Hydrogen
scaling up

A sustainable pathway for the global energy transition

Hydrogen Council November 2017

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The Hydrogen Council is composed of 18 steering members that authored the report and 10 supporting members: Mitsui & Co, Plug Power, Faber Industries, Faurecia, First Element Fuel (True Zero), Gore, Toyota Tsusho, Hydrogenics, Ballard, Mitsubishi.

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Content

Executive summary

The Hydrogen Council is the largest industry-led effort to develop the hydrogen economy. Launched in January 2017 at the World Economic Forum, its members include leading companies that invest along the hydrogen value chain, including transportation, industry, and energy exploration, production, and distribution.

As members of the Council, we are convinced that hydrogen can offer economically viable, financially attractive, and socially beneficial solutions. Furthermore, in certain sectors and geographies it will be unavoidable to enable the energy transition and improve air quality in cities.

In this report, we present the first comprehensive vision of the long-term potential of hydrogen and a roadmap for deployment. This ambitious yet realistic approach would deliver deep decarbonization of transport, industry, and buildings, and enable a renewable energy production and distribution system. To realize this vision, investors, industry, and government will need to ramp up and coordinate their efforts.

Our vision: The hydrogen economy in 2050

Hydrogen is a central pillar of the energy transformation required to limit global warming to two degrees Celsius. To achieve the two-degree scenario, the world will need to make dramatic changes year after year and decrease energy-related CO_2 emissions by 60% until 2050[1] – even as the population grows by more than 2 billion people[2] and billions of citizens in emerging markets join the global middle class. Hydrogen can play seven major roles in this transformation:

- Enabling large-scale renewable energy integration and power generation
- Distributing energy across sectors and regions
- Acting as a buffer to increase energy system resilience
- Decarbonizing transportation
- Decarbonizing industrial energy use
- Helping to decarbonize building heat and power
- Providing clean feedstock for industry.

In all seven application areas, hydrogen can offer economically viable and socially beneficial solutions. In our vision, hydrogen enables the deployment of renewables by converting and storing more than 500 TWh of otherwise curtailed electricity. It allows international energy distribution, linking renewable-abundant regions with those requiring energy imports. It is also used as a buffer and strategic reserve for power.

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1 From 34 Gt in 2015 to 26 Gt in 2030 and 13 Gt in 2050 (IEA, 2017)

2 From 7.6 to 9.8 billion people in 2050 (United Nations, 2017)

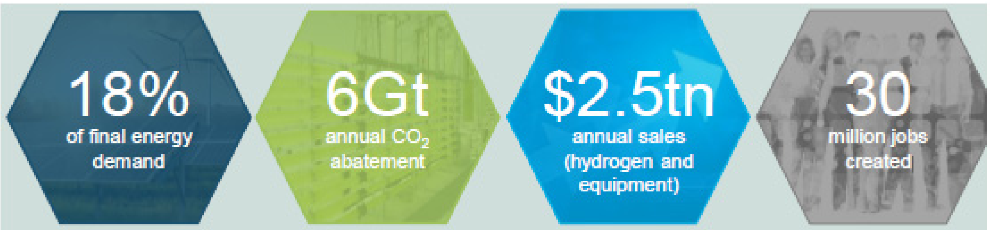
On the demand side, too, hydrogen molecules are a critical complement to electrons in the challenge of far-reaching decarbonization. Our vision sees hydrogen powering more than 400 million cars, 15 to 20 million trucks, and around 5 million buses in 2050, which constitute on average 20 to 25% of their respective transportation segments. Since hydrogen plays a stronger role in heavier and long-range segments, these 20% of the total fleet could contribute more than one-third of the total CO_2 abatement required for the road transportation sector in the two-degree scenario.

> The hydrogen vision would achieve almost one-quarter of the required CO_2 abatement in 2050[1]

In our vision, hydrogen also powers a quarter of passenger ships and a fifth of locomotives on non-electrified tracks, and hydrogen-based synthetic fuel powers a share of airplanes and freight ships.

For buildings, hydrogen builds on the existing gas infrastructure and meets roughly 10% of global demand for heat. In industry, hydrogen is used for medium- and high-heat processes, for which electrification is not an efficient option. Current uses of hydrogen as a feedstock are decarbonized through clean or green production pathways. In addition, hydrogen is used as renewable feedstock in 30% of methanol and about 10% of steel production.

Exhibit 1: Our hydrogen vision for 2050



SOURCE: Hydrogen Council; IEA ETP Hydrogen and Fuel Cells CBS; National Energy Outlook 2016

Achieving this vision would create significant benefits for the energy system, the environment, and the global economy. Across all seven roles, hydrogen could account for almost one-fifth of total final energy consumed by 2050. This would reduce annual CO_2 emissions by roughly 6 Gt compared to today's technologies, and contribute roughly 20% of the additional abatement required to limit global warming to two degrees Celsius (above and beyond already agreed commitments). It would also eliminate local emissions such as sulfur oxides, nitrogen oxides, and particulates linked to smog formation, and reduce noise pollution in cities. The transportation sector would consume 20 million fewer barrels of oil per day, and domestic energy security would rise significantly.

Alongside its environmental benefits, the hydrogen economy could create opportunities for sustainable economic growth. We envision a market for hydrogen and hydrogen technologies with revenues of more than $2.5 trillion per year, and jobs for more than 30 million people globally.

Getting there: A roadmap to the hydrogen economy

To realize this vision and achieve its desired impact, a significant step-up across the value chain would be required. Many of the required technologies are already available today – now is the time to deploy hydrogen infrastructure and scale up manufacturing capacities so as to achieve competitive costs and mass market acceptance.

In the transportation sector, hydrogen-powered FCEVs could complement BEVs to achieve a deep decarbonization of all transportation segments. FCEVs are best suited for applications with long-range requirements, heavier payloads, and a high need for flexibility. Decarbonizing these segments is particularly important as they consume a large share of total energy – while trucks and buses would account for only 5% of all FCEVs in 2050, they could achieve more than 30% of hydrogen's total CO_2 abatement potential in the transport sector.

> In 2030, 1 in 12 cars sold in California, Germany, Japan, and South Korea could be powered by hydrogen

Hydrogen can already lower the total cost of ownership of trains and forklifts, and we expect all transportation segments to be within a 10% range by 2030. These cost reductions require a significant scale-up of manufacturing capacities. If realized, FCEVs would have lower investment costs than BEVs in long-range segments, with much shorter refueling times. Environmentally, FCEVs produce 20 to 30% less emissions than conventional cars even when hydrogen is produced from natural gas without carbon capture; with renewable and clean hydrogen, FCEVs emit very little CO_2 and require less resources and energy in the manufacturing process than BEVs.

FCEV buses, medium-sized cars, and forklifts are commercially available today. The next five years will see the introduction of more models in medium-sized and large cars, buses, trucks, vans, and trains, and it is likely that additional segments such as smaller cars and minibuses will follow until 2030. To realize our vision, 1 in 12 cars sold in California, Germany, Japan, and South Korea should be powered by hydrogen by 2030, when sales start ramping up in the rest of the world. More than 350,000 hydrogen trucks could be transporting goods, and 50,000 hydrogen buses, thousands of trains and passenger ships could be transporting people without carbon and local emissions. Towards 2050, our vision also includes hydrogen as a feedstock for renewable fuels for commercial aviation and freight shipping.

Large amounts of hydrogen are used as feedstock for refining and the production of methanol. Decarbonization of these processes is starting, and with the right regulatory framework, the first oil refineries and ammonia plants could produce hydrogen from clean sources in 2030.

10 to 15 million tons of chemicals could be produced using hydrogen and carbon

In addition, hydrogen could be used together with captured carbon or carbon from biomass to replace fossil fuels as feedstock for the chemical industry. By 2030, 10 to 15 million tons of chemicals could be produced from such renewable feedstock. In the iron and steel industry, where hydrogen can be used to reduce iron ore to iron, we expect the use of clean hydrogen will be demonstrated by 2030 and gain momentum by 2035.

For heat and power for buildings and industry, hydrogen can make use of existing gas infrastructure and assets. For buildings, low concentrations of green hydrogen could be blended into public natural gas networks without any infrastructure upgrades. Alternatively, entire cities could be converted to pure hydrogen heating. Both processes have already started and could start scaling up around 2030, with the equivalent of more than 5 million households connected to a gas network with blended or pure hydrogen. A second wave of commercialization could start once the costs of producing hydrogen have fallen enough to drive uptake in more cost-sensitive industry segments. While hydrogen penetration may not reach the same rates in industry as in other segments, industry's large energy consumption implies substantial hydrogen demand beyond 2050. By 2030, up to 200 steel, chemical, and automotive plants could be pioneering the use of hydrogen for heat and power.

250 to 300 TWh of excess solar and wind power could be converted to hydrogen

As the energy system relies more heavily on renewables, hydrogen could also play a growing role in the storage of renewable electricity and the production of clean electricity. Hydrogen allows to store and transport renewable electricity efficiently over long periods of time and is therefore a key enabler of the transition to renewable energy. By 2030, 250 to 300 TWh of surplus renewable electricity could be stored in the form of hydrogen for use in other segments. In addition, more than 200 TWh could be generated from hydrogen in large power plants to accompany the transition to a renewable electricity system.

What needs to be done: A call to action

To achieve this hydrogen vision, companies across the value chain will need to step up their efforts from hydrogen production and infrastructure to end-use applications.

Building the hydrogen economy would require annual investments of $20 to 25 billion for a total of about $280 billion until 2030. About 40% ($110 billion) of this investment would go into the production of hydrogen, about a third ($80 billion) into storage, transport, and distribution, and about a quarter ($70 billion) into product and series development and scale-up of manufacturing capacity. The remainder, some $20 billion, could go into new business models, such as fuel-cell-powered taxi fleets and car sharing, on-demand transportation of goods, and contracting of combined heat and power units. Within the right regulatory framework – including long-term, stable coordination and incentive policies – attracting these investments to scale the technology is feasible. The world already invests more than

$1.7 trillion in energy each year, including $650 billion in oil and gas, $300 billion in renewable electricity, and more than $300 billion in the automotive industry.

The cost of refueling stations and fuel stacks have been cut in half

Industry would have to bring down costs of hydrogen and applications through scale. Significant cost reductions have already been achieved in some areas; the cost of refueling stations and fuel cell stack production have been cut in half in the last ten years, for example. We expect major reductions in the coming years from scaling up manufacturing to industrial levels. Further cost reductions are also necessary to bring down the cost of hydrogen itself. These are possible through cost reductions in the hydrogen production and renewable power generation for electrolysis.

We propose large-scale deployment initiatives to start the roadmap

To start down the road to a hydrogen economy, we propose large-scale deployment initiatives supported by long-term policy frameworks in countries that are early adopters. These deployment initiatives should use current activities as platform and scale their successes nationally and, at a later stage, globally. In the transportation sector, we propose a three-phased deployment plan at national level, led by an overall roadmap and targeted support to ramp up the infrastructure and deploy more vehicles. In building heat and power, we propose to replicate the approach taken in the UK, which is investigating a city-by-city transition from natural gas to hydrogen. For industrial applications, we propose to support large-scale pilots in steel manufacturing, power generation, and clean or green hydrogen feedstock for the chemicals, petrochemicals, and refining industries. Once these technologies are proven, a long-term regulatory framework should be put in place to promote uptake. A critical factor here is a fair distribution of costs so that competitiveness and employment are not compromised in industries exposed to international trade.

The sector-specific deployment initiatives should be synchronized to achieve additional synergies. We propose to build national action plans, such as those in Japan, for the adoption of a hydrogen economy. These plans should have clear targets, specific deployment initiatives, and be underpinned by a long-term regulatory framework to unlock investment.

The 18 steering members of the Hydrogen Council, who represent companies with a combined market capitalization of more than $1.15 trillion, are working towards making this vision and roadmap a reality. Our research shows that hydrogen is an essential element in achieving deep decarbonization of the global energy system at scale.

We believe the world cannot afford to put off the efforts required to reach our common goals of deploying hydrogen and limiting global climate change as agreed in Paris in 2015. We hope to accelerate this transformation and are looking forward to investors, policymakers, and businesses joining us on this journey.

Methodology

The first comprehensive vision of hydrogen's potential in the energy system of the future

In this report, we present the first comprehensive vision of the long-term potential of hydrogen and a roadmap for deployment. It is structured in three parts:

In Chapter 1 of this report, we lay out our vision. It is a systemic view of the potential of hydrogen technology, considering it as an enabler in the energy system as well as an energy vector for a wide range of applications in transport, buildings, and industry. Our vision is ambitious yet realistic. It does not rely on unknown scientific breakthroughs but on technologies whose viability has been demonstrated. It is not about imaginary solutions but about scaling existing technologies and considering the beneficial linkages and virtuous circles of deploying hydrogen technology across the energy system. It also does not promote hydrogen as a winner-take-all solution, but considers it together with other low-carbon technologies.

Making this vision a reality will require aggressive deployments of technology. In Chapter 2, we describe a roadmap to achieve the 2050 vision, detailing the role that hydrogen will play in each application as well as the required medium-term milestones, investments, and deployment initiatives until 2030 that enable this vision.

In Chapter 3, we show how investors, policymakers, and industry can work together to make the transformation a reality. We estimate the required capital investments, describe the hurdles to adoption, and highlight deployment projects that aim to put infrastructure in place, scale up production, and accelerate the transition to a low-carbon economy.

To quantify the vision and roadmap, we used two main sources: the IEA Energy Technology Perspective (2017), which projects final energy demand in the transport, industry, building, and power sectors under the two-degree scenario; and Hydrogen Council members' input on the potential for hydrogen adoption in each sector.

To arrive at sector-level results, the members first developed a market segmentation for each sector (e.g., vehicle segments for the transportation sector). The size of these segments was estimated by breaking down the IEA Perspective using a range of external data sources. The members then submitted their perspective on hydrogen adoption in each segment in 2050 to a neutral party, who aggregated the results after trimming the top and bottom quartile, and led an alignment process towards reaching a consensus among members. From the long-term vision, the 2030 figures were calculated as realistic and required milestones on the way to 2050.

In some instances – particularly in industry feedstock uses – we used external projections as the basis of the vision, all referenced in the relevant chapters. All financial figures are in US dollars ($) and refer to the world as a whole unless otherwise indicated. While 2030 milestones are generally calculated only for likely early adopters, the period towards 2050 is expected to see a global rollout of hydrogen technologies.

Our vision.

The hydrogen economy in 2050.

We, the members of the Hydrogen Council, are convinced that hydrogen can offer economically viable, financially attractive, and socially beneficial answers to the challenges of transitioning to low-carbon energy and improving air quality in cities. Our vision for the hydrogen economy in 2050 is the first comprehensive quantification of the long-term potential of hydrogen.

In our vision, hydrogen is a central pillar of the energy transformation. In seven application areas, hydrogen will enable the renewable energy system and decarbonize end uses. Achieving the hydrogen vision would create significant benefits for the energy system, the environment, and businesses around the world. It would avoid 6 Gt of CO_2 emissions, create a $2.5 trillion market for hydrogen and fuel cell equipment, and provide sustainable employment for more than 30 million people.

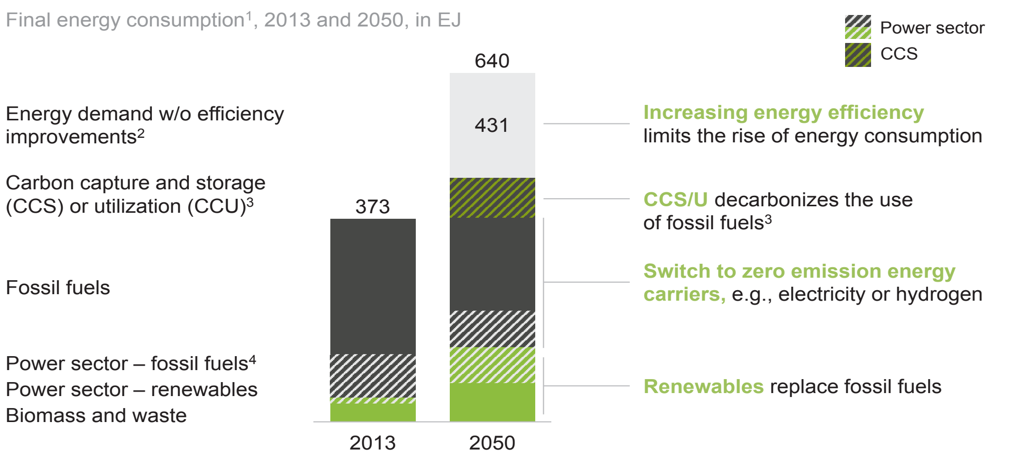
Hydrogen is a central pillar of the energy transformation required to limit global warming to two degrees

At the COP21 (Conference of the Parties) meeting in Paris in 2015, 195 countries signed a legally binding agreement to keep global warming "well below two degrees Celsius above pre-industrial levels, and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius" within this century. This target is ambitious, since it will require the world to limit the cumulative energy-related carbon dioxide emissions to less than 900 Gt by 2100 – an amount the world will exceed before 2050 if it continues on its current path.

To stay within the carbon budget, the world will need to make dramatic changes year after year and decrease energy-related CO_2 emissions by 60% until 2050[3] – even as the population grows by more than 2 billion people[4] and hundreds of millions of citizens in emerging markets join the global middle class.

Achieving such deep decarbonization will require a radical transformation of the global energy system. Four levers are needed, each of which presents its own challenges (Exhibit 2):

Exhibit 2: Achieving the energy transition will mean overcoming multiple challenges



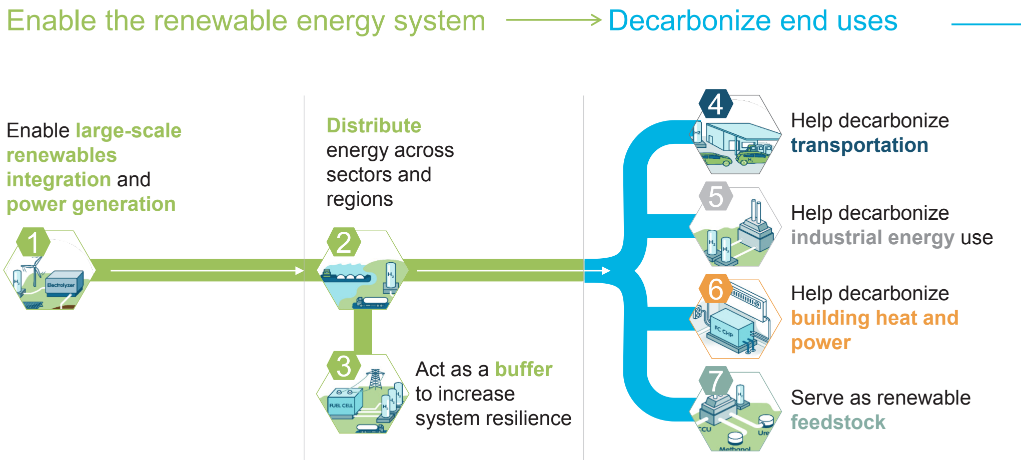
1 Within the 2°C scenario of the IEA
2 Determined via the relative increase of CO_2 emissions without energy efficiencies
3 Determined as 25% of the total amount of fossil fuels by relating the CO_2 emission reduction compared for the 2°C and 6°C scenario
4 Includes nuclear energy

SOURCE: Hydrogen Council; IEA ETP 2016

First, the world will need to become much more energy efficient. In the two-degree scenario of the IEA, the increase in primary energy demand until 2050 is limited to 10%, although global GDP will more than triple as almost 70 million people are added to the population each year.[5]

3 From 34 Gt in 2015 to 26 Gt in 2030 and 13 Gt in 2050 (IEA, 2017)
4 From 7.6 to 9.8 billion people in 2050 (United Nations, 2017)
5 Annual growth assumptions: GDP 3.3%; population 0.8% (IEA, 2017)

Exhibit 3: Hydrogen can play 7 roles in the energy transition



SOURCE: Hydrogen Council

Second, the energy supply needs to transition to renewable sources. In the two-degree scenario, the share of renewable energy sources triples from 23 to 68% of power generation, which creates challenges in matching power supply and demand.

Third, end-use applications in the transportation, buildings, and industrial sectors need to switch to low-carbon energy carriers such as renewable electricity, biomass or biogas, and green or clean hydrogen. While some applications, such as small cars and low-grade heat, can be readily decarbonized with electricity, others, such as long-range passenger cars, large trucks, planes, and high-grade heat, pose serious challenges.

Fourth, carbon emissions, which are created by the remaining fossil fuels in the system, need to be captured and stored through CCS or used in the chemicals industry through CCU.

Hydrogen – abundant, versatile, clean, and safe – can play seven vital roles to meet the challenges of the transition (Exhibit 3):

1. Enabling large-scale renewable energy integration and power generation
2. Distributing energy across sectors and regions
3. Acting as a buffer to increase energy system resilience
4. Decarbonizing transportation
5. Decarbonizing industrial energy use
6. Helping to decarbonize building heat and power
7. Providing a clean feedstock for industry.

In all seven application areas, hydrogen can offer economically viable and socially beneficial solutions

Hydrogen technology is not new. The world already produces and consumes more than 55 Mt of hydrogen annually in a wide range of industrial processes.

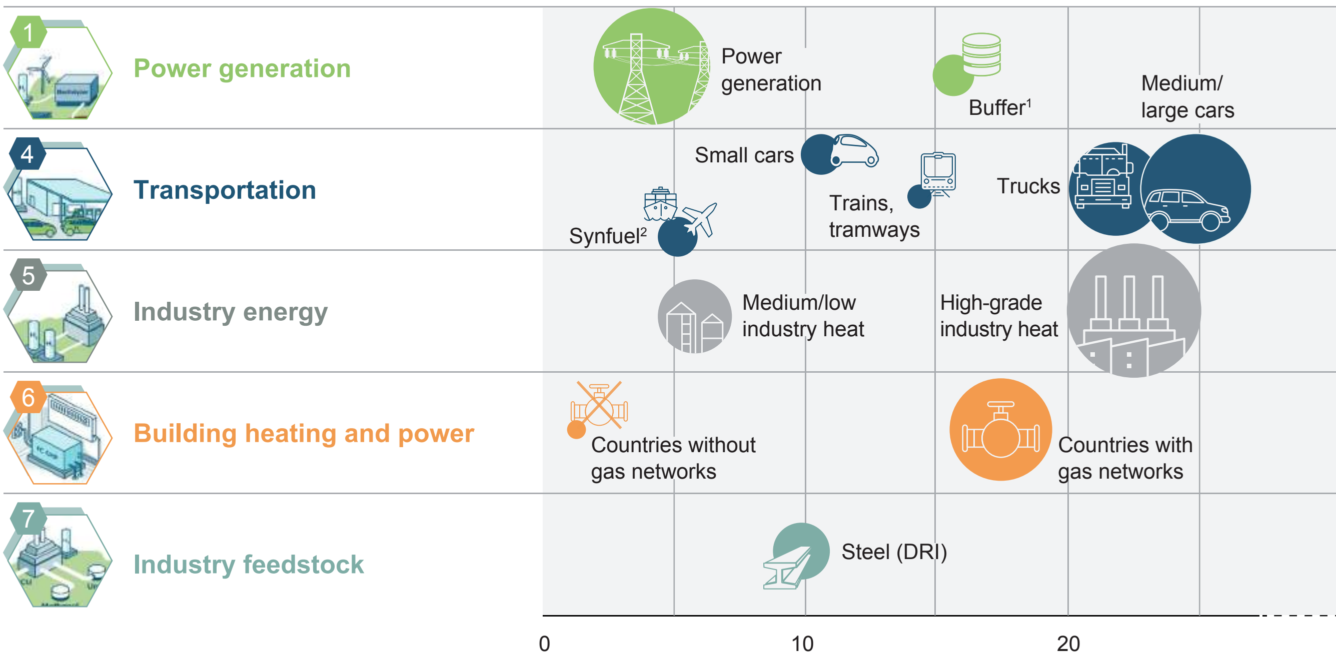
> The world already produces and consumes more than 55 Mt of hydrogen annually in a wide range of industrial processes

In our vision, current uses of hydrogen will be outpaced by new uses in all seven applications (Exhibit 4).[6]

By 2050, hydrogen could power a global fleet of more than 400 million cars, 15 to 20 million trucks, and around 5 million buses, which constitute on average 20 to 25% of their respective transportation segments. In automotive segments, the adoption of hydrogen vehicles will range from roughly 10% for small cars and 20 to 25% for large cars and trucks to roughly 35% for vans. Hydrogen-powered trains could replace around 20% of the world's diesel trains. Hydrogen could also replace 5% of the world's fuel supply to airplanes and freight ships by 2050.

6 The hydrogen vision is based in part on input from the members of the Hydrogen Council. Please see the methodology chapter for details.

Exhibit 4: Hydrogen can play a critical role in the low-carbon technology portfolio



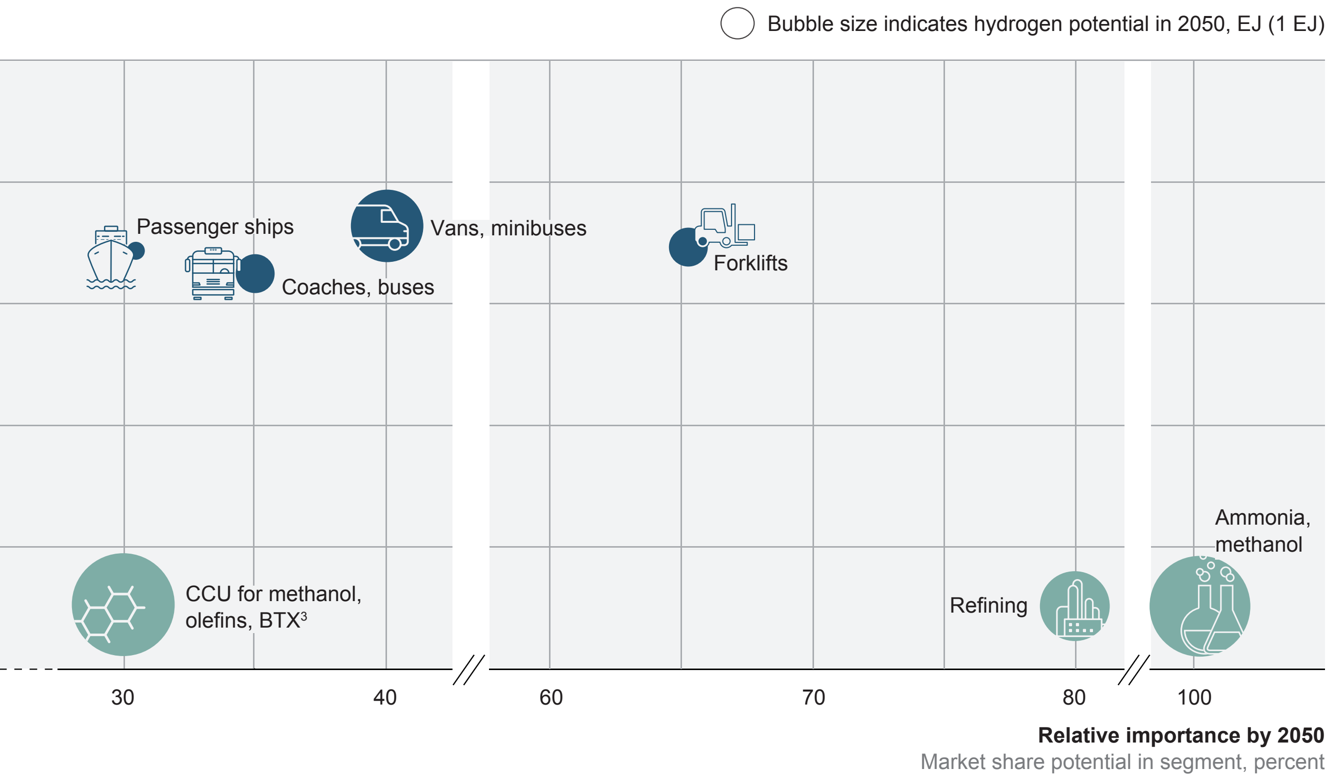
1 Percent of total annual growth in hydrogen and variable renewable power demand
2 For aviation and freight ships
3 Percent of total methanol, olefin, BTX production using olefins and captured carbon
SOURCE: Hydrogen Council

In the power generation sector, domestic or imported hydrogen could generate roughly 1,500 TWh of electricity. It could provide roughly 10% of the heat and power jointly required by the global household and industry sectors. These shares are higher for residential heat and power in regions with high winter heating demand (15 to 20% of heat demand). Such regions tend to have a natural gas infrastructure on which hydrogen can piggyback. They are also higher in industrial processes using high-grade heat (20 to 25% of heat demand), which is harder to decarbonize than lower-grade heat.

Current uses of hydrogen as industry feedstock could be decarbonized fully. In addition, hydrogen could be used to produce 30% of methanol and derivatives from captured carbon instead of methane, recycling more than 350 Mt of CO_2 into products. It could also be used to produce about 10% of steel – roughly 200 Mt – using low-carbon direct reduction processes.

The use of hydrogen for power generation (Role 1) and the decarbonization of end uses (Roles 4 to 7) are complemented by the roles that hydrogen can play as an energy carrier for energy distribution and storage (Roles 2 and 3), which are not quantified separately since they do not add to total demand.

Overall, the annual demand for hydrogen could increase tenfold by 2050 – from 8 EJ in 2015 to almost 80 EJ in 2050 (Exhibit 5), enough to meet the world's current energy demand for two and a half months. (For other comparisons, see Box 1.) This increase is due to an increase



in uses – from feedstock to the industry, residential, transportation and power sectors – as well as a global rollout from priority markets to the rest of the world that is expected to start beyond 2030.

How big is 1 EJ?

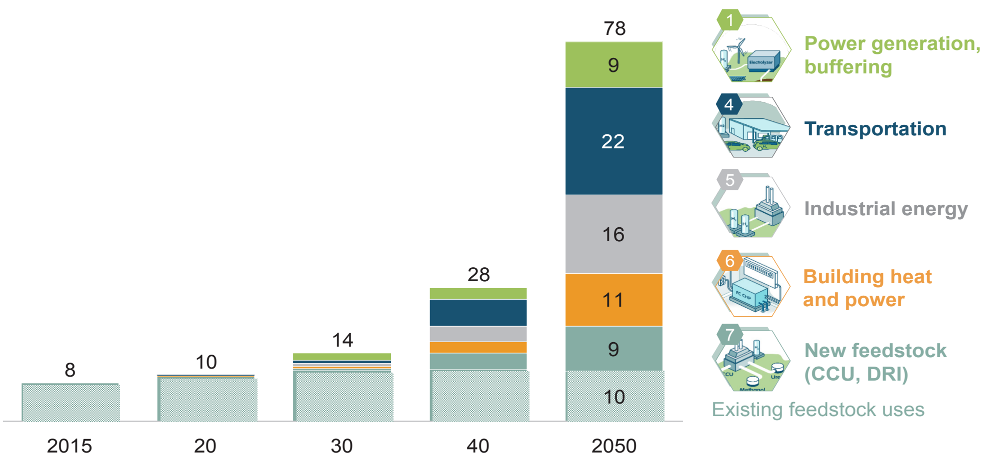
1 EJ is roughly equivalent to:

- One day of the world's total final energy demand
- The energy consumed in two years by the transportation sector in the New York metropolitan area
- The heat used by Germany's steel industry in one year
- The energy required to heat all of the houses in France for one winter
- The energy needed to recycle the annual CO_2 emissions of Michigan's industrial sector.

1 EJ is provided by 7 million tons or 78 billion cubic meters of gaseous hydrogen. It is equivalent to 990 billion British thermal units, 278 TWh of electricity, and roughly 170 million barrels of oil or 290 billion cubic feet of natural gas.

Exhibit 5: Hydrogen demand could increase 10-fold by 2050

Global energy demand supplied with hydrogen, EJ



SOURCE: Hydrogen Council

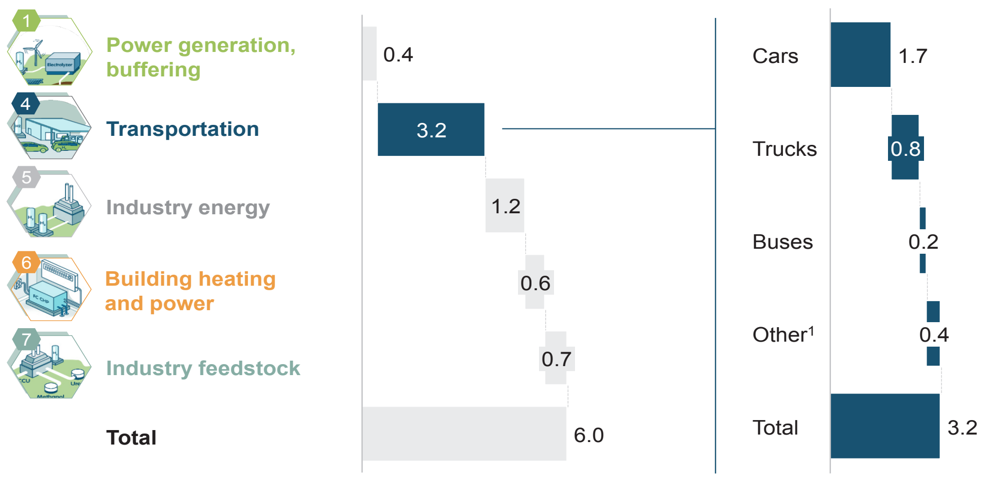
Achieving the hydrogen vision would create significant benefits for the energy system, the environment, and businesses around the world

Producing almost 80 EJ worth of hydrogen would meet 18% of total final energy demand, or 12% of the world's total primary energy demand in the 2050 two-degree scenario. With hydrogen, the energy system would enjoy an additional energy carrier with attractive properties. It can be flexibly produced, stored for long periods at low cost, and transported across regions. It can couple sectors, transforming electricity into a fuel for producing heat and vice versa. Its flexibility would make higher renewable shares in the power system cost efficient where they would otherwise not be. Its deployment potential would avoid the consumption of more than 20 million barrels of oil per day compared to today's energy composition. It would radically decrease the need and energy required to transport fossil fuels across the world and increase self-reliance and energy security.

Using this amount of hydrogen would reduce annual CO_2 emissions by roughly 6 Gt compared to today (Exhibit 6) and meet roughly 20% of the abatement to reach the two-degree scenario compared to the reference case. In end-use applications, it would eliminate local emissions such as sulfur oxides, nitrogen oxides, and particulates, which are linked to smog formation and cause an estimated 3 million premature deaths annually.[7] It would also reduce other nuisances, such as noise pollution in cities and water pollution in lakes, rivers, and ports.

Exhibit 6: Annual CO_2 emissions could be reduced by 6 Gt in 2050

CO_2 avoidance potential 2050, Gt



1 Aviation, shipping, rail, material handling

SOURCE: Hydrogen Council

The transition to hydrogen would also create opportunities for sustainable economic growth. As the technology reaches mass markets, it would create sustainable value chains that do not require further government support. We calculate that using hydrogen at this scale would

7 WHO estimates of air pollution exposure and health impact, September 27, 2016

create a revenue potential of more than $2.5 trillion per year. Half of this revenue would come from hydrogen sales, the other half from sales of vehicles, trains, heaters, machinery, industrial equipment, and components.

> The application of hydrogen at this scale would create a revenue potential of more than $2.5 trillion per year

Most of the value creation in a hydrogen economy would occur in advanced industries. These industries create more employment and domestic value than the value chains of fossil fuels – directly, indirectly, and through implied effects. Given current estimates of roughly 12 jobs created directly and indirectly per million dollars of revenues in advanced industries, the hydrogen economy would directly and indirectly employ more than 30 million people. Roughly 15 million additional jobs would be associated with the value added around fuel cells, for instance in the production of vehicles based on the fuel cell powertrain.

Investments in the ramp-up of infrastructure and manufacturing would create additional revenues and jobs, mostly in construction and machinery.

Getting there.

A roadmap to the hydrogen economy.

To realize the vision outlined in the previous chapter and achieve its desired impact, a significant step-up will be required across the value chain. This chapter describes the roadmap in detail, focusing in particular on the segments most relevant until 2030.

For most applications outlined in this report, the technology has been proven and is ready for use. Now is the time to roll out hydrogen infrastructure and manufacturing capacity and lead the technology to competitive costs and mass market acceptance.

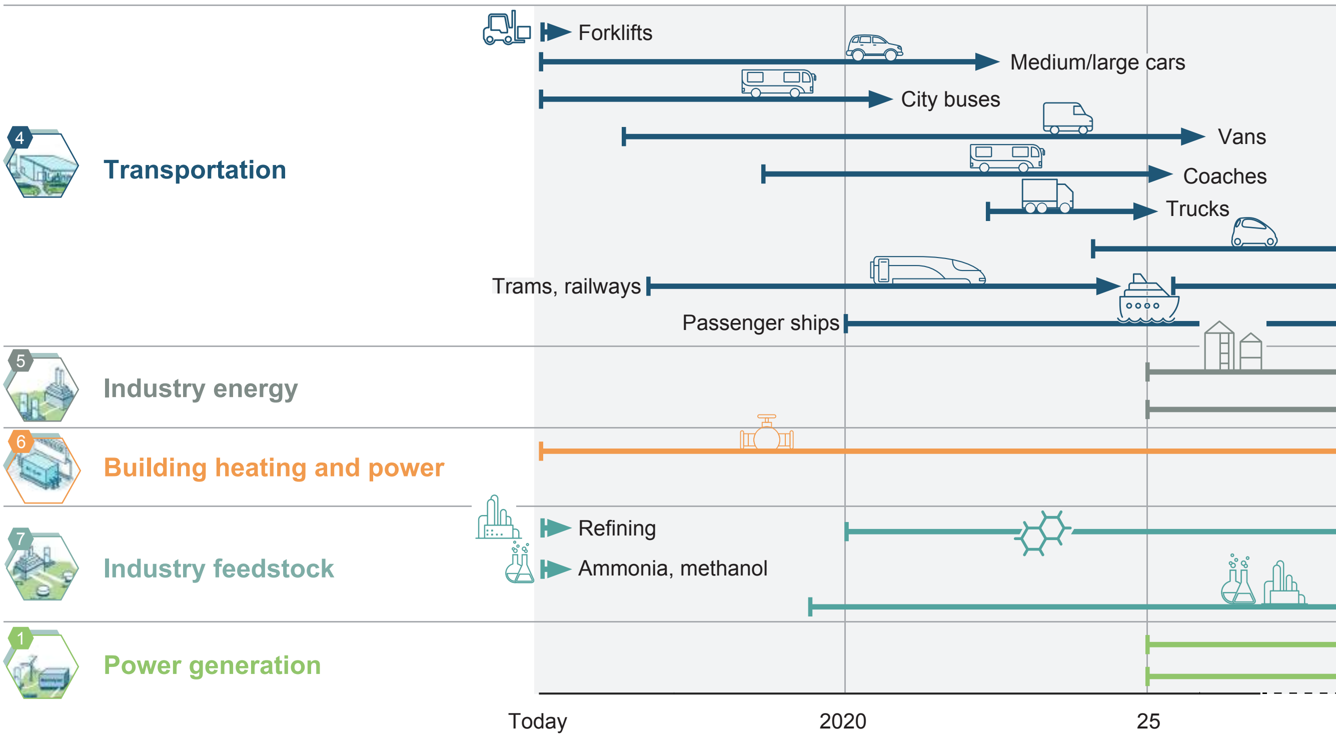
Overview: Hydrogen technology is ready for deployment

For most applications, commercialization could start before 2020 (Exhibit 7).

In transportation, hydrogen-powered vehicles are commercially available now or will become available in the next five years in medium-sized and large cars, buses, trucks, vans, trains, and forklifts.[8] In these segments, FCEVs meet the performance and convenience requirements best. In the next wave, costs are likely to drop with scale, allowing hydrogen to compete in more segments such as smaller cars and minibuses. By 2030, 1 in 12 cars sold in California, Germany, Japan, and South Korea could be powered by hydrogen, more than 350,000 hydrogen trucks could be transporting goods, and thousands of trains and passenger ships could be transporting people without carbon and local emissions. Beyond 2030, hydrogen will increasingly be used to create renewable synthetic fuels to decarbonize commercial aviation and freight shipping, which are harder to decarbonize using pure hydrogen and fuel cells.

8 Please see the transportation chapter for examples of models across all these segments.

Exhibit 7: Hydrogen technology is ready to be deployed

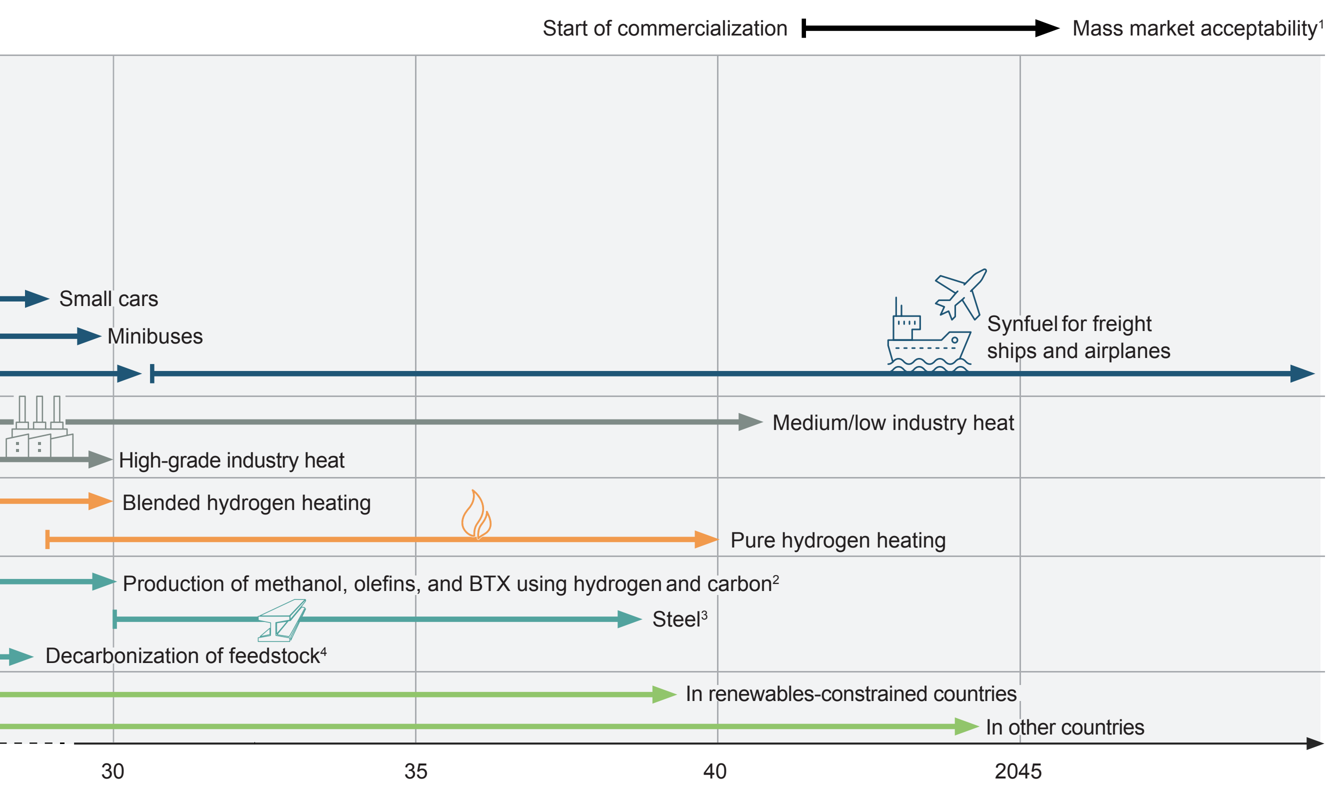


1 Defined as sales >1% within segment in priority markets
2 Market share refers to the amount of production that uses hydrogen and captured carbon to replace feedstock
3 DRI with green hydrogen, iron reduction in blast furnaces, and other low-carbon steel making processes using hydrogen
4 Market share refers to the amount of feedstock that is produced from low-carbon sources

SOURCE: Hydrogen Council

In feedstock, large amounts of hydrogen are already used in refining, ammonia, and methanol production. Large-scale projects are already under way, and by the middle of the next decade, the first refineries and ammonia plants could start producing their hydrogen from clean sources, reducing upstream emissions in the petrochemicals and chemicals industries. At the same time, carbon capture is expected to gain momentum in the two-degree scenario. Combined with hydrogen, this captured carbon could be used as industrial feedstock and thus replace fossil fuels. Similarly, carbon from biomass could be turned into a renewable feedstock using hydrogen. As the costs of carbon capture and hydrogen production decrease, up to 5% of the global production of methanol and derivatives could be based on renewable feedstock by 2035. In the iron and steel industry, where hydrogen can be used to reduce iron ore to iron, the use of clean hydrogen is also expected to be demonstrated by 2030 and gain momentum by 2035.

For heat and power for buildings and industry, low concentrations of green or clean hydrogen could initially be blended into public natural gas networks, before entire cities could be converted to pure hydrogen heating. Both processes have already started and could start scaling up around 2030. A second wave of commercialization could start once the costs of producing hydrogen have fallen enough to drive hydrogen uptake in the more cost-sensitive



industry segment. While hydrogen penetration may not reach the same rates in industrial energy use as in other segments, the large energy consumption for industrial purposes implies substantial potential for hydrogen demand.

As the energy system relies more heavily on renewables, hydrogen could also play a growing role in the storage of renewable electricity and the production of clean electricity. By 2030, 250 to 300 TWh of surplus renewable electricity could be stored in the form of hydrogen for use in the other end-use segments. In addition, more than 200 TWh could be generated from hydrogen in large power plants to accompany the transition to more renewable electricity.

The following sections will describe the roadmap in more detail along the four end uses in transportation, industrial energy, buildings, industry feedstock, and as enabler for the energy system. It outlines the importance of decarbonization, the role of hydrogen in our vision, as well as the investment need and deployment projects in each.

Transportation.

Hydrogen and fuel cells are critical elements in the decarbonization of the transportation sector.

- FCEVs are a necessary complement to BEVs to achieve deep decarbonization of the transportation sector.
- They are convenient for consumers due to long ranges and fast refueling times and particularly competitive for heavily-used vehicles.
- Hydrogen-powered vehicles are commercially available now or within the next five years in medium-sized/large cars, buses, trucks, vans, trains, and forklifts.

2030 milestones

- 1 in 12 cars in Germany, Japan, South Korea, and California powered by hydrogen
- Globally 10 to 15 million cars and 500,000 trucks powered by hydrogen
- Deployment of hydrogen-powered trains and passenger ships

2050 target picture

- Up to 400 million passenger vehicles (~25%), 5 million trucks (~30%), and more than 15 million buses (~25%) running on hydrogen
- 20% of today's diesel trains replaced with hydrogen- powered trains
- 20 million barrels of oil replaced per day, 3.2 Gt CO_2 abated per year

Decarbonizing road transport is a key to achieving the two-degree scenario

Today's transportation sector depends almost entirely on fossil fuels, emits more than 20% of all CO_2 emissions – and is almost certain to grow significantly in the years ahead. The IEA predicts that CO_2 emissions will increase by about 35% by 2050 in the reference scenario, whereas the two-degree scenario requires reducing emissions by 40% until 2050. Average emissions per kilometer need to decrease by more than 70%, despite an increase in more carbon-intensive freight and air traffic.

> More than 80 million zero-emission vehicles will need to be on the roads by 2030 – just 12 years from today

To achieve the two-degree scenario, the equivalent of 160 million low-emission vehicles – 80 million zero-emission and 80 million plug-in hybrid electric vehicles (PHEVs) – will need to be on the roads by 2030, just 12 years from today.[9] Reaching this ambitious target will require a wide range of technologies. Since vehicle range, flexibility, and performance requirements differ widely between segments, BEVs, FCEVs, biofuels, and synthetic fuels will be required in different segments to varying degrees. To bet on a single technology to solve the decarbonization challenge in transportation is not only likely to fall short of the required emission reductions, it is also risky if the hoped-for advances in that single technology – or the speed at which production lines and supply chains are developed – do not materialize.

But technological developments will not take place at the expense of one another. In fact, the development of BEVs and FCEVs is likely to be synergetic: both technologies rely on electric powertrains and benefit from technological improvements in these components. Likewise, the development of fuel cells for passenger cars could enable fuel cell applications in freight transport, trains, on ships, and even beyond the transportation sector – and vice versa.

Hydrogen is a key technology in a decarbonized transport system

Each segment of the transport sector – from motor scooters to ocean-faring container ships – can be characterized by range and payload. These two metrics roughly determine the performance requirements for the engine (payload) and storage requirements for the fuel (range). Today, all of these segments rely heavily on fossil fuels.

Decarbonizing the segments is possible with a range of technologies that offer different energy efficiency (the energy required as input) and their energy density in terms of weight and volume (Exhibit 8):[10]

9 IEA, 2017

10 Stolen, 2017

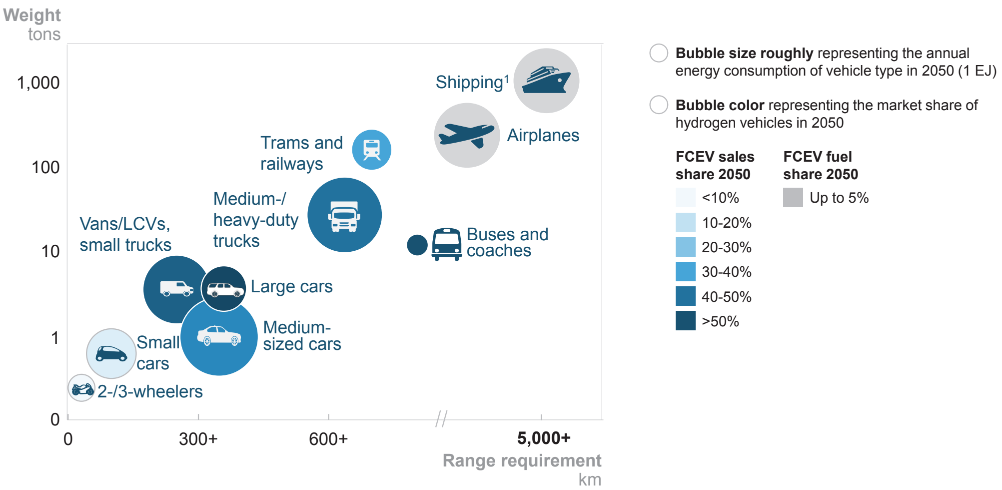
- BEVs have the highest well-to-wheel energy efficiency (60% when powered by electricity from renewables, 30 to 35% when powered by gas- or coal-based electricity; compared to roughly 25 to 30% for ICEs[11]), while batteries have the lowest energy density per weight (0.6 MJ per kg), making them well suited for lighter vehicles and shorter ranges.

- Hydrogen, when stored aboard a vehicle, has a much higher energy density per weight than batteries (currently around 2.3 MJ per kg[12]), allowing FCEVs to travel longer distances and perform better for heavier vehicles for which batteries become impractical and inefficient. The energy efficiency of FCEVs is lower than that of BEVs, however (roughly 30% from well to wheel if produced through electricity).

- Synthetic fuels have the highest specific energy, which allows them to be used in aviation and shipping, but they suffer from low overall energy efficiency of about 10%.

Exhibit 8: FCEVs can help decarbonize segments with longer ranges and more weight

Transportation market segmentation



1 Hydrogen-based fuels or fuel cells

SOURCE: IEA ETP; IHS; A Portfolio of Powertrains for Europe (2010); Thiel (2014); Hydrogen Council

While the requirements of range and weight are related to transport segments, as shown in Exhibit 8, it is the specific pattern of usage that determines the attractiveness of a technology. While some consumers drive only locally, for example, others regularly drive their cars long distances, making FCEVs more attractive. Trucks for local distribution may be able to run on batteries, while those for long-haul freight will profit much more from the longer range of hydrogen.

Although FCEVs and BEVs are sometimes represented as competing technologies, they are actually complementary. While some transport segments will rely primarily on one technology – commercial aviation is unlikely to be powered by batteries or fuel cells, for example – others

11 A portfolio of power trains for Europe: A fact-based analysis 2010

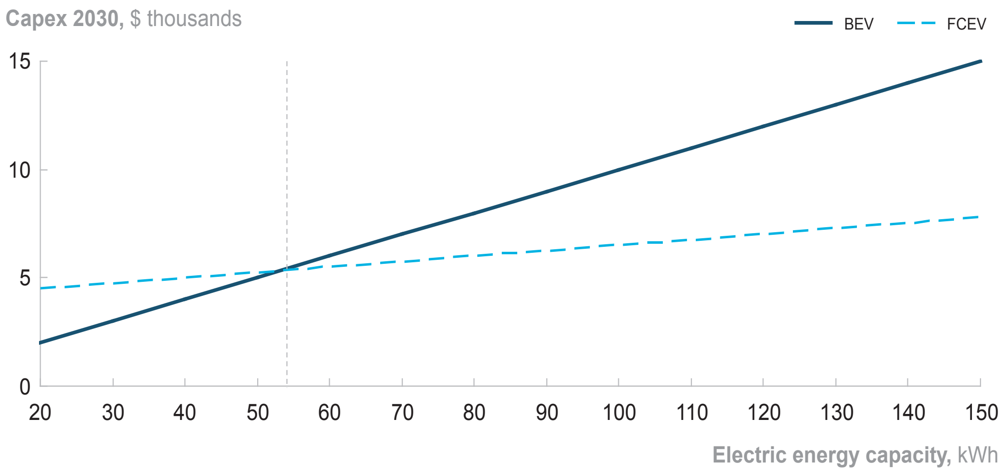
12 Based on Toyota Mirai tank and fuel cell weight

are less clearly divided. In these segments, cost, convenience, available infrastructure, and other factors will play large roles.

Hydrogen is advantageous for vehicles with long range, mileage, and heavy payloads (Exhibit 9). Using 2030 cost estimates, for example, a BEV powertrain with a 30-kWh battery (the size of the battery in a 2016 Nissan Leaf) would be about 35% less expensive than an FCEV with similar storage capacity. As capacity increases, however, the FCEV becomes cheaper, since adding hydrogen storage costs less than adding batteries. At about 55 kWh, both powertrains cost the same, which translates into a range of about 300 km. Beyond that, FCEVs are likely to be less expensive than BEVs. At a range of around 1,000 km, which is the range offered by conventional thermal engines for passenger cars, the FCEV has a cost advantage of about 55%. For trucking, even larger capacities are required to move heavy payloads across long distances, for which hydrogen is well suited.

Exhibit 9: FCEVs have lower investment costs for long-range vehicles

Scenario analysis of powertrain costs for FCEVs and BEVs at different capacity levels, 2030



Assumptions: battery $100/kWh, fuel cell of 100 kW with $40/kW, hydrogen tank $24/kWh, FCEV battery with 1% of total capacity, FC to electricity efficiency 55%

SOURCE: Avere-France; DoE fuel cell technology office; McKinsey: Automotive revolution – perspective towards 2030

Improvements in fuel cell efficiency will likely reduce fuel consumption by 20 to 35% until 2030 (Exhibit 10). In addition, fuel costs per kg hydrogen are expected to fall as distribution and retail infrastructure scale up. These improvements could give FCEVs an advantage over diesel in all segments, even if oil prices remain near today's low levels. This is particularly relevant for consumers who drive long distances and commercial vehicles used extensively.

The costs of hydrogen refueling infrastructure are less than often thought. Our roadmap shows that building the required refueling infrastructure would cost $1,500 to 2,000 per FCEV until 2030. This is in the same order of magnitude as the cost for the recharging infrastructure

Exhibit 10: FCEVs' fuel costs will fall by 20 to 35% until 2030

SOURCE: A Portfolio of Powertrains for Europe (2010) [Updated]

for a BEV, as a home charger currently costs around $2,000.[13] By 2030, costs of refueling infrastructure could decrease to less than $1,000 per FCEV. A study comparing infrastructure costs for 20 million FCEVs and 20 million BEVs in Germany found that, when required grid investments are considered, the total cost per FCEV may even be lower than for BEVs.[14]

Considering the total costs of ownership – purchasing, fueling, and maintaining a powertrain – the FCEV cost disadvantage compared to ICEs could drop below 10% between 2025 and 2030 (Exhibit 11) for C/D segment passenger cars, depending on annual range and fuel prices. The cost reductions – as much as 80% – are driven primarily by scale, with most of the reductions coming from scaling up manufacturing and the fuel retail infrastructure between now and 2025. Ultimately, TCO depends heavily on utilization – the more a vehicle is used, the higher the advantages for FCEVs and BEVs compared to ICEs.

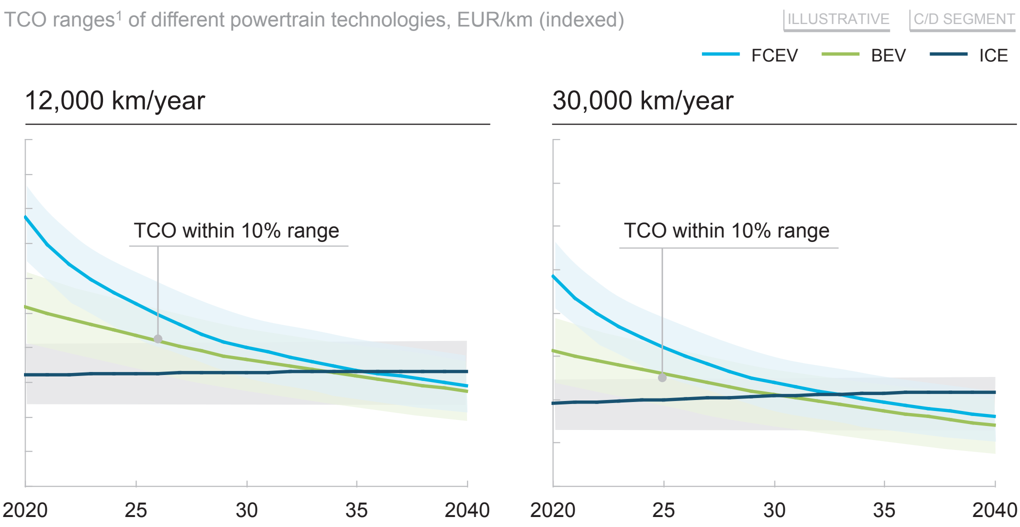
For trucks, a TCO breakeven could come even earlier. In certain use cases, such as long-haul trucking, FCEVs could break even with ICEs between 2025 and 2030.[15] One reason for the earlier breakeven is the higher mileage and energy demand of trucks, making the fuel cost benefit of FCEVs more important. Another is the limited need for infrastructure. The fuel cell trucks under development aim for long ranges and typically drive along major highways. With a limited amount of refueling stations, complete coverage can be achieved, resulting in lower infrastructure cost. This network would also provide a good minimum network for passenger cars.

13 Schaufenster Elektromobilität, 2016

14 The study considered infrastructure costs for hydrogen production, transmission, distribution, and retail for FCEVs; distribution, fast chargers, and home chargers for BEVs; it did not consider the costs for the production of electricity (FZ Jülich, 2017).

15 ICCT, 2017

Exhibit 11: FCEVs could become cost competitive between 2030 and 2040



1 Based on fuel price variants and sensitivities to learning curves

SOURCE: A Portfolio of Powertrains for Europe (2010), updated with Hydrogen Council vision

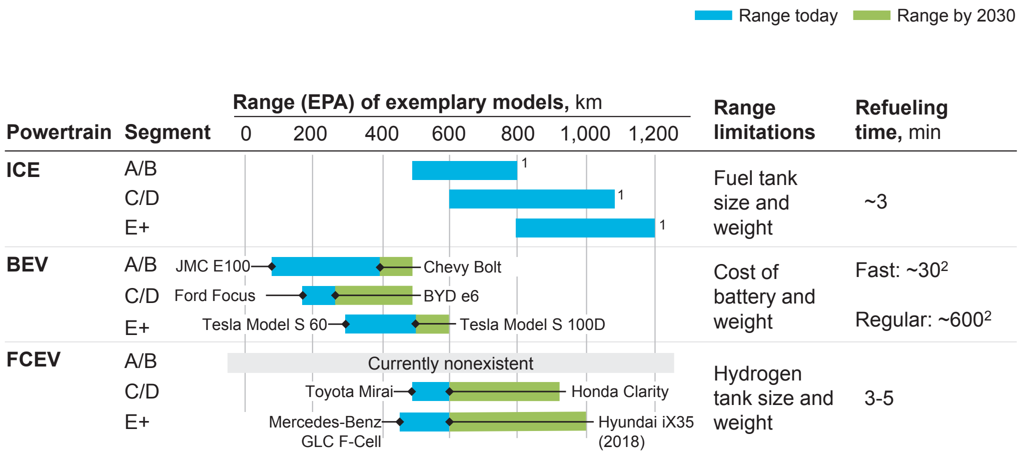
Lowest costs, however, are not the only reason to consider the adoption of new technologies. While many models of future energy systems are based on a lowest-cost principle, it is not the only factor that most consumers or even businesses consider. For most of them, performance, flexibility, and convenience are at least as important as price. The wide array of brands and models attests to these differences; car manufacturers use complex models of buying criteria to develop and market new vehicles. In a recent survey in the Netherlands, for example, about 75% of all customers said they would consider an electric vehicle, but only 35% would settle for a car with a range of less than 600 kilometers. While the vast majority of current EV owners charge at home, only 40 to 50% of parking takes place at a dedicated spot at home or at work, making charging less convenient for customers without access to dedicated overnight charging spots.[16] For these consumers, the least-cost option may not be the one they settle on – the long ranges and fast refueling times offered by FCEVs may outweigh price considerations (Exhibit 12).

For commercial vehicles, the cost of purchasing the vehicle is only part of the total calculation. Flexibility, fast refueling, and range provide economic benefits that fleet managers weigh against price. Being able to carry more payload on a truck, since hydrogen tanks and fuel cells weigh significantly less than batteries, provides a clear economic advantage. The flexibility of accepting customers for long-distance rides implies higher revenue for taxis.

Trends that increase the utilization of transportation assets – such as autonomous driving and car sharing – further increase the need for continuous operation without long recharging periods. Further improvements in charging speeds could alleviate some of these range issues for BEVs, but any advances will need to avoid degrading battery capacity or lifetime.

16 TU Dresden, 2015

Exhibit 12: FCEVs have superior range and refueling times



1 Indicative
2 Charging time depends on battery size and charge rate; PHEV indication refers to a 8.7 kWh battery and home charging at a standard domestic socket; BEV indication refers to a 24 kWh battery at 50kW for fast charging and a standard domestic socket for regular charging

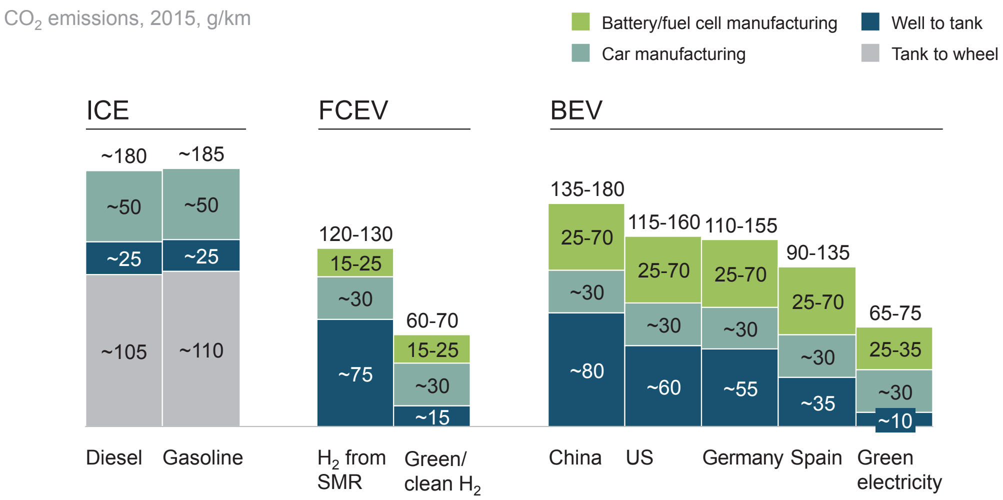
SOURCE: EV-volumes.com; OEM websites; web and press search

A comparison of environmental benefits should cover the whole lifecycle of a car, since the CO_2 emissions of a vehicle comprise those from the tailpipe as well as those emitted upstream during fuel production and car manufacturing.[17] Regulation, such as CAFE standards in the US and the emission performance standards for new passenger cars in the EU, have focused on downstream emissions – from the tailpipe. Tailpipe emissions from a diesel- or gasoline-powered B-class vehicle are around 105 to 110 g of CO_2 per km, while they are zero for FCEVs and BEVs since no combustion takes place in the vehicle. For FCEVs and BEVs, the emissions of producing the hydrogen/electricity drive the overall environmental performance. For BEVs, in addition, a significant contributor to the environmental performance are the CO_2 emissions and water use from battery manufacturing (Exhibit 13) and the required resource extraction.

Considering the whole lifecycle, the carbon emissions of FCEVs are very low. Even if hydrogen were produced entirely from natural gas through steam methane reforming (SMR) without the use of carbon capture, FCEV emissions are 20 to 30% lower than those of ICEs. In reality, hydrogen is already less CO_2 intense than this: much hydrogen is produced as a by-product in the chemical industry (leading to very low CO_2 intensity); a number of refueling stations draw their hydrogen supply from electrolysis with renewable electricity; and SMR can be paired with effective CCS. Over time, fully decarbonized hydrogen could lead to very low emissions for fuel production. The car manufacturing emissions for an FCEV are slightly higher than for an ICE, totaling around 45 to 55 g per km. In total, an FCEV powered by green or clean hydrogen in our example could achieve combined CO_2 emissions of 60 to 70 g per km.

17 The TCO calculation uses a compact car with a lifetime of ten years and 12,000 km annual driving range as reference. For simplification, we excluded emissions from vehicle recycling and disposal.

Exhibit 13: FCEVs can achieve very low CO_2 emissions if the whole lifecycle is considered



Assumption: compact car (C-segment) as reference vehicle (4.1 l/100 km diesel; 4.8 l/100 km gasoline; 35.6 kWh battery), 120,000 km lifetime average grid emissions in China, Germany, Spain in 2015; EV manufacturing (excl. fuel cell and battery) 40% less energy-intensive than ICE manufacturing; 10 kg CO_2/kg H_2 from SMR; 0.76 kg H_2/100 km; 13 kWh/100 km

SOURCE: EPA; A Portfolio of Powertrains for Europe (2010); Toyota Mirai LCA; IVL; Enerdata; expert interviews

This is highly competitive with the environmental performance of BEVs. BEV carbon emissions are dependent on the generation mix for the power that fuels the car and the power that fuels the energy-intensive manufacturing process of the batteries. For fueling the car, the equivalent emissions currently range from about 35 g CO_2 per km in Spain to about 80 g in China for a small BEV. For manufacturing, batteries require significant mineral resources, which are energy intensive to mine and process. Since most of the required energy is electricity, the intensity depends on the power mix of the battery factory. Studies estimate emissions between about 70 g per km (current power mix) and 25 g per km (fully renewable electricity). This puts total emissions of a BEV produced and driving in China on par with an ICE; in Germany on par with an FCEV driven with hydrogen from SMR without CCS. Using green electricity for manufacturing and fueling, BEVs exhibit a similar carbon intensity as FCEVs.

From a lifecycle analysis standpoint, larger vehicles are likely to favor FCEVs slightly over BEVs, as the incremental capacity of the battery increases its emissions. Longer lifetime and higher utilization will play out in favor of FCEVs and BEVs compared to vehicles with ICEs, as their emissions for driving additional distances are lower.

Hydrogen technology for transportation is technologically ready

The Hydrogen Council believes FCEVs will play an important role in the decarbonization of transport, complementary to other technologies.

We expect that **FCEV passenger cars** could represent almost 3% of new vehicle sales in 2030, ramping up to about 35% in 2050, for total sales of 4 million vehicles in 2030. In the markets leading global FCEV adoption – Germany, Japan, California, and South Korea – almost every 12th car sold in 2030 could be powered by hydrogen.

Achieving these sales figures would require a rapid scale-up of manufacturing and refueling infrastructure until 2030, but they are feasible. The technology is proven – three models of FCEVs are already offered commercially in Japan, South Korea, California, and Germany (Honda Clarity, Hyundai ix35/Tucson, Toyota Mirai), and one model is available as a retrofit (Renault Kangoo, retrofitted by Symbio FCell).[18] Ten additional models are slated for release by 2020.[19] FCEVs have driven more than 20 million km under real-world conditions and satisfy all safety certifications and regulations. Hundreds of refueling stations have been operational for years. Model choices will expand in the next few years, as additional manufacturers join the race. And while the implied growth rates are ambitious, they are not unlike the growth of early hybrid-electric vehicles.

Deployment is likely to be led by fleet applications such as taxis and other commercial fleets. In several cities worldwide, taxi or ride-sharing start-ups using FCEVs exclusively (e.g., BeeZero in Munich or Hype in Paris) or alongside BEVs (e.g., CleverShuttle in Germany or J'Car in South Korea) have sprung up. Early uptake is likely to be highest in the sedan (C/D), luxury (E+), and SUV (J) segments, as they require the power and ranges of fuel cells, and their owners are somewhat less price sensitive. As costs decline through the scale-up of manufacturing and hydrogen, FCEVs could also compete for shares of smaller segments.

Small vans and light commercial FCEVs are on the road today. Adoption could increase to almost 6% of sales by 2030 and almost 50% by 2050, as cities put more stringent regulations in place to reduce local emissions from delivery vehicles and other commercial fleets.

Fuel cell buses are also getting significant traction due to concerns about local pollution, in particular in Europe, Japan, South Korea, and China. While smaller buses and buses with shorter-range requirements will run on batteries, fuel cells will allow larger buses to go longer distances and operate with fewer interruptions. For buses, the infrastructure hurdle is less relevant, as most rely on purpose-built refueling stations. More than 450 FCEV buses from different OEMs (including ADL, Daimler, Foton, Solaris, Solbus, Van Hool, VDL, Yutong, and Wrightbus) are on the road in the US, Europe, Japan, and China today, and countries have ambitious plans to deploy thousands over the next few years. South Korea plans to replace 26,000 buses from compressed natural gas with fuel cell buses until 2030; Shanghai alone is planning to operate 3,000 buses by 2020.

> Europe, Japan, South Korea, and China have ambitious plans to deploy thousands of fuel cell buses over the next few years

Coaches and intercity buses that travel long distances are also well suited for a hydrogen powertrain. Most intercity buses travel from bus depot to bus depot – hence a refueling station in every depot suffices. Due to their high mileage and fuel requirements, buses can reduce road emissions significantly: a single city bus running 16 hours a day emits as much as 50 tons of CO_2 per year, equivalent to roughly 25 medium-sized passenger cars. Our roadmap sets a

18 Not all models are offered in all markets

19 IHS/Markit

target share of as much as 30% of the total bus fleet by 2050 for FCEVs, which would imply a 10% share of sales by 2030 in priority markets, for annual sales of about 20,000 buses and minibuses globally. This fleet would save about 5 to 10 million tons of CO_2 per year; as much as a million individual FCEVs.

An even larger decarbonization potential lies in **trucks.** With freight transport booming – the IEA projects an annual growth of freight kilometers of almost 3% per year – truck emissions that account for roughly 25% of CO_2 emissions from the transportation sector today will grow to 35 to 40% by 2050. In particular, heavy trucks could be decarbonized with hydrogen (alongside liquefied or compressed natural gas or biogas, which competes for this segment but suffers from local emissions), accounting for about 25% of the total fleet by 2050. This would require a sales share of about 2.5% in 2030, for a 350,000-strong fleet of light, medium, and heavy trucks. While the number of trucks seems small compared to passenger cars, the emission abatement could be large: due to their high mileage and heavy weights, the truck fleet would have the same abatement potential as almost 2.5 million FCEVs in the passenger car segment. The first models are commercially available in China, where Nation Synergy has recently signed contracts for the delivery of more than 3,000 captive fuel cell trucks.[20] Several additional models, also in heavy and long-haul segments, are expected to be commercially available within the next five years (e.g., by Toyota, Nikola Motor, and VDL).

Overall, hydrogen and fuel cells could constitute up to 20% of road vehicles in 2050, but contribute more than a third of the transport sector CO_2 abatement needed to reach the two-degree scenario relative to the reference case. This is due to the higher mileage and consumption of the vehicles for which hydrogen is best suited.

Hydrogen applications for **material handling** have experienced the largest uptake so far. Fuel-cell-powered forklifts, in particular, outperform battery-powered alternatives in a TCO comparison where high uptime is needed. More than 15,000 fuel cell forklifts (such as by the producers Plug Power and Toyota) are operational in global warehouses today, with major projects in Amazon and Walmart warehouses in the US.[21] Many other captive fleets that are otherwise challenging to decarbonize – such as airport ground operations, logistics, mining, and construction – could benefit from fuel cell applications.

More than 15,000 fuel cell forklifts are operational in global warehouses today

Hydrogen-powered trains are an attractive alternative to diesel trains, in particular on nonelectrified railways – where roughly 70% of the world's 200,000 locomotives operate today – and in the markets of Europe and the US (together about 55,000 diesel locomotives today). Besides avoiding carbon emissions, hydrogen trains reduce noise and eliminate local emissions such as particulates. Since they use significant amounts of hydrogen, the required infrastructure is limited and can be immediately utilized. Hydrogen-powered trains are already being introduced for light-rail vehicles and regional railways – such as the trams produced by the China South Rail

20 Mao, 2017

21 Argonne National Laboratory, 2017

Corporation/Sifang, which are being deployed in several Chinese cities. Other models, including regional trains by Alstom, are expected to be deployed in the coming years. By 2030, one in ten trains sold for currently nonelectrified railways could be powered by hydrogen; by 2050, one in five trains running on nonelectrified railways or one in ten trains overall could run on fuel cells.

> By 2030, one in ten trains sold for currently non-electrified railways could be powered by hydrogen

For water transport, fuel cells are most relevant for **passenger ships** such as river boats, ferries, and cruise ships. Passengers, in particular those using boats for recreation and tourism, will value lower local emissions, less noise, and less water pollution. River, lake, and port authorities will easily ban such emissions once viable alternatives are available. Besides propulsion, fuel cells can provide auxiliary power on ships, replacing diesel-based units. Prototypes for fuel-cell-powered passenger ships are already in operation, including the "MS Innogy" in Germany or the "Energy Observer" under the French flag. In Norway, Viking Cruises is planning to build the world's first cruise ships powered by liquid hydrogen and fuel cells.

In freight shipping and aviation, hydrogen could play a role as feedstock for synthetic fuel. Ultimately, these fuels mimic the properties of conventional fossil fuels and are burned in combustion engines. Those synfuels that use CO_2 and hydrogen form a closed carbon cycle and are hence a route to decarbonize combustion engines. Since the efficiency losses in the process make synfuels less attractive than other applications of hydrogen, they are likely to be deployed only towards 2050.

Progress is under way in some of the world's biggest markets

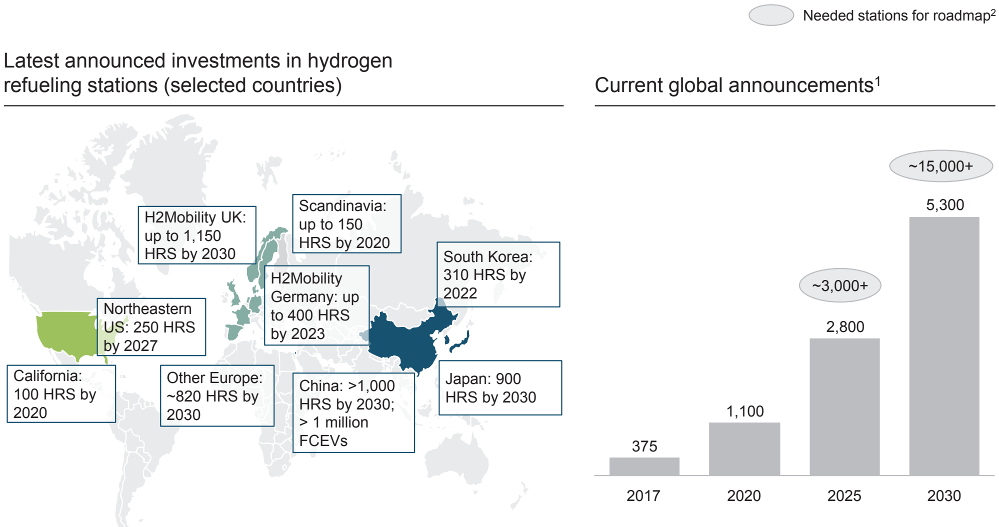
The deployment of transport solutions has begun around the world, with Japan, South Korea, California, and Germany leading the way. Activities in other European countries, in the Northeast US, and in China are also under way. Japan has set itself the target of having 40,000 FCEVs on the road by 2020 and 800,000 by 2030; China plans 1 million FCEVs by 2030 and is already investing in growing its manufacturing capabilities.[22]

Large-scale deployment of hydrogen transport solutions would require major investments in hydrogen infrastructure. Serving a fleet of 10 to 15 million FCEVs, for example, would require the equivalent of roughly 15,000 large filling stations[23] by 2030. Developing and building this refueling infrastructure could cost roughly $20 billion – about $1.25 to 1.5 million per large station. These costs are significantly lower than current costs in many countries: in Germany, an average small to medium-sized station costs around €1 million ($1.2 million); in Japan, the costs are three to five times higher due to regulatory requirements and geographical and geological conditions. The cost reduction underlying our estimate is driven by three factors related to the manufacturing scale-up: technological and operational improvements, increasing station sizes, standardization, and rationalized regulatory requirements.

22 Mao, 2017

23 1,000 kg daily capacity

Exhibit 14: More than 5,000 hydrogen refueling stations have been announced



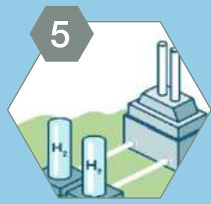
1 Announcements for shaded countries/regions: California, Northeastern US, Germany, Denmark, France, Netherlands, Norway, Spain, Sweden, UK; Dubai; China, Japan, South Korea
2 Equivalent number of large stations (1,000 kg daily capacity)

SOURCE: Air Liquide; Honda; Hydrogen Mobility Europe; H2Mobility; E4tech; NREL; web search

Overall, these stations would sell about 12,000 tons of hydrogen per day; more than 4 million tons of hydrogen per year in 2030. This hydrogen could be sourced from a central production site using distribution trucks or pipelines, or be produced on-site (e.g., through smaller local electrolyzers). Building this production capacity would entail investments of $10 to 12 billion. Some countries have already set targets for hydrogen refueling stations (Exhibit 14) and a hydrogen supply chain, but a significant acceleration would be required to achieve the goals of our roadmap.

An important barrier to this infrastructure development is the synchronization of FCEVs ramp-up and infrastructure development. Investments in refueling stations pay off only if vehicle numbers grow, but developing, building, and marketing vehicles is viable only with an adequate refueling infrastructure. No single fuel retailer has an incentive to be the first mover, and neither does a car manufacturer. The need for “synchronization” is obvious.

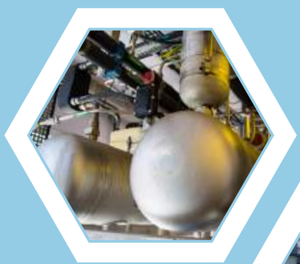
Governments can catalyze this synchronization by providing clarity and certainty on the policy and regulatory framework, and initiate structures for industry-government cooperation. In Germany, the H2 Mobility initiative is funded by car manufacturers, gas companies, and fuel retailers and enjoys government support. It has committed to building 100 stations by the end of 2019, independent of the number of FCEVs sold in the country. After this initial phase, it aims to build another 300 stations to provide full coverage of the country, contingent on FCEV sales. The joint venture, which builds and operates the stations, has achieved significant capital and operational cost reductions. Similar initiatives exist in the UK (H2 Mobility UK), South Korea (H2Korea), California (California Fuel Cell Partnership), Scandinavia (Scandinavia Hydrogen Highway Partnership), and Japan. Chapter 3 describes how such a coordinated rollout of stations and vehicles could be scaled.



Industry energy.

Hydrogen can provide decarbonized high heat for industrial processes.

- Clean or green hydrogen can be used as alternative to post-combustion carbon capture and storage
- Hydrogen is the main option for decarbonization of industrial processes requiring high heat and/or combustion



2030 milestones

- One in ten steel and chemical plants in Europe, North America, and Japan uses hydrogen for low-carbon production
- 4 million tons (0.6 EJ) additional hydrogen used

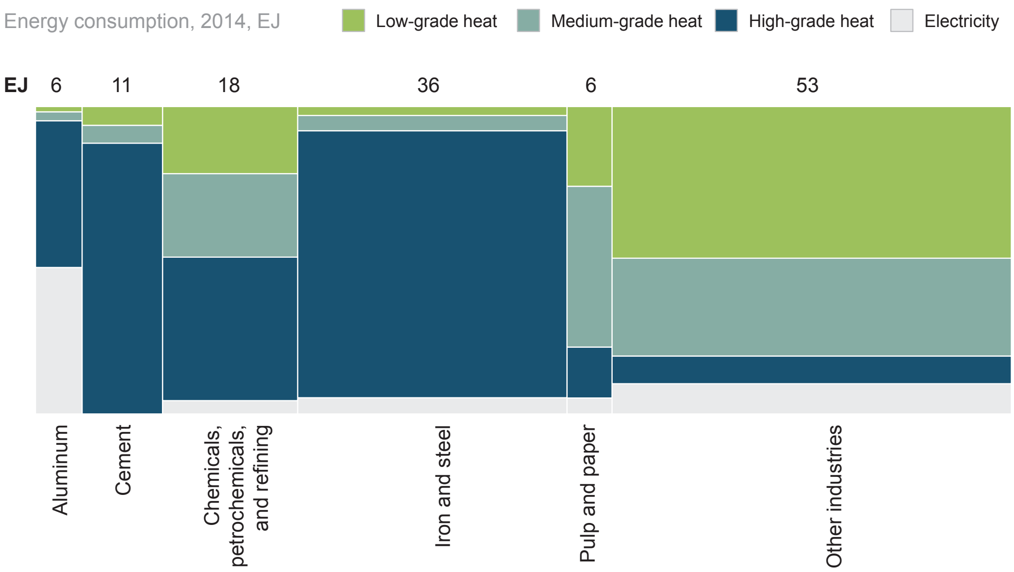
2050 target picture

- 12% of global industry energy demand (16 EJ) met with hydrogen – 23% of high-grade, 8% of medium-grade, and 4% of low-grade heat and power
- ~1 Gt CO_2 abated per year

Decarbonizing industry is a global necessity

After the power sector, industry is the biggest consumer of energy: it accounts for a third of final energy consumption and a quarter of CO_2 emissions. Two-thirds of all energy is consumed by only five industries: aluminum, chemicals, petrochemicals, and refining; cement; iron and steel; and pulp and paper, all of which require large quantities of energy to run equipment such as boilers, steam generators, and furnaces (Exhibit 15).

Exhibit 15: High-grade heat constitutes a large share of energy use in heavy industry



SOURCE: IEA; Hydrogen Council

Fueled by economic growth, particularly in South- and Southeast Asia, the final energy consumption of global industry is expected to increase by 10% by 2050. At the same time, the two-degree scenario calls for CO_2 emission reductions of 30% in this sector: 2.5 Gt less compared to today's levels, or 4.6 Gt less compared to the reference scenario that the IEA predicts based on current trajectories.

Industry can reach this decarbonization goal using three levers:

- Improving energy efficiency by deploying best available technologies and production processes and recycling materials
- Switching from fossil fuels to bio-based fuels, renewable electricity, and/or hydrogen
- CCU/CCS.

The first lever, improving efficiency by deploying the best available technologies, could achieve roughly half of the cumulative emission reduction target for the two-degree scenario. For instance, average emissions in the iron and steel industry range from 1.3 tons CO_2 per ton of steel produced in Brazil to 3.8 in India. By boosting efficiency using existing tools, such as better furnace technology and heat and energy recovery, steel producers in India could reduce emissions by 40%.[24]

Yet advances in efficiency, while vital, will not be enough to reach targets. This is in part because much of the momentum to reduce emissions comes from countries that already use highly efficient processes. Switching to electricity and/or hydrogen will therefore be necessary to achieve a deep decarbonization in industry, complemented by capturing and storing or using carbon emissions through CCS and CCU.

How hydrogen can reduce emissions in industry

In many energy-intensive industries using high-grade heat, hydrogen could be a more feasible or efficient route to decarbonization than electrification. Certain processes require combustion-based heaters, in which solids, liquids, or gases are burned as the heat is transferred to the material. Blast furnaces for iron making are a good example: the coke used in these furnaces not only creates heat needed to melt iron, but enables the chemical reaction between the carbon electrodes in the coke and the oxygen in the iron ore that is necessary to reduce the ore to iron. While it is possible to enhance the heat of the blast furnace with other combustible fuels (such as natural gas or hydrogen), it is therefore not possible to substitute the blast furnace with an electric furnace.

> Adopting hydrogen could help a wide range of industries make progress toward national and global CO_2 reduction targets

Clean or green hydrogen can create high temperatures while producing little or no CO_2. Equipment can be retrofitted to run on hydrogen or a combination of hydrogen and other combustible fuels. In the steel industry, as in the chemicals industry, hydrogen is already used to produce heat and power, as in the heat treatment of steel billets. Research shows that much larger shares of hydrogen-rich off-gases could be captured and used to generate power or enhance production elsewhere in the plant – either as fuel for the blast furnace[25] or as a reducing agent in direct reduction iron-making processes (see chapter “Industry feedstock” on these uses for hydrogen). A similar intensification of hydrogen use could also support decarbonization in other industries, notably in chemicals and petrochemicals (where by-product hydrogen is also produced and could be used to retrofit equipment such as ethylene crackers), in aluminum recycling (where gas-fired furnaces could be retrofitted to run on hydrogen), in cement production (where hydrogen could be combined with waste-derived fuels), and in the pulp and paper industry (where hydrogen could provide the high-purity flame needed to flash-dry paper).

For medium- and low-grade heat, from under 100 to 400 degrees, hydrogen could complement electrification and heat pumps. Hybrid boilers, which switch between electricity and hydrogen,

24 IPCC, 2007

25 Nogami, Kashiwaya, and Yamada, 2012

could allow factories to exploit price or supply differences. Hydrogen-based cogeneration units allow to heat and power factories with a low carbon footprint. This is particularly relevant when hydrogen is readily available because it is used as an input into an industrial process and wherever it is produced as by-product.

Adopting hydrogen could help a wide range of industries make progress toward national and global CO_2 reduction targets. By 2030, first large-scale projects could pioneer the use of hydrogen in industry, accounting for a total of 4 Mt in our roadmap. This would abate the rough CO_2 equivalent of more than 10 million diesel cars, but still constitute less than 0.5% of the sector's final energy demand. By 2050, hydrogen could meet about 12% of final industrial energy demand (16 EJ), providing up to 23% of high-grade heat, 8% of medium-grade heat, and 4% of low-grade heat.

Investments and activities

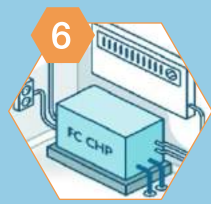
Given the cost sensitivity and long equipment lifetimes in energy-intensive industries, their uptake of hydrogen may be slower than in other sectors. Since retrofitting of existing equipment to burn hydrogen is inexpensive compared to new (electrical) equipment, the main barrier to the uptake of hydrogen is the comparatively high cost of hydrogen production itself.[26]

But pioneering projects are under way now to demonstrate the value of hydrogen in generating heat and power.

As part of the STEPWISE project – cofunded with a $15 million grant from the EU Horizon 2020 program – a steel plant in Luleå, Sweden, is converting blast furnace gases from the iron-making process into CO_2 on the one hand and a hydrogen-nitrogen mixture on the other. The project demonstrates the feasibility of storing the CO_2 and using the hydrogen-rich gas to generate power in a combined cycle turbine or enhance steel production elsewhere in the plant. The project, led by Swerea MEFOS and ECN since mid-2015, will run for four years with the help of nine industrial and scientific partners. It aims to decrease carbon emissions from about 2 tons of CO_2 per ton of steel to less than 0.5 tons. The demonstration plant currently captures and removes 5,000 tons of CO_2 each year, offsetting the emissions of about 2,500 cars.

In Japan, Toyota has challenged itself to eliminate all CO_2 emissions from manufacturing by 2050 – the "Plant Zero CO_2 Emissions Challenge." Hydrogen energy is a central pillar in this strategy, along with the use of renewable electricity and improvements in energy efficiency.

26 Mathieu and Bolland, 2013



Building heat and power.

Hydrogen can help decarbonize building heat and power.

- Hydrogen is a cost-effective option for decarbonization of building heat and power in regions with existing natural gas networks.
- It can be blended in concentrations of up to 20% with natural gas, converted to synthetic natural gas, or replace natural gas all together in 100% hydrogen networks.

2030 milestones

- The equivalent of 6.5 million households heated with blended or pure hydrogen using about 3.5 million tons (0.5 EJ) of hydrogen
- 10% of users connected to the hydrogen-natural gas grid using fuel cell combined heat and power units (micro-CHPs)

2050 target picture

- 8% of global building energy use for heat and power (11 EJ) provided by hydrogen
- About 700 Mt CO_2 abated per year

Decarbonizing buildings requires fuel switching alongside efficiency gains

Buildings, both residential and commercial, require almost as much energy for heating and power as the industry sector and more than the transport sector. About 60% of household energy is used to heat living spaces, water, and food; the balance is used for power, including lighting, appliances, and space cooling.

Emissions from building power uses will decrease as the renewables' share in the electricity mix increases. Most heat, however, is generated by fossil fuels, particularly natural gas. Not surprisingly, the countries where heating demand is highest are those with cold winters, and most households there are connected to natural gas networks. Others rely on oil, coal, biomass, or electricity for heating.

Achieving the two-degrees scenario will require CO_2 emissions reductions of almost 50% by 2050. Making this advance will require two levers:

- Improving energy efficiency, primarily through better building insulation and more efficient appliances such as LED lighting, but also through more energy-efficient ways of heating with current fuels (e.g., gas-condensing boilers, gas-heat pumps, or CHP/cogeneration units that combine heat and power and increase efficiency by 30%)

- Switching to lower-carbon energy sources and carriers for heating, such as recovered waste heat, bio-based fuels, renewable electricity, or clean hydrogen.

Hydrogen can make use of existing gas networks to decarbonize buildings

Communities have three main options to decarbonize building heating: waste-heat recovery (e.g., in district heating networks where sustainable sources of waste heat are available), electrification (e.g., installing electrical heat pumps), or transitioning from natural gas to clean hydrogen. All options are needed to achieve deep emissions reductions.

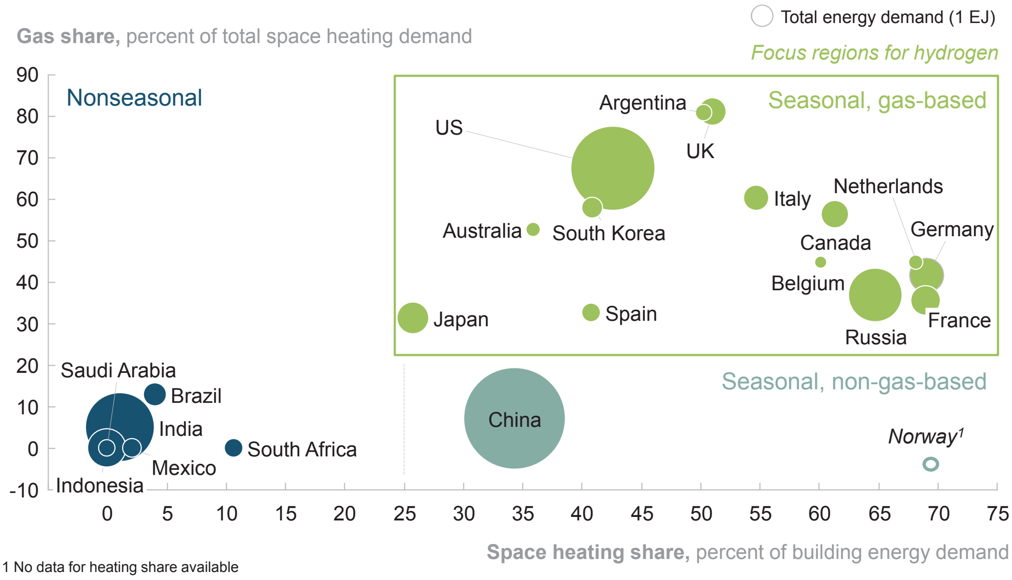
> Hydrogen can piggyback on existing natural gas infrastructure and equipment and can therefore be less expensive than other approaches

Hydrogen is most attractive in countries that already have an extensive natural gas infrastructure – generally those with cold winters such as the UK, the US, Canada, Argentina, the countries of continental Europe, and South Korea (Exhibit 16). Hydrogen offers three main advantages in these countries:

- It can piggyback on existing natural gas infrastructure and equipment. It can therefore be less expensive than other approaches, such as converting to electric heat pumps,[27] as investments to upgrade infrastructure or convert appliances are minor compared to a full switch from gas to electric heating (see below).

27 KPMG, 2016

Exhibit 16: Most countries with cold winters rely on natural gas for heating



1 No data for heating share available

SOURCE: Hydrogen Council; McKinsey Energy Insights

- Unlike electricity, hydrogen is easy to store for long periods. This is relevant as heating demand is highly seasonal. A large share of electrical heating would create a strong seasonal variation in demand for power, which would require extensive additional renewable capacity that will be used only in winter. With hydrogen, a lower amount of renewable capacity could produce and store hydrogen throughout the year. For example, peak heating demand in the UK is about six times higher than peak electricity demand (Exhibit 17). Today, the country meets about 80% of those peak demands with gas; full electrification would require a tripling of total electricity generation capacity – a politically and financially daunting prospect.[28]

- Third, converting to hydrogen heating may be more convenient than full electrification. No extra space or rewiring is needed to install new heating equipment, and no adjustments to heating patterns need to be made. This is in contrast to the installation of air-sourced electric heat pumps, which require space – often not available in densely populated urban areas – and offer no on-demand heat or hot water.

Hydrogen can be used to decarbonize the natural gas grid in three ways: it can be blended with natural gas, methanized, or used in its pure form.

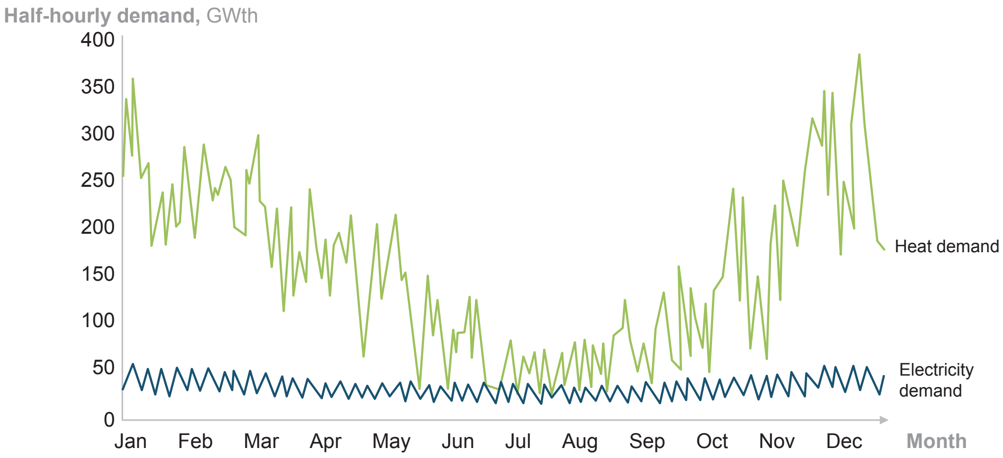
Low percentages of hydrogen can be safely blended into existing gas networks without major adaptations to infrastructure or appliances. Depending on the pipeline network system and the local natural gas composition, hydrogen can make up 5 to 20% of the volume content of natural gas supply.[29] Blending hydrogen is actually an old, safe, and proven technology: from

28 Howard and Bengherbi, 2016; Sansom, 2014

29 National Renewable Energy Laboratory, 2013

Exhibit 17: Hydrogen can be stored, balancing seasonal demand variations

Synthesized half-hourly heat and electricity demand, 2010, UK



SOURCE: Reproduced from Sansom (2014)

the mid-1800s to the 1950s in the US and the 1970s in the UK and Australia, manufactured gas or "town" gas was used in what is today the natural gas network. It contained 30 to 60% hydrogen, generally produced from coal or oil. Hydrogen blends are still common in Hawaii, Singapore, and some other areas with limited natural gas resources.

> Hydrogen can make up 5 to 20% of the volume content of natural gas supply without any infrastructure modifications

Hydrogen can also be converted into methane through a process called methanation. This requires a CO_2 source and energy for the conversion, leading to a lower efficiency of about 20% compared to direct blending and creating additional costs. The advantage is that the resulting substitute or SNG is pure methane and hence fully compatible with the existing natural gas networks and storage infrastructure as well as all appliances.[30]

Pure hydrogen networks are possible if infrastructure and appliances are upgraded accordingly. Leakage control needs to be improved, and any remaining steel pipelines need to be retrofitted or replaced with noncorrosive and nonpermeable materials, such as polyethylene or fiber-reinforced polymers. In some countries, however, old pipelines are being replaced independently of a hydrogen transition, which limits the need for additional investment. Appliances, including ovens and stoves, boilers and hot water tanks, would need to be converted or replaced. Costs in a reference project in Leeds have been estimated at £3,100 ($4,160) per household for appliance conversion. Still, this may be less expensive than electrification, which requires

30 The methanation process entails an energy conversion loss of about 20% from hydrogen, reducing the process efficiency from 70 to 80% (electricity to hydrogen) to 55 to 65% (electricity to hydrogen to methane). (Schaaf, Grünig, Schuster, Rotenfluh, and Orth, 2014); (Götz, et al., 2016); (E&E Consultant, Hespul and Solagro, 2014)

new power generation and transmission infrastructure and the installation of new electric heat pumps.[31] With scale, costs of appliances are expected to decrease further.

If hydrogen is used in micro-CHP units rather than burners, it can create power alongside heat with a total efficiency of more than 90% and an electrical efficiency of about 40 to 45%. This further improves the efficiency of hydrogen use for heating and power by 30% over conventional gas boilers. CHP units can be deployed in family homes, in residential or commercial building blocks, or centrally in district heating networks.

In our vision, hydrogen could meet up to 18% of heat-related energy demand in colder climates using existing gas networks. Globally, this means that hydrogen could provide 10% of building heat and 8% of building energy by 2050. By 2030, the hydrogen share in building heating could be about 1% in priority countries but less than 0.5% of total building energy demand globally.

Investments and activities

Until 2030, hydrogen use in heating is likely to be driven by blending with or without methanation, as this requires little or no investment in infrastructure or appliance conversion. In our roadmap, about 50 million households could consume hydrogen that is blended into the natural gas grid. In addition to hydrogen blending, pure hydrogen could heat and power about 1.5 million households globally. Together, this would require about 3.5 million tons of hydrogen production capacity. Based on a balanced production mix, this is roughly equivalent to cumulative investments of $10 billion for hydrogen production, $3 billion for infrastructure upgrades, and $1.5 billion for the development of boilers and CHP units until 2030.

Hydrogen blending and methanation initiatives are under way to demonstrate the large-scale feasibility of hydrogen in buildings. In France, for example, a project called “Network Management by Injecting Hydrogen to Reduce Energy Carbon Content” (GRHYD is the French acronym) is preparing to blend up to 20% hydrogen into the local natural gas grid. In Germany, Italy, and Switzerland, the “STORE&GO” project pilots large-scale efficient electrolysis and methanation using wind, solar power, and a combination of sources for CO_2 – including biomass, sewage gases, and ambient air – to produce SNG. Other, even larger electrolysis projects that are blending hydrogen into the natural gas grid are discussed in the chapter “Enabling a global renewable energy system.”

Although pure hydrogen networks are likely to be rolled out later, pilot cities could transition to hydrogen by 2030. Among the first communities converted to hydrogen is the industrial city of Ulsan in South Korea, where 130 households were connected to CHP units running on purified by-product hydrogen from nearby petrochemical companies.

The “H21 Leeds City Gate” project in the UK is a substantially larger initiative to decarbonize the heating system within a long-term vision. The city of 750,000 inhabitants is assessing

31 KPMG estimates the household adaption costs of full electrification at £10,000 to 12,000 per property for air source heat pumps and other equipment (such as hot water tanks). This compares to appliance change costs for hydrogen conversion at £4,500 to 5,500 per property (KPMG, 2016).

The “H21 Leeds City Gate” project in the UK is planning to progressively convert all households to 100% hydrogen before 2030

the technical feasibility and preparing the regulatory and financial framework to progressively convert all households to 100% hydrogen between 2026 and 2029. The project will replace natural gas with hydrogen from four steam methane reformers with a capacity of 1 GW, or about 150,000 tons of hydrogen per year, equipped with 90% carbon capture. The produced hydrogen, about 70 GWh will be stored in salt caverns and fed into the existing gas distribution network through a hydrogen transmission system. The city will be converted in waves of about 2,500 homes, disconnected for about five days during the summer months before being fully on the hydrogen network. Beyond the Leeds transition, Northern Gas Networks is currently assessing scenarios in which ten times the equivalent of Leeds are converted between 2025 and 2035, and 50 times the equivalent of Leeds are converted between 2025 and 2045. This experience could provide a “blueprint” for a rollout in other countries and regions.

Industry feedstock.

Hydrogen as feedstock can be decarbonized and used to replace fossil feedstock.

- 55 million tons of hydrogen are currently used as feedstock for refining, fertilizer, and chemical production – these can be decarbonized through clean production pathways.
- Other industries, such as methanol and iron production, can replace fossil feedstock with clean hydrogen and carbon.

2030 milestones

- Steel plants pioneering zero-carbon iron making using hydrogen reduction (using about 100,000 tons hydrogen)
- 10 to 15 million tons of methanol and derivatives, such as olefins and aromatics, produced from clean hydrogen and carbon (using about 2.5 million tons hydrogen)
- Demonstration of clean hydrogen use in chemicals and refining industries

2050 target picture

- 10% of crude steel production, about 200 million tons, based on hydrogen, saving 190 million tons of CO_2 per year
- 30% of methanol and ethanol derivatives produced through hydrogen and carbon, recycling 360 million tons of CO_2 per year
- Existing feedstock uses for chemicals and refining industry decarbonized, saving 440 million tons of CO_2 per year

Demand for hydrogen as feedstock is rising

Chemical and petrochemical industries use about 25 EJ worth of fossil fuels as feedstock each year – and about 8 EJ of hydrogen; most of which is produced from natural gas, oil, or coal. Almost all the hydrogen is used in refineries and in the production of fertilizers and other chemicals (Exhibit 18). The total amount of hydrogen produced each year is enough to power more than 100 million FCEVs and creates some 350 to 400 Mt of CO_2 per year.[32]

> This year, industry will use about 55 million tons of hydrogen as feedstock – enough to power more than 100 million FCEVs

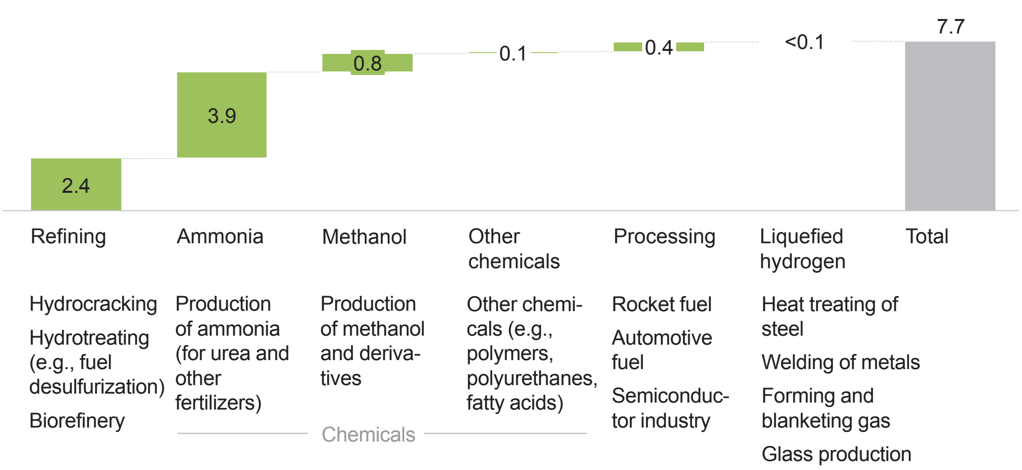
As industry production rises globally, the demand for feedstock is likely to increase. By 2050, the demand for hydrogen could rise to 70 million tons (10 EJ) in current applications alone, driven by the growth in global chemicals production. If this hydrogen is produced from nonclean sources, it would create emissions of about 500 Mt of CO_2.

At the same time as global industry needs to decarbonize its feedstock, it also needs to capture its emissions to reach ambitious climate targets. In the IEA two-degree scenario, carbon capture technology is expected to increase rapidly to meet the ambitious targets: by 2030, 0.5 Gt of CO_2 should be captured in the industry sector each year; by 2050, this number should rise to 1.4 Gt. Lacking a useful purpose, the captured CO_2 would need to be stored permanently underground. Assuming very conservative costs of $40 per ton, the annual costs of capturing and storing CO_2 might amount to more than $55 billion by 2050.

32 Based on estimates of current average emission intensities (US Environmental Protection Agency, 2008)

Exhibit 18: Industry uses about 7.7 EJ of hydrogen annually

Total hydrogen use, 2015 estimate, EJ



SOURCE: IEA Energy Technology Roadmap Hydrogen and Fuel Cells; IEA ETP 2017; expert interviews; Hydrogen Council

Industry feedstock can be decarbonized using more and cleaner hydrogen

Hydrogen can contribute to decarbonizing feedstock in two ways:

- Hydrogen used as feedstock can be decarbonized by producing it from clean sources, such as natural gas with CCS or through electrolysis from renewable electricity.

- Clean hydrogen could replace other fossil fuels as feedstock. Notably, it could replace carbon (from natural gas or coal) as a reducing agent in the iron-making process, and it could be used together with captured CO_2 (or CO_2 from biomass) to replace fossil feedstock in the production of hydrocarbon-based chemicals such as methanol and derived products.

Industries using hydrogen as feedstock include the refining industry as well as in the production of fertilizers (based on ammonia) and chemicals (based on methanol). Together, the use of hydrogen in conventional processes and industries could increase from 8 EJ to more than 10 EJ in 2030 and 2050. Hydrogen demand in these industries will be shaped by different trends:

- Oil refineries use hydrogen to lower the sulfur content of fuels. Due to stricter desulfurization requirements around the world, hydrogen use is expected to increase until around 2030, when the increasing electrification of the transport sector starts to reduce overall demand.

- In the fertilizer and chemicals industries, where hydrogen is used to react nitrogen into ammonia or to convert methane and water to methanol, the demand for hydrogen is likely to grow continuously in line with the overall demand for ammonia and methanol projected in the two-degree scenario.

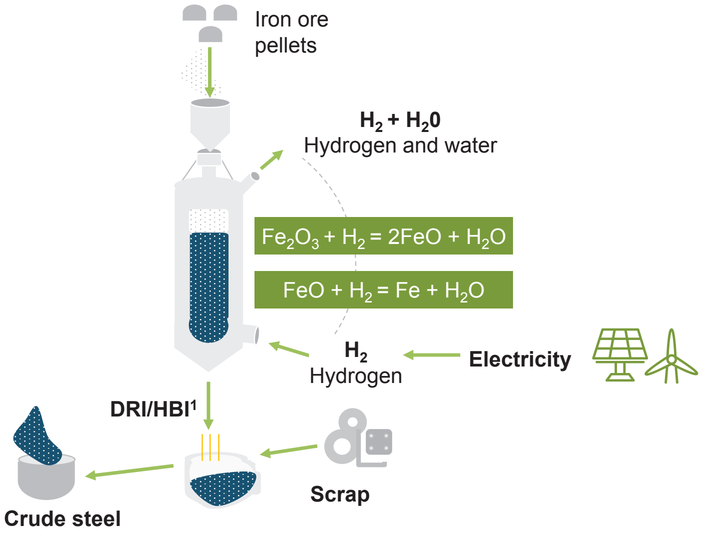
The production of this feedstock could be decarbonized. Almost all the hydrogen used as industry feedstock is currently produced on-site in dedicated plants or as a by-product from other processes (20 to 30%). If hydrogen production were to be largely decarbonized (through carbon capture or electrolysis as well as through the increased use of by-product hydrogen), this could reduce annual CO_2 emissions by as much as 440 million tons in 2050.

In steel production, hydrogen can substitute for carbon as a reductant. About 4% of global crude steel is produced through the DRI process (Exhibit 19). More energy efficient than the traditional blast furnace route, this process is growing much faster than overall steel production. By 2050, about 10% of crude steel could be produced through DRI.

DRI making currently relies mainly on natural gas as reducing agent. If it was replaced with clean or green hydrogen, this could reduce emissions by up to 190 million tons of CO_2 annually. About 15 million tons of hydrogen (2 EJ) would be needed to produce 200 million tons of steel through this route.

Hydrogen can be used to convert captured CO_2 to chemicals. Carbon capture is considered an important contributor to reaching the two-degree scenario by the IEA. While CCS has raised questions about risks and costs, CCU offers the potential of converting CO_2

Exhibit 19: Hydrogen-based reduction allows emission-free ironmaking



1 Direct reduced iron/hot briquetted iron

SOURCE: LKAB: HYBRIT – Iron Ore to Steel based on Hydrogen; Lulea, 2016

to high-value chemicals and could encourage the uptake of carbon capture technologies (Exhibit 20). The main barriers to broader CCU uptake today are the cost of carbon capture – about $100 per ton of CO_2 for small capture plants – as well as the cost of electrolysis.

As the costs of carbon capture and electrolysis decrease with scale and technology breakthroughs (to $40 per ton of CO_2 captured[33]), the industry could gain momentum. By 2050, 30% of methanol, olefins, and aromatics could be produced using captured carbon and hydrogen from electrolysis. This would require about 50 million tons of hydrogen (7 EJ) and would allow industry to recycle 360 million tons of CO_2 into some 260 million tons of product in 2050. This compares to CO_2 sequestration needs of 5.4 Gt CO_2 in the two-degree scenario of the IEA in 2050. As an alternative, the same amount of CO_2 could be sourced from biomass.

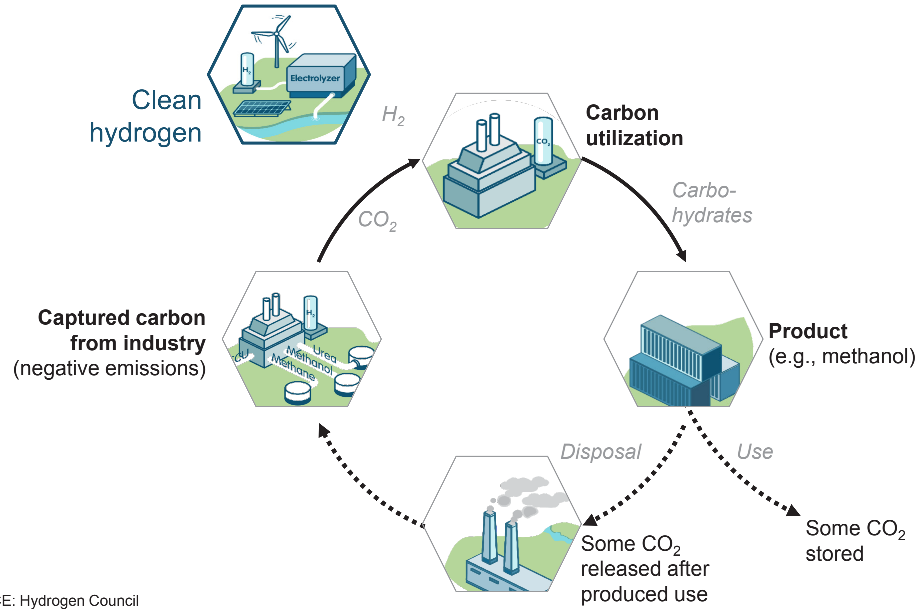
By 2030, the share could amount to some 2% (roughly 0.5 EJ of hydrogen and 20 million tons of CO_2) and constitute some of the earliest applications for carbon capture.[34]

Overall, feedstock uses of hydrogen could grow from about 55 million tons (8 EJ) to 75 million tons (11 EJ) in 2030, and to 140 million tons (20 EJ) by 2050. As hydrogen use grows while its production is increasingly decarbonized, it could reduce CO_2 emissions by more than 700 Mt annually in 2050.

33 IEA, 2017

34 These estimates are based on the intermediate scenario presented by DECHEMA and the European Chemical Industry Council (DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V. , 2017).

Exhibit 20: Hydrogen enables the recycling of captured carbon to chemicals



SOURCE: Hydrogen Council

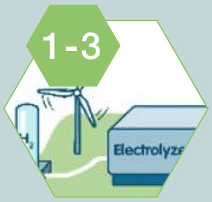
Investments and activities

We expect a range of efforts to demonstrate and commercialize the use of clean or green hydrogen in the industry to be well under way by 2030. Producing the amount of hydrogen foreseen in our roadmap and converting production equipment accordingly would require investments of some $50 billion over the next 12 years, the majority of which in existing industries.

Selected plants are already pioneering the use of clean or green hydrogen for existing feedstock applications. In the refining industry, Shell and ITM Power recently announced a plan to install a 10-MW electrolyzer at a Shell site in the Rheinland Refinery Complex in Germany. The scale is significant: once implemented, it would be the world's largest PEM electrolyzer and could contribute to reducing the upstream emissions at the site. In the iron and steel industry, a recently formed Swedish joint venture by SSAB, LKAB, and Vattenfall is demonstrating zero-carbon steelmaking using DRI with green hydrogen from electrolysis (project HYBRIT).

Current initiatives in new feedstock uses include Carbon Recycling International's George Olah plant in Iceland, which produces hydrogen from electrolysis and captures CO_2 from a geothermal power plant to produce about 4,000 tons of methanol per year and recycle about 5,500 tons of CO_2 in the process. Other initiatives are not yet commercialized, but may allow carbon capture at much larger scale once successfully demonstrated. In Germany, Carbon2Chem, a €160 million ($190 million) project financed by 16 industrial partners and the German government, is investigating advanced processes of converting process gases from steel production and hydrogen from surplus renewable electricity. Now operating at a ThyssenKrupp plant in Duisburg, the project is intended to reach industrial scale within ten years, with a process that has the potential to recycle 20 million tons of CO_2 emissions annually – or 10% of annual German industry-sector CO_2 emissions.

These large-scale projects will demonstrate the feasibility of clean hydrogen use in industry and will allow the more widespread adoption of low-carbon feedstock in the time horizon beyond 2030.



Energy system.

Hydrogen is a versatile energy carrier that can enable the renewable energy system.

- Hydrogen enables large-scale renewable integration through cost-effective long-term storage.
- It allows distribution of energy across sectors and regions.
- It acts as buffer to increase system resilience.
- It provides clean dispatchable power generation in peaker plants.

2030 milestones

- 250 to 300 TWh of excess solar and wind electricity converted to hydrogen
- More than 20 power plants generating 100 to 200 TWh of dispatchable power from clean hydrogen
- More than 10 ships transporting a total of about 100,000 tons hydrogen per year
- 200 TWh hydrogen stored in underground salt caverns

2050 target picture

- 500 TWh of excess solar and wind electricity converted to 1.5 EJ hydrogen
- 1,500 TWh of dispatchable power produced from 9 EJ clean hydrogen
- 55 million tons of hydrogen, or 8 EJ, transported/ shipped overseas
- 3,000 TWh of hydrogen, or 18 EJ (worth 55 days of wind, solar, and hydrogen demand) stored in strategic reserves

Hydrogen can help the world meet the challenges of the transition to a renewable energy system

Limiting global warming to two degrees Celsius will require a dramatic increase in the renewable electricity share, from 23% in 2015 to 68% in 2050 according to the IEA. This may seem daunting, but global advances of this magnitude are not unknown. Given the consequences of global warming, nearly every country has agreed to take major steps to increase their renewable electricity share.

Managing the complexity of this effort will present challenges, however. These include matching demand and supply as more power is generated from intermittent sources, transporting energy across sectors and regions, and buffering supplies with strategic reserves.

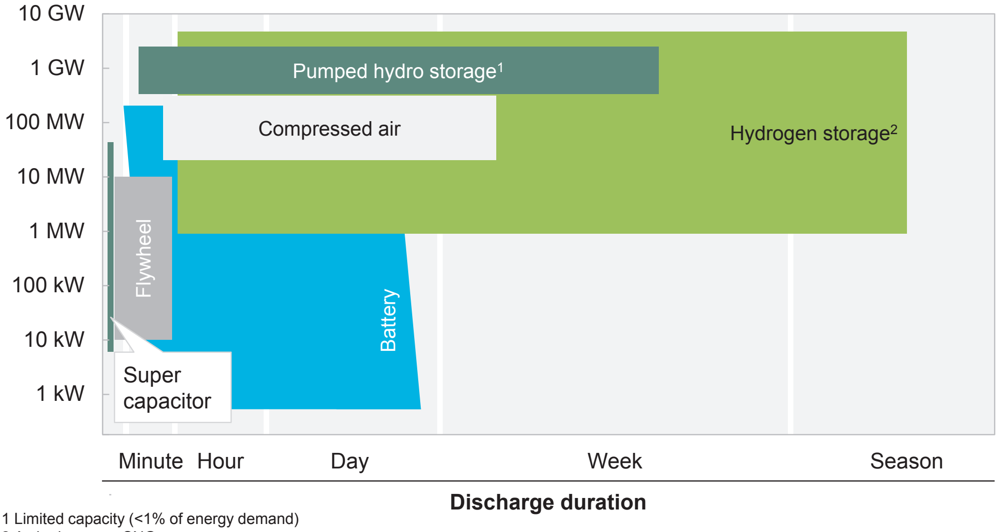
Hydrogen can contribute to this transition as an enabler in renewable power storage, distribution and buffering, as well as a complementary source of clean power generation.

Hydrogen enables large-scale renewables integration through cost-effective long-term storage

Hydrogen is exceptionally well suited to store large quantities of energy for long durations (Exhibit 21). At a large scale, hydrogen can be stored in underground salt caverns in pure or methanized form. Estimates put the cost at around $50 to 150 per MWh, which is significantly less than other storage technologies for electricity. Only pumped hydro storage is even more competitive, but its remaining untapped potential is subject to local geographic conditions.

Exhibit 21: Hydrogen can be stored for months without losing much of its power

Technology overview in power and time



1 Limited capacity (<1% of energy demand)
2 As hydrogen or SNG

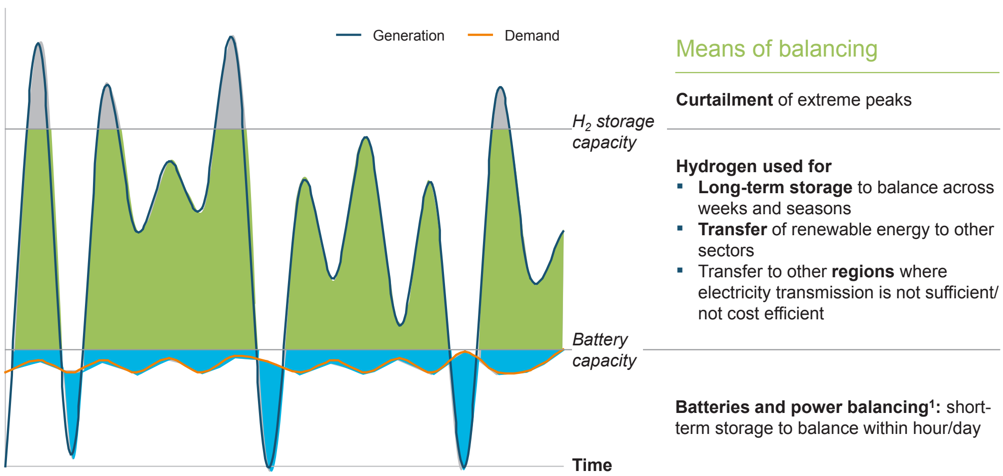
SOURCE: IEA Energy Technology Roadmap Hydrogen and Fuel Cells

Long-term energy storage is required for large-scale renewable power integration. First, most renewables have very low operating costs. This implies they have to be “always on” to be efficient, regardless of actual electricity demand. Europe, the US, and Australia already experience days during which electricity prices reach negative levels due to surplus wind or solar supply. In addition, production levels of renewables vary significantly between seasons. For example, solar generation in Europe is about 60% lower in winter than in summer, which coincides with higher electricity demand (about 40%) as days get colder and shorter. While short-term balancing is likely to employ technologies such as demand-side management and batteries, hydrogen could be used for longer-term storage (Exhibit 22).

Exhibit 22: Hydrogen storage bridges gaps in supply and demand

Electricity supply and demand, TWh

ILLUSTRATIVE



1 Demand-side load balancing, etc.

SOURCE: McKinsey

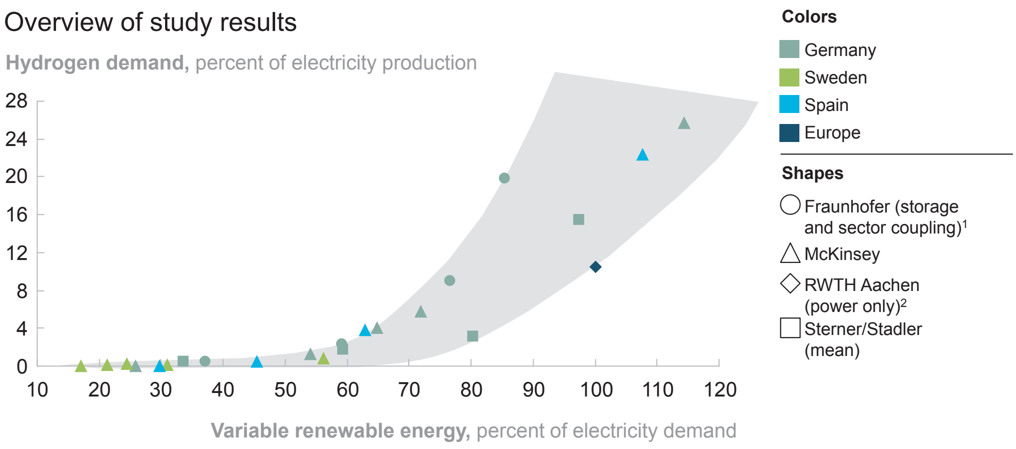
The amount of long-term storage required increases with the share of variable renewable energy. Multiple studies of energy systems show an exponential increase of demand for long-term storage, with a rapid increase at a share of 60 to 70% (Exhibit 23). If Germany, for example, builds an energy system with around 80 to 90% renewable electricity, around 15% of the total electricity generated would go into the production of hydrogen.[35] Without long-term storage, additional renewable capacity above a certain threshold would not be efficient to build, and other non-zero-emission technologies would be required (e.g., gas-based peaker plants). By providing seasonal storage, a higher share of renewables could become feasible.

When considering the renewable share as forecast by the IEA two-degree scenario, more than 500 TWh of electricity globally could be converted into roughly 1.5 EJ hydrogen each year by 2050.[36] This figure is significant by itself, but could be substantially higher if renewable penetration exceeds the forecasts of the IEA two-degree scenario or due to specific local

35 Fraunhofer ISE, 2015; Sterner und Stadler, 2014; McKinsey

36 At an electrolyzer efficiency of 75% (US Department of Energy – Fuel Cell Technologies Office, 2017)

Exhibit 23: The need for hydrogen storage increases exponentially with the variable renewable energy share



1 Least-cost modeling to achieve 2°C scenario in Germany in 2050 in hour-by-hour simulation of power generation and demand; assumptions: no regional distribution issues (would increase hydrogen pathway), no change in energy imports and exports
2 Simulation of storage requirements for 100% European RES; only power-sector storage considered (lower bound for hydrogen pathway)

SOURCE: Fraunhofer Institute for Solar Energy Systems ISE, 2017; BMW; RWTH Aachen; Sterner and Stadler (2014); McKinsey

conditions preventing adequate matching of supply and demand. Annual capacity additions of renewables have consistently outpaced analyst projections – as wind and solar prices hit record lows around the world, it is likely that capacity will grow at an even faster pace than in the past.

Hydrogen can provide clean dispatchable power

In addition to storing power during periods of peak renewable generation, hydrogen could be a source of clean power where there are insufficient renewables capacities or during times of peak demand. In Japan, South Korea, and Taiwan, for example, imported hydrogen could be used to generate clean power from imported hydrogen.

Hydrogen can also play a role in decarbonizing current power generation. Existing natural gas power plants can be retrofitted to burn hydrogen, which can be derived from, e.g., natural gas or biogas. This type of "pre-combustion CCS" is currently being deployed in a large-scale project in the Netherlands (see deployment projects). The carbon emissions impact from such plants is large: if retrofitted, the plant would reduce CO_2 emissions by 4 million tons per year, about equivalent to 1 to 2 million cars. Globally, our roadmap sees potential for 1,500 TWh of clean power from hydrogen, using about 9 EJ of hydrogen by 2050.[37]

Hydrogen allows distribution of energy across sectors and regions

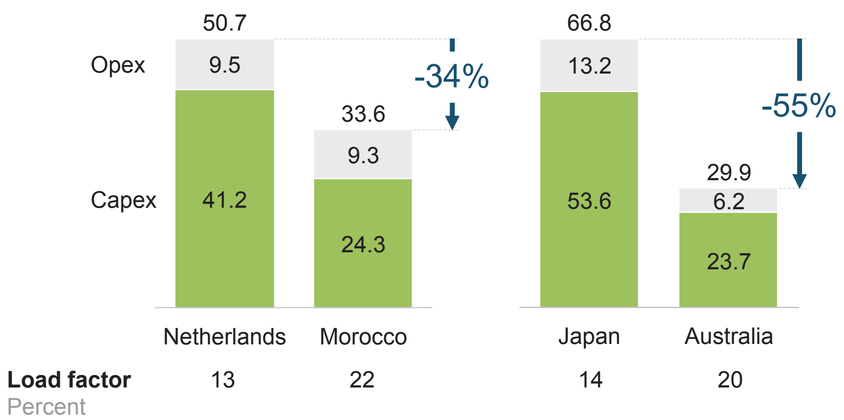
Hydrogen storage could clearly be used to decarbonize the power system, but also to distribute energy between sectors and regions. Major drivers of such energy transports

37 At a CCGT efficiency of 65%

are availability and cost. For renewables, regions with abundant wind and sunshine can achieve significantly lower costs of generation. For instance, the average cost of solar power is about 35% lower in Morocco than in the Netherlands, and about 55% lower in Australia than in Japan (Exhibit 24).

Exhibit 24: Solar has cost advantages in regions with more sunshine

LCOE of solar,[1] EUR/MWh, 2040



1 Morocco: EU capex, Middle East opex, Australia: India capex and opex

SOURCE: WOE; IEA; renewables.ninja

Hydrogen could be the energy carrier to realize this cost advantage. Sea delivery of liquefied hydrogen, ammonia, or liquid organic hydrogen carriers are cost-efficient delivery methods over long distances, despite energy losses of about 20 to 30% during liquefaction, transportation, and storage.[38] For distances above 3,500 to 4,500 km – such as from Australia to Japan – converting power to hydrogen and shipping it overseas can be less expensive than transmitting it through cables as electricity.

By 2050, we expect that about 10% of total annual hydrogen demand, or 8 EJ, could be transported by sea. This would require about 400 ocean-going vessels, a small fleet compared to roughly 4,000 large or very large oil and chemical tankers plying the seas today.[39]

Hydrogen can act as strategic reserve and buffer

The global energy system today has a buffer capacity of about 50 days of final demand to guarantee national and global energy security. This buffer absorbs supply chain shocks, provides strategic reserves at a country level, and helps countries manage supply and demand imbalances. It is held almost entirely in the form of fossil or nuclear energy carriers,

38 Cardalla, Decker, and Klein, 2017

39 Equasis: The world merchant fleet in 2014

such as strategic petroleum or gas reserves, which reflects their high share in final energy demand – in the power sector and in transport and heating.

Although the transition to a largely renewables-based energy system will decrease the reliance on fossil energy imports and reduce the risk of geopolitical shocks, the system may remain exposed to other shocks, including earthquakes and other major hazards that can affect domestic electricity generation capacity.

For the projected hydrogen demand of almost 80 EJ in 2050 and the projected power generation of about 16,700 TWh from variable renewable sources in the IEA two-degree scenario, a strategic reserve of about 18 EJ in 2050 would be adequate compared to current buffers. It would require an average annual buildup of 0.6 EJ starting in 2020.

A range of companies are investing into large-scale hydrogen projects in the energy system

Enabling the renewable energy system through hydrogen would require capital investments of about $20 billion in distribution infrastructure, including liquefaction plants and tankers, and $30 billion in storage capacity, such as salt caverns, until 2030 – in addition to any upstream investments for power generation or natural gas exploration and production. It would also imply sales on the order of $10 billion for power production equipment, including retrofitting gas turbines to run on hydrogen.

A range of companies are investing in hydrogen technology for renewable energy integration:

- In Germany, a consortium formed by Linde, Siemens, the RheinMain University of Applied Sciences, and the local utility Mainzer Stadtwerke in 2015, invested roughly $20 million to build and test a PEM electrolyzer with a peak performance of 6 MW (and a likely production rate of 1,500 kg hydrogen per day) – the world's largest to date. It converts surplus wind energy to hydrogen and injects it into the public natural gas grid. The "Energiepark Mainz" project is finishing the research phase and plans to start operating commercially. In France, a newly formed company (H2V Product) plans to raise and invest €3.5 billion ($4 billion) in annual production capacities which could produce 500,000 tons of hydrogen from renewable electricity every year and inject them in the natural gas network.

- In the Netherlands, Statoil, Vattenfall, and Gasunie signed a memorandum in 2017 to evaluate the conversion of Vattenfall's Magnum power plant to run on hydrogen. If implemented, the power plant with a capacity of 1,320 MW could reduce emissions by 4 million tons of CO_2 per year; equivalent to the emissions of more than two million cars. It could be rolled out for any number of gas power plants worldwide.

- In Japan, Kawasaki, Obayashi, Kansai, Iwatani, Kobe City, and Osaka University will demonstrate a 1,000-kW-class power plant that runs on a flexible blend of natural gas and hydrogen (from 0 to 100% hydrogen).[40] The project will begin operations in 2018 and

40 "Development of smart community technology by utilization of hydrogen CGS" (2016 to 2018)

be the first of a series of potential projects in Japan and overseas. At the same time, two groups of companies are investigating hydrogen imports to ensure a sustainable and affordable hydrogen supply to Japan. In 2016, Kawasaki, Iwatani, Shell Japan, and J-POWER formed the CO_2-free Hydrogen Energy Supply-Chain Technology Research Association (HySTRA), seeking to establish and demonstrate technologies necessary for the production, storage, and transport of hydrogen from Australia.[41] In parallel to this project, the companies Chiyoda, Mitsubishi, Mitsui & Co., and Nippon Yusen formed the Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD) initiative, which aims to demonstrate the supply chain of hydrogen from Brunei Darussalam and could commercially supply up to 210 tons of hydrogen to Japan in 2020.[42] These projects, all supported by Japan's New Energy and Industrial Technology Development Organization (NEDO), will initiate the formation of global hydrogen supply chains.

41 "Demonstration Project for Establishment of Mass Hydrogen Marine Transportation Supply Chain Derived from Unused Brown Coal" (2015 to 2020)

42 "Demonstration of the Hydrogen Supply Chain by Organic Chemical Hydride Method Utilizing Unused Energy" (2017 to 2020)

What needs to be done.

A call to action.

Making the two-degree scenario a reality will require hydrogen solutions across the whole energy system. The technology is proven, safe, and ready to be deployed at scale. The world can – and should, we believe – build on existing infrastructure and knowledge to expand hydrogen production, distribution, and use.

Momentum for hydrogen is building. About 20 countries – led by Japan, Korea, Germany, California, and China – are initiating the market scale-up through public-private partnerships and targeted incentives. To realize our ambitious vision, however, major step-ups are required by all stakeholders. This chapter describes the required investments until 2030 to double hydrogen production, provide distribution infrastructure, and produce equipment such as FCEVs, trains, heating equipment, and components at decreasing costs.

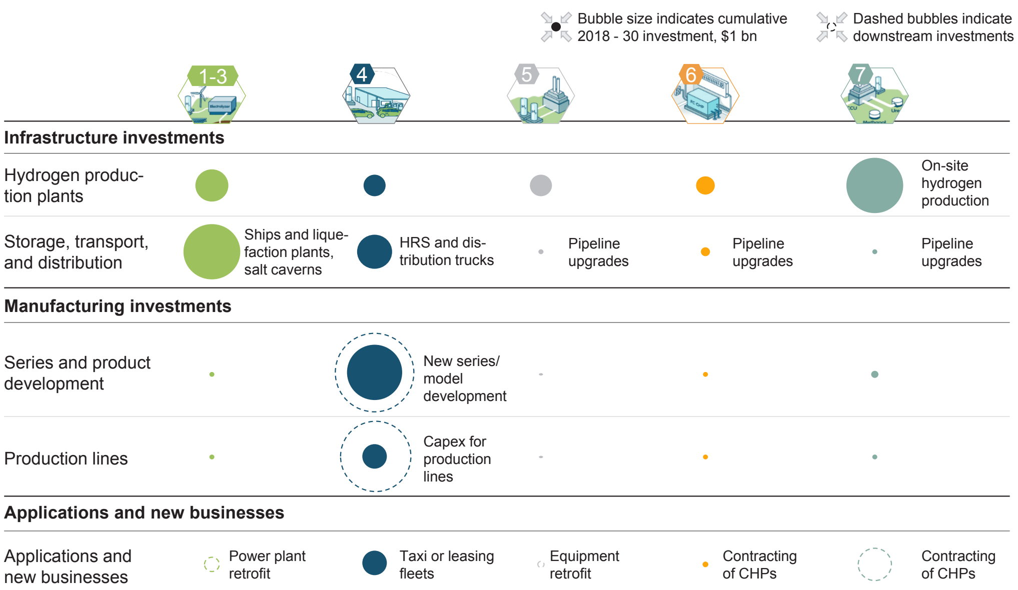
To kick-start the roadmap, we then set out proposals for deployment initiatives. These describe how regulators, investors, and industry could work together to deliver this roadmap, which type of support is required, and where such projects are being successfully implemented. We invite all stakeholders to join us to deliver them.

Building the hydrogen economy would require annual investments of about $20 to 25 billion for a total of about $280 billion until 2030

Building the hydrogen economy described in this report represents total investments of $280 billion until 2030 along the whole value chain for hydrogen – from production over distribution to retail – and in the industries delivering the equipment for end-use applications: car manufacturers, producers of heating equipment, component manufacturers, and other applications (Exhibit 25).

A significant share of this investment is required for hydrogen production equipment: adding production capacities for an additional 6 EJ of hydrogen by 2030 would require about $110 billion. To achieve the scale-up and meet demand with a low carbon footprint, a range of production technologies (SMR, electrolysis), feedstocks (natural gas, biogas, power), and sizes of plants (large centralized, medium-sized, small decentralized) is likely to be used.

Exhibit 25: Building the hydrogen economy will require a step-up across the value chain



SOURCE: Hydrogen Council

The infrastructure to store, transport, and distribute hydrogen could require investments of about $80 billion. Of this, about $20 billion would flow into the buildup of the hydrogen refueling network including the distribution and retail infrastructure. By 2030, the costs of additional hydrogen refueling stations is expected to have decreased to less than $1,000/FCEV. The biggest hurdle to this investment is the classic chicken-and-egg problem – customers will not choose FCEVs until hydrogen is readily available while investors may not want to build the storage and distribution capacity until sufficient FCEVs are on the road. This infrastructure challenge is best addressed through cooperative approaches such as industry joint ventures and public-private partnerships, and risk-mitigating financial instruments (see section on delivery initiatives).

A quarter of all investments described in this report (around $70 billion) is required for product and series development and to scale up manufacturing capacity. This figure counts only investments related closely to the hydrogen and fuel cell technology – not the development and production of associated product components (e.g., the body and interior of the FCEV). Counting these investments would add another $150 billion to the investment volume.

The majority of these investments need to flow into the automotive industry and component suppliers. The investment for the development and production of fuel cell powertrains could amount to $6 billion per year, which is only around 2% of total capital investments of OEMs and suppliers ($310 billion in 2015). Counting the development and production of the entire vehicles based on fuel cell powertrains would bring this sum to $15 to 20 billion or around 5% of annual automotive investments.

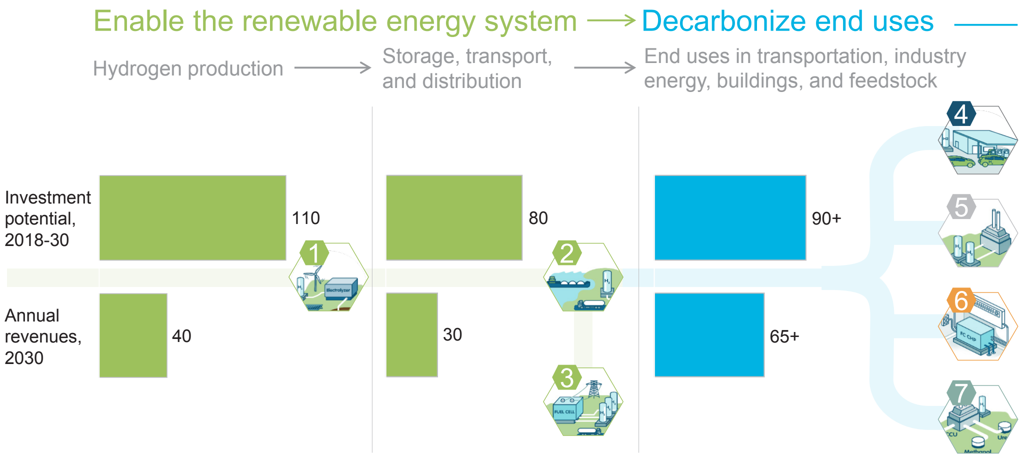
On top of the described investments into infrastructure for hydrogen and manufacturing of hydrogen equipment, a number of new business opportunities are expected around the end uses of hydrogen. These could include fuel-cell-powered taxi fleets and carsharing, on-demand transportation of goods, and contracting of CHP units, and could represent investments in the order of $20 billion per year.

While $20 to 25 billion would be a major step-up in annual investments for the hydrogen industry, the world already invests more than $1.7 trillion in energy each year

While $20 to 25 billion would be a major step-up in annual investments for the hydrogen industry, the world already invests more than $1.7 trillion in energy each year, including $650 billion in oil and gas, $300 billion in renewable electricity, and more than $300 billion in the automotive industry. By 2030, the investments in hydrogen could create an industry with annual revenues of up to $140 billion while still in a strong growth phase (Exhibit 26). Realizing

Exhibit 26: $280 billion in investments until 2030 will enable $140 billion in annual revenues

$ billions[1]



1 Excl. existing feedstock uses
SOURCE: Hydrogen Council

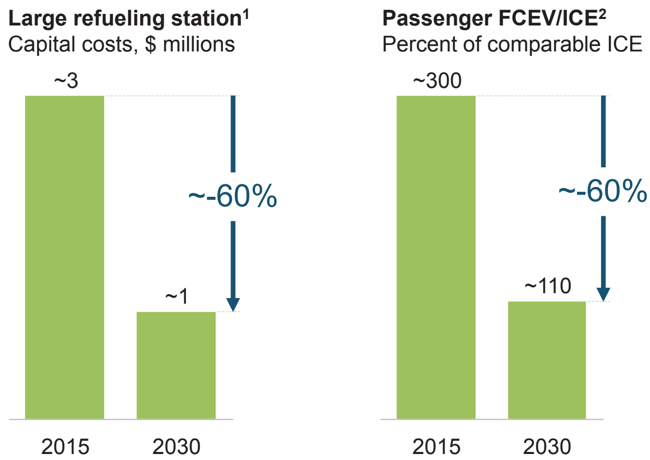
the 2050 vision would eventually bring annual revenues up to more than $2.5 trillion in the immediate industries associated to the hydrogen technology, or $4 trillion if revenues from associated products such as FCEVs are counted in total.

Investments in the hydrogen economy represent a relatively small but vital part of a much larger shift in investments from fossil fuels to clean energy alternatives – and a sharp increase in demand-side investments. If the world remains on a trajectory towards the two-degree scenario, fossil fuel investments would decrease significantly compared to renewables and other low-carbon energy carriers.[43]

Industry has to bring down costs of hydrogen and applications through scale

A scale-up in investments and production volumes is likely to translate into major cost savings for hydrogen production and infrastructure as well as for fuel cell components, vehicles, and other end-use applications, which are necessary to grow the industry further (Exhibit 27). These cost reductions are expected to be achieved through continuous technology and manufacturing efficiency improvements as well as through higher capacity utilization.

Exhibit 27: Capital costs are expected to decrease with scale



1 1,000 kg daily capacity
2 C/D segment

SOURCE: A Portfolio of Powertrains for Europe (2010); DoE Fuel Cell Technologies Office; Hydrogen Council

Significant cost reductions have already been achieved in some areas, such as in the transportation sector. In Germany, average costs of small and medium-sized hydrogen refueling stations built by the CEP/H2Mobility initiative decreased from €2 million ($2.4 million) per station in 2008 to €1 million ($1.2 million).[44] The cost of fuel cell stack production also decreased by at least 50% over the last ten years, driven in part by a fivefold reduction in the required platinum content. If produced at 100,000 to 500,000 units per year, the US Department of Energy (DoE) estimates that fuel cells would cost around $55 per kW using the current technology, or $5,500 for a

43 International Energy Agency and IRENA, 2017

44 NOW GmbH, 2017

100-kW system. These costs could fall further to $4,000 by 2020. For comparison: production of fuel cell stacks at lower volumes costs more than $20 to 25,000 for a 100-kW system.[45]

Further cost reductions are necessary to bring down the costs of hydrogen itself. If produced at high volumes, the DoE estimates that hydrogen could already be cost competitive with gasoline using today's technology, costing less than $4 per kg at the pump (which has a comparable energy density to one gallon of petrol). At current low volumes, however, hydrogen costs $10 to 15 per kg at the pump if unsubsidized.

A virtuous cycle between scale and cost reductions is of course also needed in the other application areas for hydrogen: at the current scale, demonstration projects for hydrogen use in the building, industry, and power sectors are not cost competitive with fossil fuels. A much larger scale is needed to render commercial adoption viable.

A virtuous cycle between scale and cost reductions is needed

45 US Department of Energy – Fuel Cell Technologies Office, 2016

The cost of CO_2 abatement in a hydrogen economy

The presented vision for a hydrogen economy has many advantages – but what are the costs of making it a reality?

To assess the costs of the hydrogen transition, we estimate CO_2 avoidance costs based on the ramp-up derived from our roadmap.[1] These estimates compare all costs of using hydrogen (e.g., for transportation, costs for the vehicle, its maintenance, the cost of hydrogen, and the cost of the refueling infrastructure) instead of conventional technologies and set them in relation to the amount of CO_2 that is avoided at each point in time. These avoidance costs are very high in early years of the roadmap when the technology is still expensive, and decrease relative to conventional technologies as scale is reached and costs for production and use of hydrogen decrease.

In the transportation sector, CO_2 avoidance costs of new fuel cell vehicles are higher than $1,500 per ton of CO_2 avoided today. With scale, these costs could decrease to less than $50 by 2030 and even become negative in the long run, as total cost of ownership of FCEVs drop below those of ICEs (Exhibit 28). Calculated across the whole deployment trajectory from 2015 to 2050, a recent study estimates the cumulative costs of building a fleet of 7.5 million vehicles in Germany at €50 to 60 ($60 to 70) per ton of CO_2 avoided.[2] Our vision, with its global scope and ambitious ramp-up (and therefore accelerated cost reduction), is likely to result in even lower cumulative avoidance costs.

1 Please note that a full study of GHG abatement costs for hydrogen and competing technologies is beyond the scope of this roadmap. The shown estimates provide only a point of reference. Cost estimates are based on (FCH JU, 2011), (Mathieu and Bolland, 2013) and expert input by the Council members.

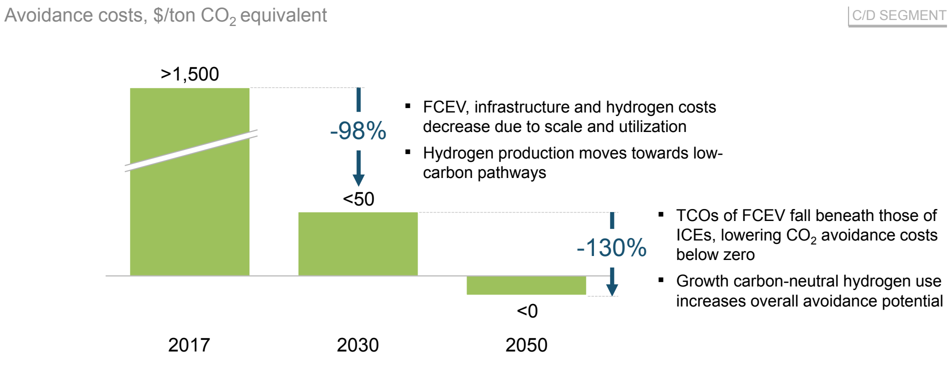
2 Creti, Kotelnikova, Meunier, and Ponssard, 2017; abatement costs considered an upper bound due to higher TCO differences for Germany than outlined in this vision report for the global market

In applications where heat is produced from hydrogen (e.g., in the power industry and building energy sectors), the avoidance costs are mostly dependent on the cost difference between hydrogen and natural gas. Over the lifetime of these applications, equipment costs tend to be small. To replace natural gas in an industrial process, for example, would currently result in avoidance costs of $100 to 150 per ton CO_2 and could drop to around $50 per ton by 2030.

While currently only 15% of global CO_2 emissions are priced through explicit taxes or emissions trading schemes, and less than 5% of global CO_2 emissions are priced at more than $10 per ton. Experts estimate that the two-degree scenario requires a carbon price of at least $50 to 100 per ton CO_2 by 2030.[3] At these carbon prices, the hydrogen technologies presented in this vision become relevant.

The challenge of introducing low-carbon technologies such as hydrogen is to overcome the initial period during which customers have no incentive to switch from conventional technologies and bring down costs. This transition needs to be bridged through long-term plans and regulatory frameworks. In other technologies, this has been successful. In Germany, for instance, the avoidance costs of photovoltaic deployment were initially estimated at more than $400 to 500 per ton CO_2.[4] Given the rapid cost decrease of photovoltaic technologies, newer studies estimate the costs at only $20 to 70 per ton CO_2, with much lower costs in other countries.[5]

Exhibit 28: Costs of CO_2 avoided are expected to decrease with scale



Total abatement potential in roadmap	~0	~95	~1,800	**Average abatement costs for 2015-50 estimated at roughly $60/ton CO_2[1]**

1 Creti, Kotelnikova, Meunier, and Ponssard (2017)

SOURCE: Hydrogen Council

3 Carbon Pricing Leadership Coalition, 2017

4 ifo Institut, 2012

5 Breyer, Koskinen, and Blechinger, 2015

To begin the journey, we propose large-scale deployment initiatives supported by long-term policy frameworks

Chapter 2 presented a range of activities that are already ongoing in the seven areas of application for hydrogen. They range from production and storage of hydrogen from renewable electricity, the distribution across countries, the construction of hydrogen refueling infrastructure, and the procurement of FCEV fleets all the way to the transition of a city to a hydrogen heating network and first uses of clean hydrogen in a range of industrial energy and feedstock uses.

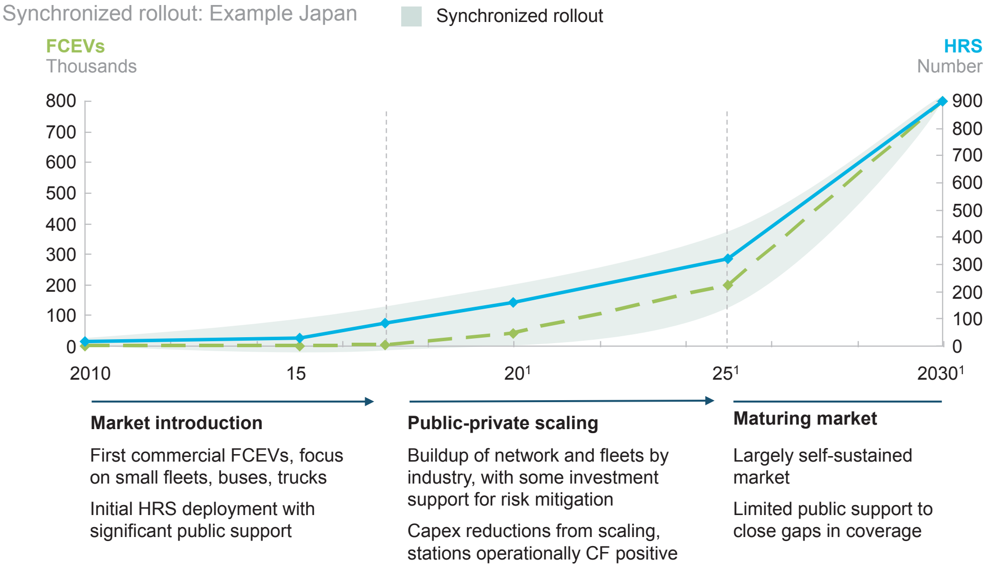
While these activities demonstrate the momentum of hydrogen today, a significant step-up is required to achieve mass market deployment and realize our roadmap. We propose to launch deployment initiatives that use current activities as their platform, learn from their mistakes, and scale their successes nationally and globally. Deployment initiatives encompass all involved stakeholders – regulators, industry, investors, and customers – and require cooperation across these groups.

Transportation sector

Deployment in the transportation sector could follow three phases (Exhibit 29).

In the first phase, market introduction of FCEVs starts with demonstration projects and small captive fleets such as hydrogen taxis as well as corporate and government fleets. These projects establish the requirements for FCEV deployment (such as refueling protocols), demonstrate the technology, and create a "minimal" HRS network, which may amount to some 50 stations in a country the size of Germany or Japan.

Exhibit 29: A synchronized rollout of vehicles and infrastructure goes through 3 phases



1 2016 government targets (METI)

SOURCE: IPHE; METI; Hydrogen Council

Due to their small scale, these projects are likely to require significant public support. National and local government is often the driving force behind early activities seen in countries around the world and supports them through RD&D grants. A key success factor in this phase is the creation of structures for industry-government cooperation, as Germany did, for example, with the Clean Energy Partnership. These platforms can then serve to prepare Phase 2, the scaling of the infrastructure and FCEV rollout.

In the second phase, infrastructure needs to be scaled and mass market deployment of FCEVs initiated. In this phase, countries need a long-term roadmap to solve the chicken-and-egg problem by developing an adequate hydrogen infrastructure that makes FCEVs attractive to mass market customers. Typically, this is achieved through industry cooperation or through large-scale public-private partnerships that involve infrastructure providers, vehicle manufacturers, and private or public investors. The initiatives H2Mobility Germany, H2Korea, the California Fuel Cell Partnership, and the Scandinavia Hydrogen Highway Partnership constitute examples for such partnerships.

In this phase, public support may progressively shift from individual RD&D grants to instruments that can be scaled at a lower cost to the government. One potential instrument for hydrogen refueling stations is the use of guarantees, with fixed payments linked to the rate of underutilization during the ramp-up phase.[46] Other instruments are preferential long-term loans, equity-loan hybrids, or refining schemes for first movers, which are tailored to the utilization rates during the ramp-up period.

Governments can also create demand for infrastructure through public procurement of vehicles (e.g., for hydrogen buses and government fleets) and fleet regulation (e.g., preferred licenses for taxis or benefits for corporate fleets).). Such instruments have been used in many countries and cities to promote BEVs and recharging infrastructure. They are shown to reduce the hurdle to private investment in itself and send a strong signal to infrastructure initiatives and vehicle manufacturers to continue scaling up.[47]

As infrastructure is scaled up, regulations and incentives can help private customers to overcome the higher initial costs of FCEVs. In some countries – including Norway and Japan – FCEVs already cost no more than comparable ICEs; in Denmark, they are significantly less expensive to purchase when all taxes are considered.[48]

To be effective, the scale-up of infrastructure and FCEVs needs to be synchronized. Clear long-term plans and targets from governments for both FCEVs and hydrogen refueling stations in these regions and segments ease much of the uncertainty hindering investment and enable the long-term commitment of investor funds into infrastructure and the development of vehicles. Japan regularly publishes plans with targets for vehicles and refueling stations (Exhibit 29). Cities or regions with high political support can also kick-start the transition by

46 i24c, 2016

47 i24c, 2016

48 Kotelnikova, 2015

cooperating with specific customer segments such as local public transport, taxi or corporate fleets, and developing regional hydrogen supply chains.

Once FCEV adoption accelerates and utilization of HRS reaches levels that cover costs, further deployment of stations will require only limited public support. In the third phase, public policy should focus on achieving full coverage (i.e., closing gaps in more remote areas), integrating the network with neighboring countries, and ensuring healthy competition in the market to lower prices for customers.

Building heat and power

Although challenges around legacy policies remain, scaling up the heating and powering of buildings is potentially less complex for market players than scaling up road transportation efforts. Nevertheless, it requires a coordinated effort between the public sector, gas utilities, and hydrogen producers.

The UK provides an example for such an effort. The “H21 Leeds City Gate” project will test the feasibility of transitioning the gas network of a medium-sized city, Leeds, from natural gas to hydrogen before 2030. Before connecting district by district to the new network, the project will establish the technical requirements and put in place the regulatory and financial framework for the transition. At the same time, the utility Northern Gas Networks is in fact already assessing scenarios to roll out the transition to the entire Northern region and eventually the entire UK. By 2035, 10 times the equivalent of Leeds could be converted to hydrogen, by 2045, 50 times the equivalent of Leeds. As these regions would benefit from the experience and scale gained in Leeds, the rollout at scale could require a fraction of the time and budget of the initial Leeds project and provide a model to follow in other countries.

The Leeds project is expected to be financed through an extra rate on gas bills which will be shared by all gas customers. An alternative or complementary arrangement to fund the transition is a subsidization of hydrogen injections into the natural gas grid in the form of digressive feed-in tariffs or contracts for difference, in which the public hand offsets the excess costs in the initial face. Around the world, digressive feed-in tariffs have been used to support investments in renewable power generation by distributing costs across a wide customer base. In the case of solar power, they enabled rapid industrial scale-up, due to which solar is now close to achieving cost parity with conventional power generation. Similar arrangements could go a long way in promoting clean hydrogen production and use.

Japan demonstrates how micro-CHP units can be rolled out at large scale: since a digressive subsidy of more than $10,000 was put in place in 2009, almost 200,000 CHP units were deployed in households by 2016. Over the course of this period, costs decreased by 75%, enabling a self-sustained market by 2020 (for a total of 5.3 million CHP units by 2030). In South Korea and Germany, comparable subsidies were introduced more recently, and markets traced the Japanese growth trajectory.[49] Other countries benefit from the cost savings achieved during the subsidized rollout, enabling them to reach self-sustained markets in much shorter periods of time.

49 Dodds, et al., 2015

Industry and power generation uses
For the industry, whether as energy carrier or feedstock, as well as in power generation, hydrogen can be adopted decentrally, plant by plant, once adequate price incentives for decarbonization through hydrogen are in place.

Large-scale projects will demonstrate the feasibility of hydrogen production and use in industrial settings. These projects, often with the support of public research and development grants (such as the HYBRIT project for low-carbon steelmaking or the STEPWISE and Carbon2Chem projects for CCU), should achieve significant cost reductions, which enable the transition to commercial operations in regions or plants with strong decarbonization incentives. In the case of power production projects (such as the Magnum power plant in the Netherlands or the Kobe power plant in Japan), the projects also develop the required infrastructure (such as the hydrogen value chain from Australia to Japan) that could accelerate hydrogen adoption in other sectors.

The uptake of hydrogen in industry and power production at large requires hydrogen to be cost competitive with current processes and fuels. A reform of the energy market in terms of feed-in tariffs or contracts for difference, curtailment management, seasonal balancing remuneration, and carbon pricing can reduce the cost difference to fossil fuels, while regulatory requirements on industrial emissions can support the adoption.[50] A critical factor here is the even distribution of costs, such that competitiveness and employment is not compromised in industries that are exposed to international trade.

National action plans
The presented sector-specific deployment initiatives can kick-start the deployment of hydrogen. Additional synergies can be achieved through coordinated deployment across all sectors. This requires long-term and stable policy frameworks that guide the energy transition and the deployment of hydrogen.

Japan leads the way in creating such a strategic framework for hydrogen. The Ministry of Economy, Trade, and Industry has developed a strategic roadmap for hydrogen and fuel cells. By the end of this year, the government is expected to unveil a new strategic action plan to build a "hydrogen society." On municipal level, the Tokyo Metropolitan Government declared that the 2020 Tokyo Olympics should leave a hydrogen society as a legacy, just as the 1964 Olympics left the Shinkansen high-speed train system. It will not only accelerate the rollout of hydrogen refueling stations and FCEVs, but will also power the Olympic village on hydrogen CHP units.

Clear national action plans for the development of hydrogen within and across sectors can kick-start the roadmap presented in this report. A coordinated approach between government and industry can reduce risk, deliver potential benefits faster, and do so more cost effectively.

As a council, we invite you to discuss next steps with us.

50 i24c, 2016

Glossary

A/B	A/B segments in the euro car segments (mini cars and small cars)
BEV	battery-electric vehicle
C/D	medium-sized and large cars
CCU	carbon capture and utilization
CCS	carbon capture and storage
CHP	combined heat and power
CO_2	carbon dioxide
DRI	direct reduced iron
E+	luxury cars in the euro car segments
EJ	exajoule, or 1018 joules
ETP	Energy Technology Perspectives model by the IEA
FCEV	fuel cell electric vehicle
Gt	gigaton, or 1012 (one trillion) metric tons
HDV	heavy duty vehicle
IEA	International Energy Agency
LCV	light commercial vehicle
LDV	light duty vehicle
LiquidMt	megaton, or 106 (one million) metric tons
MW	megawatt
PEM	polymer electrolyte membrane
RD&D	research, development, and deployment
SMR	steam methane reforming
SNG	synthetic natural gas
TCO	total cost of ownership
ton	metric ton (1,000 kg)
TWh	terawatt hour

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