventional blast furnace process, which emits nearly 2 tons of CO_2 per ton of steel. Europe is the center of early growth in hydrogen-based steelmaking, with significant activity ongoing in the industry. The region has announced more than 25 MT of clean steel capacity through 2030. Other regions will follow, with significant potential in China which today supplies about 60% of global steel demand.

12%

of flat steel demand produced from clean hydrogen

Hydrogen-based steelmaking can be very competitive near term given even relatively low carbon prices. Hydrogen's competitiveness in steel is highly dependent on the cost of coal and hydrogen, however, a carbon price of USD 50 to 100 a ton is sufficient to make clean steel competitive in most regions. However, converting a steel plant to hydrogen requires significant investments, as steelmakers cannot retrofit a blast furnace to a H2-DRI-based configuration, which may require initial public incentives for conversion.

Steel plants are large; a plant with an annual capacity of 5 MT steel – equal to about 0.25% of global steel demand – requires the equivalent hydrogen production of about 800 MW of electrolysis. Steel plants not only require hydrogen produced on-site or delivered by pipeline but also access to high-quality iron ore, the main feedstock in steel production, and scrap. Most announced clean steel projects are planning to build hydrogen supplies on-site, the way ammonia plants and refineries operate today.

Ground mobility

Ground mobility will be one of the largest new end-use segments for hydrogen with about 10 MT of production added through 2030. This would make mobility the second-largest end-use segment for clean hydrogen in 2030. About 60% of the hydrogen demand within ground mobility is from heavy-duty trucks with long-distance and high-power requirements. In 2030, the share of the global fuel-cell heavy-duty truck sales could be 11%, which could avoid emissions of about 60 MT of CO_2 a year in 2030. Accelerating the deployment of hydrogen-fueled vehicles through 2030 will be a critical element as far as building the infrastructure needed – and enabling further uptake of decarbonized road mobility.

Hydrogen-fueled powertrains should become competitive for heavy-duty trucks between 2025 and 2035 in most regions – even relative to the diesel ICE with existing diesel taxation schemes – with no additional CO_2 price needed. Battery electric vehicles are less attractive in high power / high demand use cases due to battery weight, range limitations, and recharging time. The key determinant of competitiveness in heavy-duty truck use cases is the cost of fuel. Two factors will drive hydrogen cost competitiveness. First, delivered fuel costs should decline significantly with economies of scale in hydrogen supply and higher utilization of infrastructure. Second, fuel cells allow for higher efficiency than internal combustion engines, thus making better use of the energy in the fuel.

Refueling infrastructure is critical to enable hydrogen mass-market adoption in ground mobility. End-customers will not be willing to purchase hydrogen-fueled vehicles unless they have secure fueling availability. Refueling infrastructure must be built close to main transportation axes and logistics centers. For instance, Europe has proposed a target for a hydrogen refueling station (HRS) every 150 km to encourage hydrogen vehicle uptake. Furthermore, clean hydrogen must be supplied to the HRS either through onsite production (requiring low-cost electricity) or delivered from nearby production centers.

6%

of ocean-going vessels running on clean hydrogen-based fuels in 2030

Maritime

Hydrogen-based fuels for maritime applications will contribute a significant share of hydrogen demand of about 5 MT in 2030. The shipping sector is one of the most challenging ones to decarbonize due to high loads and long ranges, and sustainable fuels are limited to biofuels or hydrogen-based fuels. Hydrogen for shipping decarbonization can be either compressed or liquefied hydrogen, or synthetic hydrogen-based fuels such as ammonia, methanol, or synthetic (liquefied) methane.

In long-distance shipping, hydrogen-based fuels are the only scalable decarbonization alternatives, and each fuel has different characteristics. It is not yet clear whether one technology will dominate, but the adoption of hydrogen-based fuels should reach about 6% to track net-zero targets. Given the long lifecycles of ships and resulting long lead-times to replace fleets, industry stakeholders must today plan for the transition by deploying "hydrogen-ready" ships. Engines must be adapted, and port infrastructure must support the bunkering of new fuels.

The economics are challenging in maritime uses, with carbon prices well above USD 100 a ton required for hydrogen-based fuels to outcompete heavy fuel oil or marine diesel. In the short term, biofuels such as biodiesel and bio-methanol cost less than hydrogen-based fuels, yet resources for low-cost biofuels are finite and are not sufficiently scalable to decarbonize all ship transport. Challenging economics are driven by the higher cost of hydrogen-based fuels, as well as additional capital expenditure required to enable ships to operate on new fuels.

New port infrastructure must be built around the world to enable bunkering of new fuels such as ammonia or methanol. The bunkering infrastructure should ideally be close to attractive renewable or low-carbon energy sources to limit transmission and distribution costs. Compressed or liquid hydrogen applications will require dedicated infrastructure to compress or liquefy and transport the hydrogen to end-users.

Aviation

Hydrogen for fueling aircraft will contribute about 4 MT of clean hydrogen demand in 2030. The aviation sector is challenging to decarbonize given the limited range of alternatives – it requires either biofuels (which are finite) or hydrogen-based fuels, with fewer potential pathways than maritime. Air travel can be decarbonized with either pure liquid or high-pressure gaseous hydrogen, or synthetic kerosene (e-kerosene) from clean hydrogen and CO_2 from biogenic sources or directly captured from the air. Initial decarbonization will likely be biofuel-based. However, hydrogen will be required to reach full decarbonization, and specific blending targets for hydrogen-based fuels are under discussion, such as a 0.7% target for renewable fuels of non-biological origin for aviation in Europe.[13] To be on the path to a decarbonized aviation sector, the initial adoption of hydrogen-based fuels should be about 1% globally in 2030.

To decarbonize medium and long-range flights, e-kerosene is crucial and the only viable pathway. This requires limited amendments to the aircraft as the clean fuel has the same molecular structure as fossil fuel-based kerosene and can be "dropped in" in the fuel mix. Pure hydrogen, likely in the form of liquid or potentially high-pressure gas, is a viable route to decarbonize shorter duration, smaller aircraft that conduct short-range, regional intracontinental flights. Pure hydrogen in liquid form will likely be the predominant pathway due to its higher energy density relative to compressed gas. Two main propulsion alternatives for pure hydrogen aircraft exist, fuel cells or hydrogen turbines, where the former is more efficient, and the latter allows for higher power required to lift the aircraft off the ground. The two technologies can be combined in one aircraft.

100,000

return trips return flights from New York to London running on e-kerosene

The economics are challenging, and e-kerosene requires carbon prices above USD 200 a ton to outcompete conventional kerosene. Higher fuel costs largely drive the poor economics, with the cost of the hydrogen feedstock and clean carbon having the biggest impact. Within direct hydrogen use, setting up the required infrastructure and developing new aircraft designs are important drivers.

[13] Part of the 'Fit for 55' proposal

E-kerosene requires only limited infrastructure investments due to its identical properties compared with conventional kerosene. Supply routes may need to be rerouted due to new concentrations of production capacity. However, the use of compressed or liquid hydrogen will require dedicated infrastructure. The hydrogen must be compressed or liquefied and brought to the refueling site. Liquid hydrogen, expected to be the main form of pure hydrogen used in aircraft, requires liquefaction plants, high-volume storage, and liquid distribution networks (e.g., distribution trucks and refueling for aircraft).

Power

Hydrogen can play multiple roles in the power sector. It can cover the baseload (mainly in regions with limited renewables or carbon storage potential), provide flexible capacity, serve as longer-term storage, and fuel backup or remote generators. Demand for hydrogen in power uses would be about 11 MT in 2030, largely driven by two sub-segments: ammonia blending in coal-fired plants, and hydrogen blending in natural gas turbines. The blending of clean ammonia in coal-fired power plants in Japan and Korea is the first step in a transition to fully ammonia-fired power plants and is a critical lever to decarbonize the power system. Blending hydrogen in existing gas turbines enables energy companies to add up to 20% to 30% hydrogen (by volume) in the fuel mix, thus avoiding about 5% to 10% of CO_2 emissions. This will likely occur primarily in markets with high renewables penetration in the grid and a strong decarbonization agenda (e.g., Europe or the US).

A small share of demand will come from hydrogen fuel cell backup and remote generators (about 0.5 MT in 2030), where hydrogen replaces diesel, for example, in data centers or remotely located telecom towers. Long-term, hydrogen will likely play a major role in applications like long-term storage and grid balancing. Initiating this ramp-up before 2030 is important, both to kickstart decarbonization efforts and to develop the technology further.

The cost of fuel is the key driver in grid power generation, accounting for more than 60% to 80% of the total cost of power generated. For hydrogen to outcompete natural gas turbines in 2030, high carbon prices of above USD 100 a ton are likely required – hence hydrogen grid power generation will be used mid-term where there is strong decarbonization pressure and limited alternatives.

For generators, the main cost drivers differ between backup and remote generation. For backup generators, the capital expenditure of the generator system is the key determinant, including the fuel cell and hydrogen storage, due to low utilization rates of only hours or days in a year. Hydrogen, besides biodiesel, is the only alternative to decarbonize backup generators because batteries would cost more and be less suited for long-term storage. For remote generators, fuel is the key cost driver, including both the production of clean hydrogen and the distance traveled to transport it to the site. Hydrogen remote generators can be the most competitive decarbonized alternative, where on-site renewables have limited potential and on-site renewables with battery storage, are not competitive. The use of hydrogen derivatives such as ammonia or methanol may make it possible to bridge some of the storage and distribution challenges. However, a high carbon tax is required for both generator applications to make them competitive with diesel.

Storage infrastructure like salt caverns is necessary to enable hydrogen-to-power for the grid at scale. Where sufficient renewable energy is available, companies will likely build the hydrogen supply on-site, or potentially deliver it by pipeline. In some regions with limited renewables potential, hydrogen (potentially in the form of ammonia) will be imported and require infrastructure for export and import by sea. Generators will rely on merchant hydrogen delivered as compressed gas or liquid hydrogen. Backup generator uses rarely require fuel and refill the fuel storage system as required. Remote generator end uses are likely to be relatively long distances from supply hubs and pipelines, with costs increasing the further the hydrogen must travel.

Industrial heating

Hydrogen's role as a fuel for industrial heating is clearest in high-grade heat applications that require temperatures above 400 degrees Celsius, such as cement production, aluminum remelting, or other metals processing. Given challenging economics in most use cases, the adoption of hydrogen in high-grade heating processes is expected to be about 1% in 2030, and close to zero for low- and mid-grade heating processes. The adoption of hydrogen in high-grade heat applications would result in about 2 MT of hydrogen demand, equivalent to 70 TWh of energy. To illustrate that is enough to produce about 90 MT of cement if all hydrogen were directed there[14], equal to all cement production in 2020 in the United States.

In industrial heat, hydrogen competes with conventional fossil fuel sources purely on a heat-value basis. To outcompete conventional fuels, low-cost hydrogen is needed at about USD 1 a kg or lower in most cases, or an equivalent penalization of conventional fuels. For instance, in Europe, a carbon price of above USD 120 a ton is needed for hydrogen to outcompete coal in a cement plant.

Industrial plants that require heat vary by size, driving different needs for infrastructure. The largest plants that require significant volumes (similar to refineries, ammonia plants, and steel plants) will have the hydrogen produced on-site or delivered by pipeline. Smaller users that only intermittently require heating could source the hydrogen via distribution trucks. However, this would increase cost and it would likely be preferable to either produce the hydrogen on-site or source it from a nearby industrial cluster through a pipeline.

Building heat

Hydrogen's role in building heat is more uncertain than in other segments such as steel, ammonia, and heavy road transport decarbonization. It is one of the sectors expected to scale up after 2030 due to the extensive infrastructure required and challenging economics. Demand for clean hydrogen in building heat should be about 2 MT in 2030 from blending hydrogen into the natural gas grid. This is sufficient to meet demand from roughly 50 million households given a 20% hydrogen blend.[15] Early volumes are expected in parts of Europe, in particular the UK, as well as parts of North America, where there is ongoing activity around blending hydrogen.

The cost of hydrogen-based heating for buildings largely depends on the cost of clean hydrogen, as well as investments required to develop a hydrogen-ready pipeline network and the necessary equipment in the buildings, such as hydrogen-ready boilers or combined heat and power (CHP) systems. The hydrogen route can be cost-competitive with other low-carbon alternatives such as electric heat pumps in certain instances, particularly in regions with existing natural gas infrastructure, high seasonal temperature variation, and buildings where the cost of installing a heat pump is high (e.g., older flats). Ultimately, competitiveness will depend on local climate conditions, the exact infrastructure upgrades required, and the costs of retrofitting the buildings themselves.

Using hydrogen to heat buildings requires a hydrogen transmission and distribution pipeline network. Development of the network is expected to accelerate after 2030, with hydrogen blending into natural gas pipelines as an early step, with up to 20% hydrogen volume considered feasible in most areas. Heating for buildings is a critical first step toward building out hydrogen-ready pipeline networks.

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[14] 2.85 GJ required per ton cement produced

[15] 18,000 kWh annual heating consumption for a house; 20% hydrogen blend by volume is equivalent to supplying 7% of energy from hydrogen

3

Hydrogen momentum and required investments

USD
540 billion

investment gap until 2030 – out of USD 700 billion required

>520

large-scale hydrogen projects announced to date

Increasingly recognized as a critical requirement for achieving net-zero targets by 2050, hydrogen deployment must be scaled up in the mid-term to reach its full potential. Momentum around hydrogen is high, as demonstrated by multiple announcements of new projects across the value chain. Yet, funding will need to accelerate to increase deployment and meet the projected 660 MT of demand required to abate 80 GT of CO_2 to achieve climate targets by 2050.

This chapter provides an overview of the status of announced projects worldwide and associated investments. It also assesses the investments required to reach deployment of 140 MT of hydrogen – including 75 MT of clean hydrogen – by 2030, and the funding gap the industry and regulators must close to implement the decarbonization pathway outlined in this report.

Hydrogen project momentum is growing

Investment momentum is building, with 520 large-scale projects[16] announced globally, representing a 100% increase since January 2021 (Exhibit 11). One hundred and fifty projects have been added in the past three months alone.

Around 70% of the projects have announced full or partial commissioning before 2030, with the remainder coming online after 2030 or not having announced a commissioning date yet. Industry players have established the availability of support or an enabling regulatory ecosystem as prerequisites for the commissioning of many of these projects.

The number of giga-scale projects[17] has more than doubled from 17 to 43 in the past year with announcements spanning all regions, confirming the momentum surrounding hydrogen is strong. The size of hydrogen giga-scale projects is also growing, with nine renewable hydrogen projects exceeding 10 GW – already equaling the scale of the world's largest renewable energy projects – and 16 low-carbon hydrogen projects exceeding 0.2 MT per annum.

9

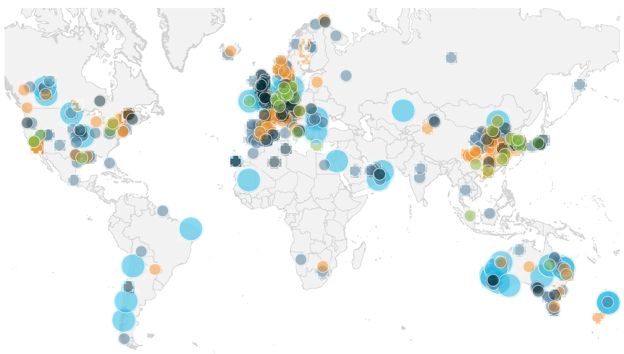
renewable hydrogen projects larger than 10 GW

16

low-carbon hydrogen projects exceeding 0.2 MT hydrogen p.a

[16] Large-scale projects defined as projects larger than 1 MW or equivalent
[17] Giga scale project is defined as >1 GW of electrolysis or >200 kiloton p.a. hydrogen production capacity

Exhibit 11 - Hydrogen project announcements



50-100% increase since last January report

100+% increase since last January report

522	Announced MW-scale projects[1]
261	Europe
121	Asia and China
67	North America
43	Oceania
10	Latin America
20	Middle East and Africa

43	221	133	74	51
Giga-scale production	Large-scale industrial usage	Transport	Integrated hydrogen economy	Infrastructure projects[2]
Renewable hydrogen projects >1 GW, low-carbon hydrogen projects >200 ktpa	Refinery, ammonia, methanol, steel, and industry feedstock	Trains, ships, trucks, cars and other hydrogen mobility applications	Cross-industry, and projects with different types of end-uses	Hydrogen distribution, transportation, conversion, and storage

1. Focus on large-scale projects including commissioning after 2030, >1000 small scale projects and project proposals not included
2. Includes 9 hydrogen production projects in China without announced end-use

Across regions, Europe accounts for the largest share of announced projects, followed by Asia and North America. In Europe, 261 projects have been announced, driven largely by strong momentum in government support, national strategies, and ambitious decarbonization policies. Of these, 16 are giga-scale production projects. In addition, there is evidence that many other projects are in the early stages of development and have not yet been publicly announced, including large-scale renewable and low-carbon projects as well as smaller R&D and demonstration projects.

Asia-Pacific and North America have also seen large growth in the number of projects, with a total of 121 and 67 projects announced in these two regions, respectively. Within Asia, China accounts for roughly half the total announcements, with multiple projects emerging to meet growing local demand and government targets. Among all announced projects in China, most focus on hydrogen use in the ground mobility sector.

Players have also announced giga-scale projects focused on hydrogen exports in Oceania, Africa, the Middle East, and Latin America; a total of 28 export projects have been announced.[18] These are regions with attractive, low-cost energy resources and strategic locations to satisfy the growing demand of Northern hemisphere hydrogen hubs such as Europe, Japan, and Korea.

[18] Of which 17 have announced commissioning prior to or in 2030

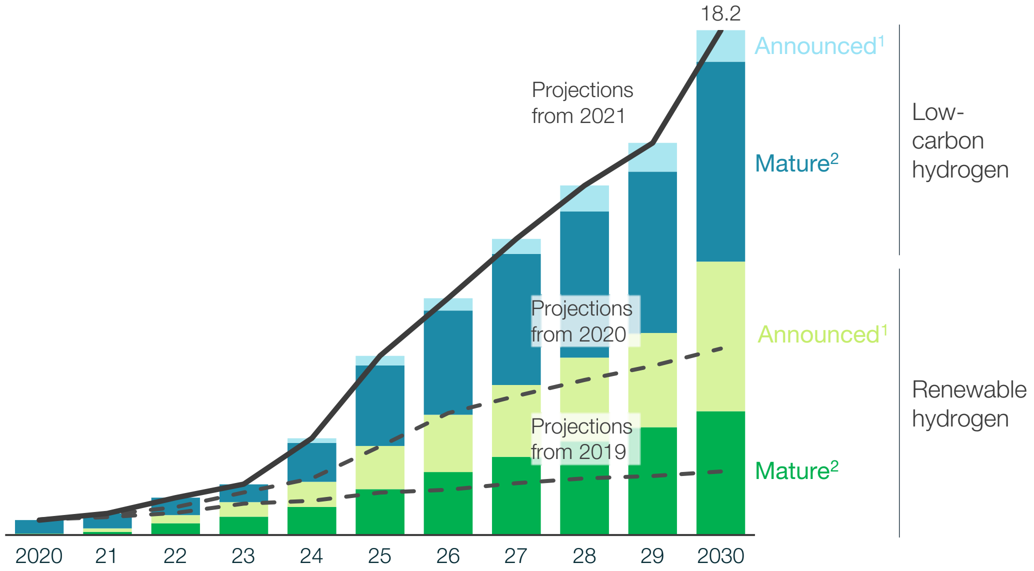
Considering clean hydrogen production, players have announced more than 18 MT of renewable and low-carbon hydrogen production through 2030 – an increase of nearly 12 MT this year, and about eight times the projections from 2019 (Exhibit 12. Additional announcements include nearly 13 MT of clean hydrogen production capacity with deployment beyond 2030. The total clean hydrogen production volume announced now exceeds 30 MT – more than 30% of current global hydrogen demand.

Renewable hydrogen capacity accounts for half the total announced capacity and is linked to 93 GW of announced electrolysis capacity globally. Since 2020, about 40 GW of electrolyzer capacity has been announced and announced volumes have grown fivefold since 2019.

>30 MT

clean hydrogen capacity announced

Exhibit 12 - Announced clean hydrogen production volume by pathway



1. Preliminary studies or at press announcement stage
2. Feasibility study, front-end engineering and design stage, final investment decision has been taken, under construction, commissioned or operational

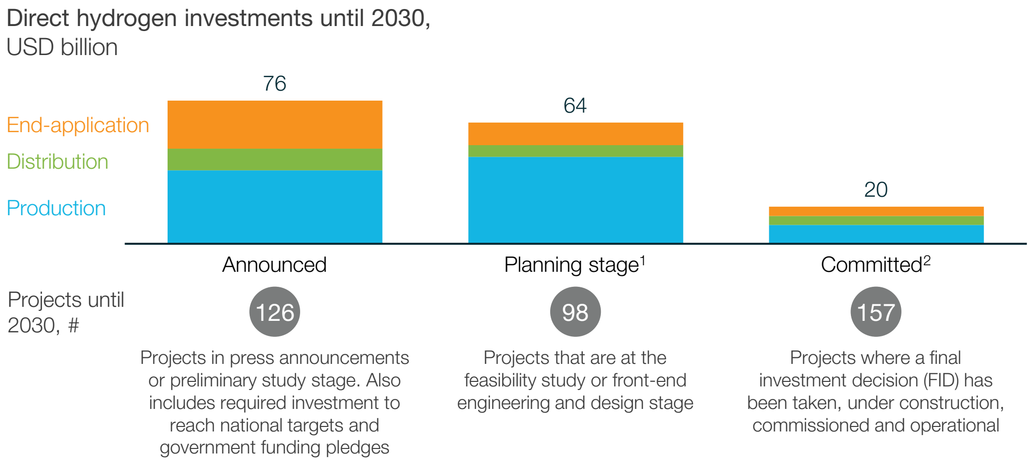
Most of the announced clean hydrogen volume is in Europe and Oceania, together accounting for more than half of the capacity through 2030, most of it from renewable hydrogen. North America follows closely with about 3.5 MT of the capacity announced through 2030, 85% of which is low-carbon hydrogen.

Announced capital investments are increasing

The strong growth in the number of hydrogen projects through 2030 implies total direct investments of USD 160 billion (Exhibit 13). Most investments are in renewable and low-carbon hydrogen production, accounting for about USD 95 billion, followed by end-use applications (about USD 45 billion) and transmission, distribution, and storage (about USD 20 billion). In end uses, mobility applications and steel account for over 75% of the announced investments, indicating particularly strong market momentum in these sectors. The momentum results from the increasing regulatory focus on decarbonization, such as the phase-out of free allowances for the steel sector in the European Trading Scheme (ETS), as well as the attractive economics of these hydrogen applications.

The lowest volume of announced funding involves power and heating applications. Heating requires the development of hydrogen pipeline infrastructure, which will only be developed when required to support growing demand for hydrogen across sectors, while hydrogen-for-power is at an early stage of deployment, with the first projects focused on blending with fossil fuels (e.g., mixing hydrogen in natural gas turbines or ammonia blended as fuel in coal power plants).

Exhibit 13 - Hydrogen project investments by stage



1. Feasibility study or at engineering study stage
2. Final investment decision has been made, already under construction or operational

Not only are projects being announced – they are also maturing. The past year has seen a significant increase in investments associated with projects in the planning stage – meaning they are performing feasibility and engineering studies – as well as projects with committed funding. Of the projects with commissioning dates before 2030, nearly 100 are now in the planning stage, accounting for USD 64 billion in investments – up from USD 18 billion in 2020. Investments in projects with committed funding have more than doubled, from USD 9 billion to USD 20 billion. Estimated investments in projects only announced (i.e., before the detailed planning stage) have surpassed USD 75 billion, with many still waiting for funding support before committing development capital. Clean hydrogen supply is the most mature, with approximately 80% and 45% of low-carbon and renewable hydrogen production capacity, respectively, already in the planning stage or more advanced.

Step-up in investments needed to remain on a net-zero pathway

While the level of project momentum in the hydrogen industry is strong, reaching established net-zero targets will require a significant push. Achieving the proposed net-zero pathway by 2050 and decarbonizing 22% of final energy demand will require 75 MT of clean hydrogen supply and demand in 2030. To achieve this and associated midstream and end-use investments, the industry needs total direct investments of USD 700 billion across the hydrogen value chain by 2030 (Exhibit 14).

The global hydrogen shipping, pipeline, local distribution, conversion, and refueling infrastructure will require investments of USD 200 billion through 2030, with more than half in infrastructure for hydrogen mobility (e.g., refueling stations).

End-uses require investments of USD 200 billion to meet projected demand for new equipment and plants. Mobility and new hydrogen industry use (i.e., steel) are the sectors that will require the largest volumes of investments, totaling USD 150 billion.

Estimated investments including indirect funding and government commitments

This chapter describes the direct hydrogen announcements observed in the industry. This measure underestimates the true commitments to hydrogen in terms of investments. To get a full picture, two additional metrics must be considered: first, national government commitments or targets may exceed the volume of announced investments and create a realistic expectation that further investments will come in certain geographies. Second, direct investments imply certain investments in the supply chain to ensure capacity can be procured and constructed. For example, investments in renewable hydrogen imply equivalent capacity investments in electrolyzer assembly lines, sub-component manufacturing capacity, and raw material sourcing.

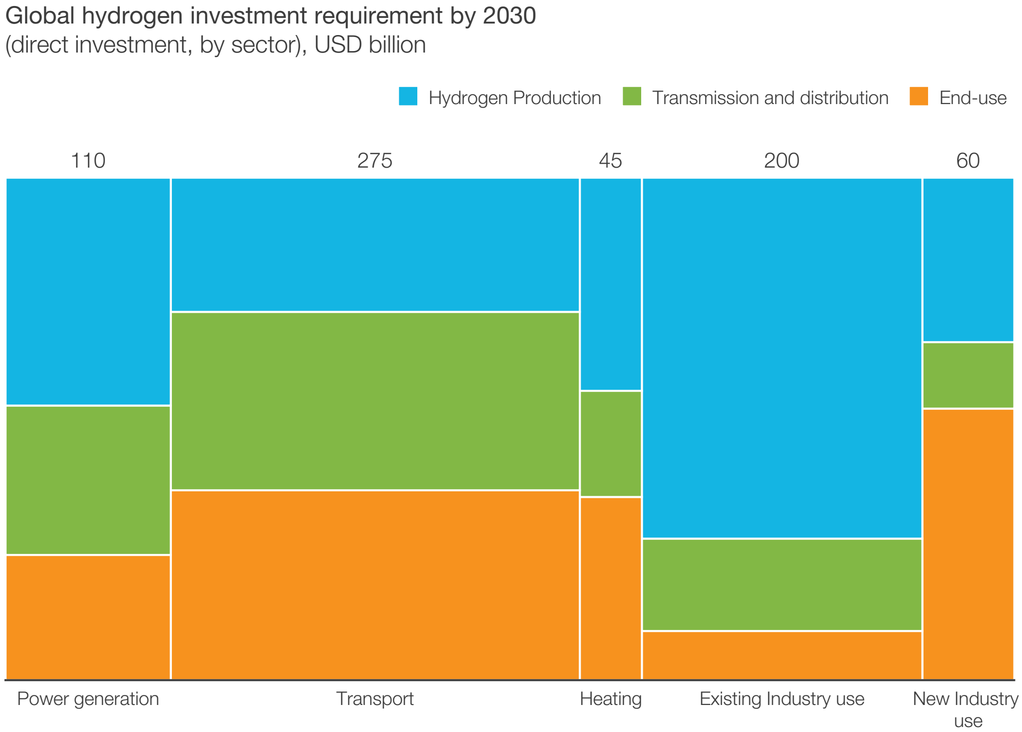
When including these government commitments and indirect investment to support the announced hydrogen projects, the total estimate of announced investments across the entire value chain exceeds USD 600 billion through 2030. This includes:

- USD 160 billion in direct investment in projects.
- USD 150 billion in additional government investments required to reach national government targets and commitments.
- USD 300 billion in investments implied from OEMs and suppliers to support the required direct investments in hydrogen projects as well as government targets along the supply chain.

Compared with 2020, the total estimated investments – announced projects, government commitments, and indirect investments – doubled from about USD 300 billion. Considering only the developments in the three months since the “Hydrogen Insights July 2021” publication, total estimated investments grew by USD 100 billion, or 20%.

Considering total investments required along the value chain for different applications, including hydrogen supply, transmission and distribution, and end-use equipment, the largest volume (USD 275 billion) is required in hydrogen mobility, of which about USD 200 billion is in ground mobility. The existing hydrogen industry is second, with total investments of about USD 200 billion required, of which more than 70% of required funding is for clean hydrogen production, either for retrofitting current supply by adding carbon capture equipment or replacing it with newbuilt clean hydrogen supply. Power generation and heating for industry, buildings, and new industry will require about USD 225 billion in total.

Exhibit 14 - Required investments along the hydrogen value chain



USD bn 300	Hydrogen production	USD bn 200	Hydrogen transmission & distribution	USD bn 200	Hydrogen end-use application

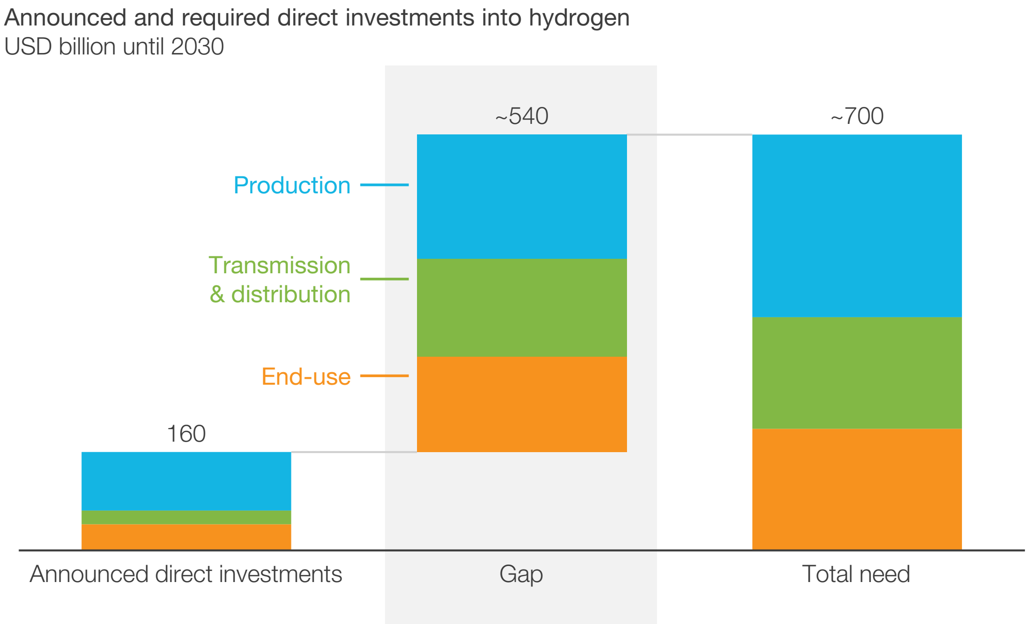
Despite the strong observed momentum and project announcements, a significant investment gap remains across the hydrogen value chain. Achieving a pathway to net-zero will require additional investments of USD 540 billion by 2030 – closing the gap between the USD 160 billion of announced projects and USD 700 billion in required investments (Exhibit 15).

Most of the progress so far has taken place in clean hydrogen production, which has the highest amount of announced investments. However, production is also the segment with the biggest investment requirements. The current investment gap is roughly USD 210 billion through 2030, implying the announcement of only 30% of needed investments to develop new renewable or low-carbon hydrogen capacity.

Meeting projected demand in the various end-use applications will require additional investments of USD 160 billion, with the largest absolute gap in mobility. New industry applications such as steel will also require significant investments of USD 35 billion for outlays like new H2-DRI plants. However, steel is also one of the most advanced segments considering announced investments, with about 45% of required investments announced, and has particularly strong momentum in Europe.

Within transmission, distribution, and storage, an investment gap of over USD 170 billion remains – constituting the largest relative gap. Investments in this part of the value chain are critical to enabling access to cost-competitive hydrogen supplies. Examples include connecting the regions with the lowest production costs to demand hubs, developing refueling infrastructure for vehicles, or building pipelines to supply industrial plants. If stakeholders fail to make sufficient investments in infrastructure, growth and the subsequent scale-up of clean hydrogen supply could be halted. However, infrastructure developers will likely require predictability and demand signals that ensure the utilization of their assets before they will invest in midstream infrastructure. Available infrastructure is a critical component of the mass-market adoption of clean hydrogen. Without it, clean hydrogen would be limited to on-site supply uses, and the required deployment and decarbonization would not be achieved.

Exhibit 15 - Investment gap in hydrogen value chains



China and Europe are the regions with the highest deployment ambitions. Even so, given their enormous demand potential, they are also the regions with the largest absolute investment gap, accounting for nearly half of the total gap. Meeting the required clean hydrogen demand of nearly 20 MT in China by 2030 will require an additional USD 160 billion. The country has only announced about 10% of its total funding requirements and needs to ramp up significantly to meet net-zero targets. In addition, Europe needs additional investments on the order of USD 90 billion by 2030 – nearly double the total amount of funding announced thus far in the region.

About 30% of required investments in North America have been announced; another USD 60 billion would be required to be on a net-zero pathway in 2030, while Japan and Korea will require more than USD 50 billion to close the investment gap. The rest of the world would need roughly USD 150 billion to develop the required supply and demand by 2030.

Investments by 2050 to rival oil & gas industry today; USD 3 trillion value created

The investment gap through 2030 is significant. Even so, ambitions for 2050 are steep, with 690 MT of clean hydrogen supply required to meet demand for 660 MT in hydrogen end-use applications. Estimates of the total required investment are around USD 7 to 8 trillion across the hydrogen value chain through 2050, generating about USD 3 trillion revenues in 2050 across the hydrogen economy. While the investments required are significant, they are comparable to investments of USD 5.7 trillion made in upstream oil and gas in the past decade (from 2010 to 2019).

Of the total, more than USD 2 trillion will support hydrogen production (excluding energy production) – the key to ensuring renewable and low-carbon hydrogen supplies across different demand sectors. Of the total investment in hydrogen production, about 75% will flow to renewable hydrogen and the remainder to low-carbon hydrogen. Additional cumulative investments of USD 5 to 7 trillion will be required to develop the necessary renewable energy capacity.

Conventional industrial uses and mobility will likely represent the largest demand segments for clean hydrogen, accounting for more than half of total hydrogen demand in 2050. Within all hydrogen end-uses, a projected USD 2.5 trillion will be needed to support hydrogen demand applications, consuming 660 MT of hydrogen globally.

USD
3 trillion
annual revenues from hydrogen in 2050

Energy and infrastructure players must develop at-scale transmission and distribution systems to ensure the interconnectedness of production regions with demand hubs and allow trade flows across all continents. Within regions, hydrogen infrastructure such as pipelines will play a critical role in cost-efficiently supplying hydrogen. Globally, this expansion is expected to require investments of about USD 3 trillion by 2050.

4

Call to action

Hydrogen is a central piece of the decarbonization puzzle. It is the only scalable and cost-efficient energy vector to decarbonize sectors that require clean molecules as fuel or feedstock. The time to scale hydrogen is now – it is a necessity to meet the net-zero targets.

Momentum is strong; industrial players across the value chain are willing and eager to invest and scale hydrogen, while governments across continents increasingly recognize hydrogen's critical contribution to decarbonization. Nevertheless, translating the momentum and intentions into real developments is becoming increasingly urgent. If we are to decarbonize economies and limit global warming to 1.5-1.8 degrees Celsius by 2050, actions must take place in the coming decade – the 2050 ambition and potential of 80 GT CO_2 abated cannot be realized unless the foundation is laid today.

There are three important levers to unlock hydrogen: Demand for clean hydrogen must be stimulated in different sectors, infrastructure must be developed to enable end-user access to hydrogen, and cost competitiveness must be strengthened through acceleration in scale-up of clean hydrogen deployment (Exhibit 16).

Exhibit 16 – Hydrogen unlocks and stakeholder roles

Hydrogen must be unlocked and scaled

Create demand
Incentivize decarbonization through clean hydrogen

Ensure access
Make hydrogen accessible through the right infrastructure

Lower cost
Create economies of scale to reduce cost and open new markets

Government and private sector have important roles to play

Governments
Incentivize the transition through incentives and enforcing mechanisms

Support hydrogen to overcome the initial economic hurdles to scale and become truly competitive

Private sector
Be willing to invest to create the change - and take some risk

Set common standards and ambition levels across industries and regions

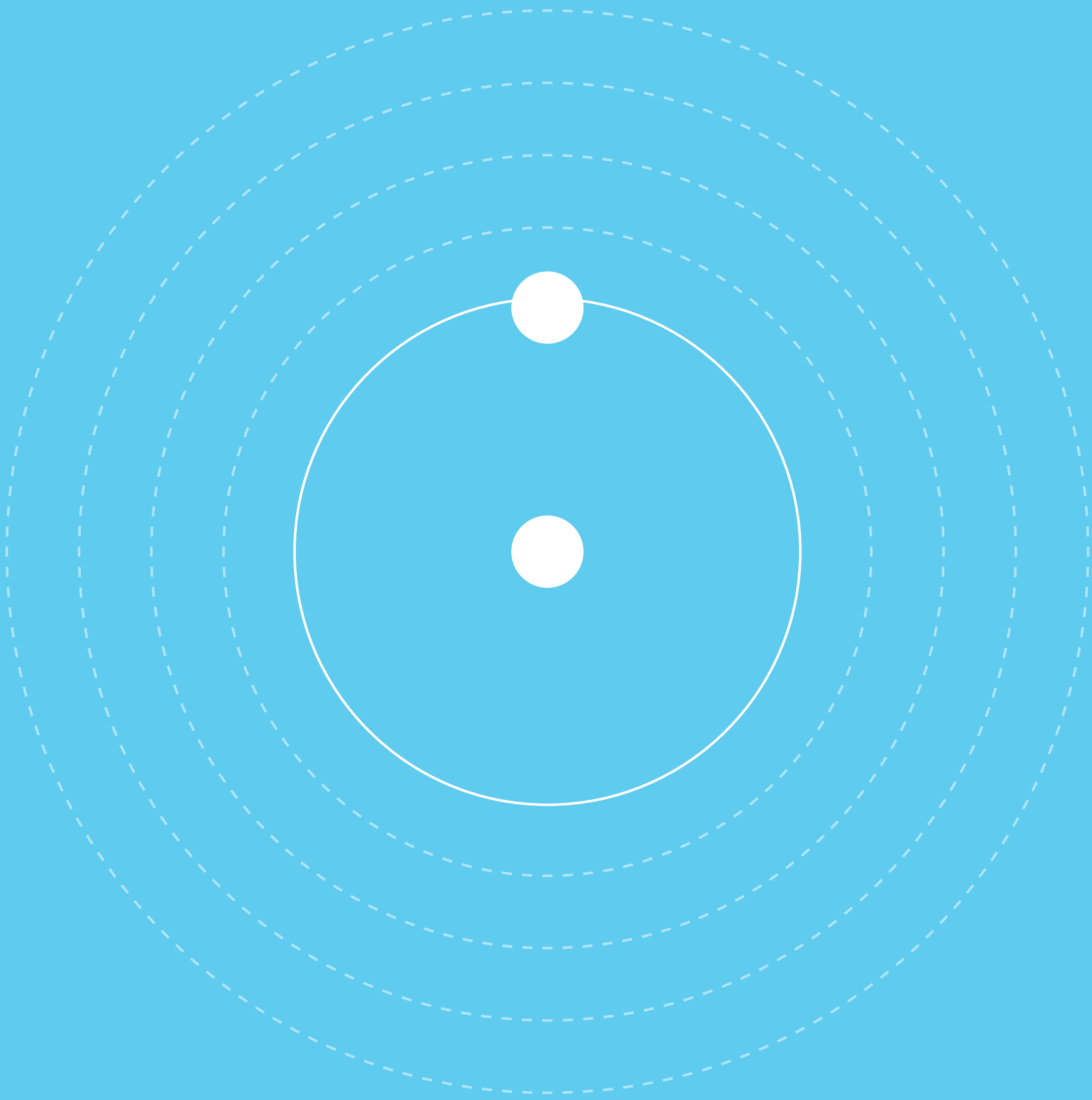
Creating demand. End-use demand will 'pull' investments throughout the system. A level playing field must be created to allow for a coordinated transition of different end-use sectors. Companies can play a role by pursuing industry-wide transition commitments, while governments must play a role through creating the right incentives, for instance, by introducing direct support mechanisms and mandating quotas or targets.

Developing infrastructure. Upfront investments are required to develop large-scale infrastructure that enables the distribution of hydrogen molecules, such as pipelines and intercontinental carrier capacity, as well as local distribution such as refueling infrastructure. Such infrastructure, while required, may initially suffer from underutilization. It enables hydrogen use and helps lower hydrogen costs by enabling access to energy from untapped "stranded" renewable assets. The infrastructure industry also needs global coordination to enable these mission-critical investments for the energy transition.

Scaling up production. Hydrogen demand will reach mass-market adoption only when low-cost clean hydrogen supply is available. It requires an unprecedented scale-up in electrolysis capacity and accompanying renewable energy capacity, as well as the buildout of carbon dioxide transmission and storage infrastructure. The sooner these investments in giga-scale production are made, the earlier hydrogen will reach cost competitiveness and reduce the economic gap.

Governments and the private sector both have critical roles to play in unlocking hydrogen. Governments and regulators must create the right, predictable frameworks to encourage the transition and support in overcoming initial economic hurdles. The private sector must also commit to investing in the clean hydrogen economy. Investments are needed and some level of risk must be accepted; the energy transition mega-trend is not a fad. Companies should be willing and boldly commit to transitioning the energy system.

We are at a pivotal moment, and the chance to act is now – before it is too late. If done correctly, hydrogen will become one of the critical clean fuels and feedstocks for our future world. The Hydrogen Council members commit to accelerating its scale-up today and ask all to join in this plight.



Appendix - Methodology, Glossary, Bibliography

39

hydrogen applications considered

5

regions modelled

Methodology for estimating hydrogen demand, investments, and abatement potential on a net-zero pathway

The underlying energy transition scenario for the “Hydrogen for Net Zero” perspective follows a trajectory that limits global warming to 1.5-1.8 C, in line with the Paris Accord and the recent IPCC 6th Assessment report. The scenario considers emission constraints and assesses the role hydrogen could play as a decarbonization vector and its complementary role with other decarbonization technologies like biofuels, direct electrification, batteries, and carbon capture and storage (CCS). Other important premises include an implicit assumption that the macro environment remains stable, i.e., steady GDP growth globally, no major geopolitical shifts, and that commodity prices remain stable over time (i.e., no long-term price spike or significant price fall long-term). Further, it is assumed that hydrogen technology reaches technological maturity and cost levels as laid out in the “Path to hydrogen competitiveness” and “Hydrogen Insights” (from January 2021). The currency used, unless stated otherwise, is the United States dollar (USD).

The report considers hydrogen across 39 sub-sectors in industry, mobility, heating, and power. In addition to estimating the hydrogen demand per sub-segment through 2050, this perspective also considers the carbon abated using clean hydrogen, the changes in hydrogen supply mix towards 2050, and the investments required in the hydrogen value chain to realize the demand projections.

The “Hydrogen for Net Zero” report has been co-created by the Hydrogen Council and McKinsey & company. Findings have been syndicated and aligned with the 129 Hydrogen Council members who have provided invaluable industry insight and expertise.

Demand projections

The potential role hydrogen could play is based on detailed cost competitiveness calculations per sub-segment combined with market intelligence. The analysis estimates hydrogen uptake for each of the 39 sub-segments by considering cost-competitiveness relative to other decarbonized alternatives per region like batteries, and carbon capture and storage, as well as conventional alternatives such as diesel and natural gas. Additionally, the perspective considers the feasibility of new or retrofit facilities like ammonia plants, and truck fleets, steel plants, and potential supply chain constraints.

Hydrogen supply mix

This perspective considers the hydrogen supply mix and addresses both the mix of new-built clean hydrogen production capacity, which is the share of renewable and low-carbon hydrogen, as well as the phase-out of grey hydrogen. The report differentiates the perspective across regions and over time and accounts for global import and export dynamics. It estimates supply chain losses through hydrogen transmission, distribution, and conversion.

The share of newly built renewable and low-carbon hydrogen is based on production cost optimization across regions and over time. The analysis reflects announced renewable and low-carbon hydrogen capacity in the near-term buildout of capacity. Import and export considers trade between markets with attractive conditions for hydrogen production such as Oceania, Latin America, the Middle East, and Northern Africa to demand hubs with limited low-cost clean energy resources – places such as Japan and Korea, Continental Europe, and parts of China. The analysis assumes all new-built hydrogen capacity through 2050 to be clean hydrogen.

The conversion of existing grey-to-clean hydrogen capacity varies across regions and is only relevant for existing hydrogen applications like industry feedstock (i.e., ammonia, refining, methanol, and other current industrial uses). The conversion rate considers regional differences (the cost of renewable or low-carbon hydrogen supply and the age and state of current grey hydrogen production plants), the regulatory environment (current and expected policies such as carbon tax schemes or government decarbonization targets), and industry momentum (announced conversion and retrofit projects).

CO_2 abatement potential

The assessment of carbon abatement potential considers the amount of CO_2 emissions avoided through the use of clean hydrogen. Other types of emissions such as particles, nitrogen dioxide, or methane are not considered. For each sub-segment, the current energy mix by region serves as a baseline (e.g., coal-based hydrogen production in China). For instance, H2-DRI steel production replaces coking coal used in the blast furnace process, whereas hydrogen-powered heavy-duty trucks replace the diesel equivalent. The analysis accounts for residual CO_2 emissions from low-carbon hydrogen production and shows the net abatement from the use of clean hydrogen.

Announced hydrogen investment and market momentum

The mapping of announced investment covers three main categories: Direct private sector investments (i.e., publicly announced projects), additional investments required to reach stated government targets, and indirect investments required to support the announced project investments. The focus of this report is primarily on direct private sector investments.

Direct private sector investment

The estimate of announced investments builds on a continuously updated database of global publicly announced projects, with results validated by Members of the Hydrogen Council every quarter. The report calculates implied project investments using public project information such as clean hydrogen volume, plant capacity, and number of vehicles. It combines this information with investment and cost data from Hydrogen Council Members, collected and aggregated by an independent third-party clean team, to derive a view on announced investments.

Furthermore, it classifies projects in terms of three maturity levels. Operational projects, those under construction or ones with the final investment decision receive a “committed” classification, while projects with ongoing feasibility or engineering studies receive a “planning stage” classification, and the remainder are tagged as “announced only.”

Government production targets and public funding

The report maps announced government targets and compares them with the project pipeline (including announced, planning stage, and committed projects) to quantify the additional capacity required to reach the targets. It estimates the additional investments required based on investment and cost data from Hydrogen Council members.

Indirect value chain investments

To quantify the total implied investments required to realize announced direct private sector investments, the analysis calculates the indirect upstream investments (e.g., factories, mines, and component supply) using industry revenue multipliers. It treats fuel cell and on-road vehicle platforms separately, with a bottom-up estimate of R&D and manufacturing costs.

Hydrogen revenue pool

To quantify the total revenues generated in the hydrogen economy, direct revenues are considered. This includes the revenue generated from selling hydrogen molecules, equipment (e.g., fuel cells, industrial plants), revenues from distributing the hydrogen (e.g., global shipping of hydrogen, refueling stations, bunkering, and pipelines), as well as revenues from operating and maintaining hydrogen facilities.

Hydrogen value chain direct investment requirement

This report presents a novel view of the direct investments required to realize the projected hydrogen economy. It builds on the demand projections, supply mix perspectives, and required capital expenditures. It employs detailed hydrogen application total cost of ownership (TCO) models and hydrogen cost and investment data collected from Hydrogen Council Members through a clean team (please refer to "Path to hydrogen competitiveness" and "Hydrogen Insights" (from January 2021). The analysis considers three main value chain steps: hydrogen supply; transmission and distribution, including storage and conversion; and end-applications.

Hydrogen supply

Estimates include the investments required to build out new renewable and low-carbon hydrogen production capacity in terms of electrolyzers and natural gas reformers with required carbon capture equipment. Further, it considers the investments required for the conversion of existing grey hydrogen production capacity to either low-carbon or renewable hydrogen sources. It does not include the upstream energy investments required to build out renewable power generation unless explicitly stated. The analysis considers a regional view of the supply mix, accounting for imports and exports, resulting in a positive or negative delta between demand and local supply in a region.

Hydrogen transmission, distribution, conversion, and storage

The report derives investment requirements from segment-specific estimates accounting for five primary hydrogen transmission and distribution routes (including on-site production, short- and long-distance transport). It also considers 15 routes in terms of shipping, trucks, or pipelines, as well as 10 conversion technologies such as liquefaction, compression, and other pathways. Furthermore, it accounts for investments in port buildouts and storage facilities in the investment estimates.

Hydrogen end-applications

Downstream investments include equipment and plants required to support hydrogen demand across applications. In mobility, for instance, fuel cells, hydrogen tanks, and refueling infrastructure are included. Other equipment includes turbines, generators, plant investment for conventional industrial feedstock uses such as ammonia and methanol, and new hydrogen applications like steel and BTX.

Definition low carbon and renewable hydrogen

There are currently no common standards for defining renewable and low carbon hydrogen. This is a consequence of the lack of international standard methodology for calculating the carbon footprint of hydrogen production pathways and thresholds for qualifying hydrogen as low carbon that would be applied, for example, across taxonomies for sustainable finance and hydrogen certification systems. This issue is explored further in section D on enabling policies in the Hydrogen Council's report Policy Toolbox for Low Carbon and Renewable Hydrogen.

In the present study we use the terms "clean", "renewable", "low-carbon", and "grey" hydrogen, whereby

- **Renewable hydrogen** refers to hydrogen produced from energy sources of renewable origin. For example, i) hydrogen produced through water electrolysis with electricity of renewable origin used as feedstock; and/ or ii) hydrogen produced through the gasification of sustainable biomass which is then reformed or pyrolyzed (if the CO2 is sequestrated the hydrogen produced can be qualified as carbon-negative). Defined thresholds for qualifying hydrogen as renewable (in tCO2eq/ tH2 or gCO2/MJ) need to be put in place.
- **Low-carbon hydrogen** refers to hydrogen produced from energy sources of non-renewable origin with a carbon footprint below a defined threshold. For example, i) hydrogen produced using natural gas as a feedstock with SMR or ATR coupled with CCS; ii) hydrogen produced through pyrolysis of natural gas into hydrogen and solid carbon; iii) hydrogen produced through gasification of coal with CCS; iv) hydrogen produced through electrolysis using electricity of non-renewable origin as feedstock. Defined thresholds for qualifying hydrogen as low carbon (in tCO2eq/tH2 or gCO2/MJ) need to be put in place.
- **Clean hydrogen** refers to renewable and low-carbon hydrogen.
- **Grey hydrogen** refers to hydrogen produced using fossil fuels as feedstock, mainly through reforming of natural gas or the gasification of coal.

GLOSSARY

DRI	Direct reduced iron (for steelmaking)
ATR	Autothermal reformer
BTX	Benzene, Toluene, Xylene (commonly defined as aromatics)
CC(U)S	Carbon capture and storage or carbon capture, use, and storage
CHP	Combined heat and power
EJ	Exajoule, 1 billion GJ
ETS	Emission Trading Scheme
FEED	Front-End Engineering Design
FID	Final Investment Decision
GJ	Gigajoule
GT	Gigaton (metric)
H2-DRI	Hydrogen Direct Reduced Iron
LHV	Lower heating value (33.33 kWh/kg hydrogen)
MT	Million metric ton
SBTi targets	Science Based Targets
SCR	Selective Catalytic Reducer
SMR	Steam methane reformer
Sponge iron	Direct reduced iron (for steelmaking)
TW/GW/MW/kW	Terawatt, gigawatt, megawatt, kilowatt (unit of power, 1 Watt=1 J (Joule) per second)
TWh/MWh/kWh	Terawatt hour, megawatt hour, kilowatt hour (unit of energy, 1 Watt-hour = 3600 J (Joule))

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