

How hydrogen empowers the energy transition



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Preface – How hydrogen empowers the energy transition

Paris, December 12, 2015: 195 countries sign a legally binding agreement to keep global warming well below 2°C – an ambitious goal that will require the economies around the globe to decarbonize large parts of the world's energy system. This energy transition faces challenges. Significant amounts of renewable energy must be installed and integrated, while securing the supply and resilience of the system is demanding. Energy end-use sectors, such as transport, must be decarbonized at scale.

In this context, we are convinced that the unique contribution that hydrogen solutions offer needs to be strongly reaffirmed now. Hydrogen and fuel cell technologies have significant potential to enable this transition to a clean, low-carbon energy system. Completing this transition will result in greatly reduced greenhouse gas emissions and improved air quality.

We formed the Hydrogen Council to both underpin and leverage the enabling role of hydrogen. This partnership of 13 players from various industry and energy sectors with global reach is committed to providing guidance to accelerate and expand the deployment of hydrogen and fuel cell solutions around the world.

Hydrogen is a versatile, clean, and safe energy carrier that can be used as fuel for power or in industry as feedstock. It can be produced from (renewable) electricity and from carbon-abated fossil fuels. It produces zero emissions at point of use. It can be stored and transported at high energy density in liquid or gaseous form. It can be combusted or used in fuel cells to generate heat and electricity.

In this paper we explore the role of hydrogen in the energy transition, including its potential, recent achievements, and challenges to its deployment. We also offer recommendations to ensure that the proper conditions are developed to accelerate the deployment of hydrogen technologies, with the support of policymakers, the private sector, and society.

We, the members of the Hydrogen Council, believe in the potential of hydrogen in making the energy transition happen. In order to unleash this potential, we ask policy makers for their support to overcome existing barriers. Hydrogen technology rollout requires large-scale efforts and Council members are willing to further increase their investments. To do so, we see a stable, long-term regulatory framework, dedicated coordination and incentive policies, and initiatives to set and harmonize industry standards as essential preconditions on a political level.

We invite governments and key society stakeholders to also acknowledge the contribution of hydrogen to the energy transition and to work with us to create an effective implementation plan – so that the compelling benefits of hydrogen deployment can be reaped.



Chapter 1



The energy transition – a necessity and a global challenge

The need for an energy transition is widely understood and shared; however, the implications and challenges that must be resolved call for a concerted effort. Hydrogen has the potential to be a powerful enabler of this transition, as it offers a clean, sustainable, and flexible option for overcoming multiple obstacles that stand in the way of a resilient and low-carbon economy.

The world needs a cleaner, more sustainable energy system

Unless the energy system changes in almost every respect, from power generation to end-uses across sectors, the global climate will be affected in the coming 50 to 100 years. The greenhouse gases emitted in a business-as-usual scenario would lead to an increase of the average global temperature of about 4°C. This, in turn, would raise sea levels, shift climate zones, and make extreme weather and droughts more frequent, as well as causing other changes, all impacting biological, social, and economic systems.

The concept of mitigating climate change by transitioning to an energy system with less greenhouse gas emissions, much reduced particulate emissions, and more sustainable, even circular, consumption and production, enjoys broad global support. The international community has embraced the idea in multiple international agreements, including the Sustainability Development Goals (SDGs), Habitat III, and COP21 in Paris. With COP21, 195 countries adopted the first universal, legally binding global climate deal. It aims to keep “the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit warming to 1.5°C”.

These goals are ambitious, and current efforts are not enough. The country plans laid out in COP21 to reduce CO₂ emissions (the INDCs) are insufficient. They will increase the average global temperature well above the 2°C mark by 2100.¹ Limiting global warming to 2°C will allow a cumulated emission of energy-related carbon emissions of approximately 900 Gt of CO₂ by 2100. At current annual energy-related CO₂ emissions of 34 Gt, that ceiling will be reached before 2050. At the same time, the world is facing a need of near-term goals for reducing air pollution, since only 1% of the global population lives in areas with emissions deemed healthy by the World Health Organization.

The need for action is pressing. To achieve the ambitions of COP21, Habitat III, and SDGs across all sectors, the world needs to embark on one of the most profound transformations in its history: a transition of energy supply and consumption from a system fueled primarily by non-renewable, carbon-based energy sources to one fueled by clean, low-carbon energy sources.

Efforts to decarbonize the energy system need to pull on four main levers: improving energy efficiency, developing renewable energy sources, switching to low/zero carbon energy carriers, and implementing carbon capture and storage (CCS) as well as utilization (CCU).

This will radically change energy supply and demand. Today, fossil fuels account for 82% of primary energy consumption; renewable energy sources contribute only 14%, and nuclear sources 4%. Towards 2050, growth in population and GDP will increase energy demand by 16%, despite projected energy efficiency achievements. By 2050, renewables are expected to increase their share of the energy mix by 3 to 5 times the current amount. At the same time, fossil fuels continue to make up a large share (partially using carbon capture and storage to offset or prevent emissions). New energy carriers will be needed to transfer the growing share of decarbonized primary energy towards the energy demand

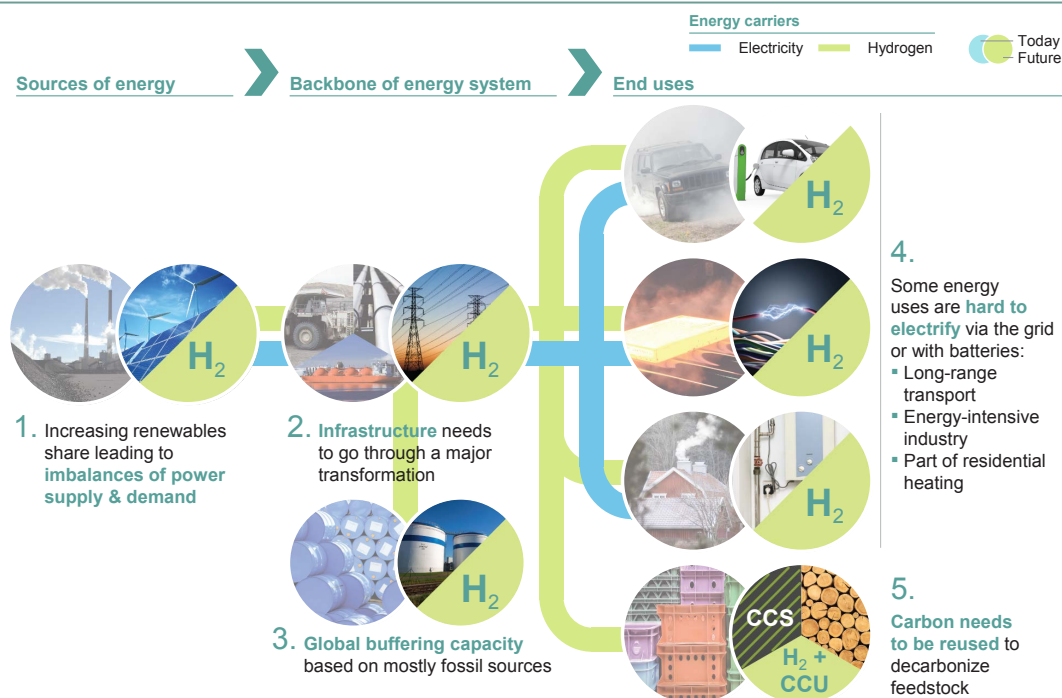
¹ IEA analysis found that implementation of the INDCs is consistent with a global temperature rise of 2.7°C by 2100 and 3°C thereafter.

side, while maintaining the quality of energy services provided to end uses (residential, industries, and transport). Two energy carriers promise to have the greatest possible impact when it comes to decarbonizing and implementing changes at scale: electricity and hydrogen.

The energy transition needs to overcome five major challenges

Transitioning towards a low-carbon economy will need nothing less than a paradigm shift (see Appendix I), requiring large scale investments. The challenges ahead come from five areas – and hydrogen has a role to play in successfully overcoming all of them (Figure 1).

Figure 1: Hydrogen as a zero-emission energy carrier needed to overcome the challenges around the energy transition



1. Using more variable renewable energy in the power sector will unbalance supply and demand.

Generating electricity from intermittent renewable energy sources and increasing electricity demand will strain the power system to its limits. Grid capacity, intermittency, as well as application of low-carbon seasonal (weeks to months) storage and back-up generation capacity will be challenges to address.

Hydrogen helps optimize the power system for renewables, facilitating further increases in renewable shares. Electrolysis produces hydrogen by using (excess) power supply and enables to valorize it either in other sectors (transport, industry, residential heat) or to store it for future re-use. Hydrogen has the potential to improve economic efficiency of renewable investments, enhance security of power supply and serve as a carbon-free seasonal storage, supplying energy when renewable energy production is low and energy demand is high, e.g., in European winter.

2. To ensure security of supply, global and local energy infrastructure will require major transformation.

Today, about 30% of the global primary energy supply is traded across borders, encompassing a mix of energy carriers (oil, gas, coal and electricity). The need for energy trading will persist, since the potential of renewable energy production varies heavily across the world's regions –

compounded by limited “storability” of electricity as such. A functioning cross-border energy infrastructure will be essential for ensuring a secured energy supply. Changes will also occur at the level of regions or cities within a country: a new mix of centralized and decentralized energy supply will emerge, amplifying the need for adjusted energy infrastructure.

Hydrogen can provide a cost-effective, clean energy infrastructure, contributing to supply security both at local and country levels. Shipped, piped, or trucked, hydrogen is a means to (re)distributing energy effectively among cities and regions.

- 3. Buffering of the energy system through fossil fuels will no longer be sufficient to ensure smooth functioning of the system.** The buffer capacity ensures the smooth functioning of the energy system by maintaining a reserve of approximately 15% of the world’s total annual energy demand. This buffer absorbs supply chain shocks, provides strategic reserves at country level, and anticipates supply and demand imbalances. Today, fossil energy carriers provide most of the storage capacity. As electrification increases, those reserves will no longer be adequate to ensure a stable energy supply for all end-users.

Due to its storability and flexibility in terms of transport, hydrogen is a viable – and clean – future option for mastering the buffer challenge.

- 4. Some energy end uses are hard to electrify via the grid or with batteries, especially in transport but also in other sectors.** In many sectors, direct electrification is and will remain technologically challenging or uneconomical even at very high CO₂ prices. This applies, e.g., to heavy-duty transport, non-electrified trains, overseas transport, and aviation, but also to some energy-intensive industries. In other sectors, such as light-duty vehicles, direct electrification, although technologically possible, does not always meet performance requirements in range and charging convenience.

In many, if not all of these sectors, where technological and/or economic obstacles prevent direct electrification, hydrogen offers a viable solution.

- 5. Renewable energy sources cannot replace all fossil feedstocks in the (petro-)chemicals industry.** Fossil fuels used for the production of, e.g., plastics will cause (carbon) emissions at the end of their life cycle when burned in incinerators. These delayed emissions need to be decarbonized too. Combining hydrogen with captured carbon creates hydrocarbons that can complement oil and natural gas as chemical feedstock. Thus, hydrogen may also help to put carbon capture and utilization into practice and to decarbonize other carbon-intensive sectors like the cement industry.

Taken together, the unique properties of hydrogen make it a promising solution to overcome the challenges facing the energy system. Hydrogen can be produced without any carbon footprint if renewable electricity is used for electrolysis, if bio-methane is used in steam methane reforming (SMR) or if SMR is equipped with CCS/CCU. The properties of hydrogen enable it to generate power and/or heat (through fuel cells, combined heat/power units (CHPs), burners, or modified gas turbines). Its chemical properties also allow for its use as feedstock in chemical processes, including production of ammonia and methanol. Hydrogen combustion does not emit SO_x or other particulates, and only limited NO_x. In fuel cells, e.g., for vehicles, hydrogen usage does not cause any emissions and makes less noise than conventional engines. Stored in tanks, hydrogen is lighter and contains more energy than a battery of similar size, offering clear benefits for energy storage and distribution. (For more information on hydrogen, see Appendix II – Hydrogen essentials.)

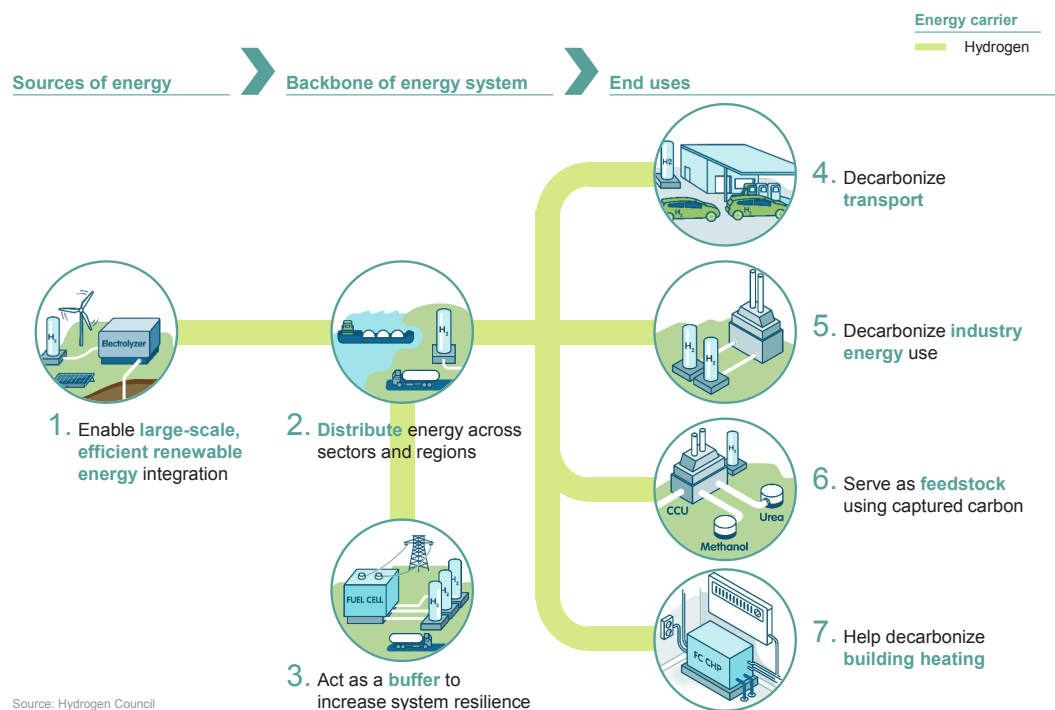
Chapter 2



The role of hydrogen in the energy transition

Hydrogen's unique properties make it a powerful enabler for the energy transition, with benefits for both the energy system and end-use applications (Figure 2).

Figure 2: Hydrogen has seven roles in decarbonizing major sectors of the economy



1. Enable large-scale, efficient renewable energy integration

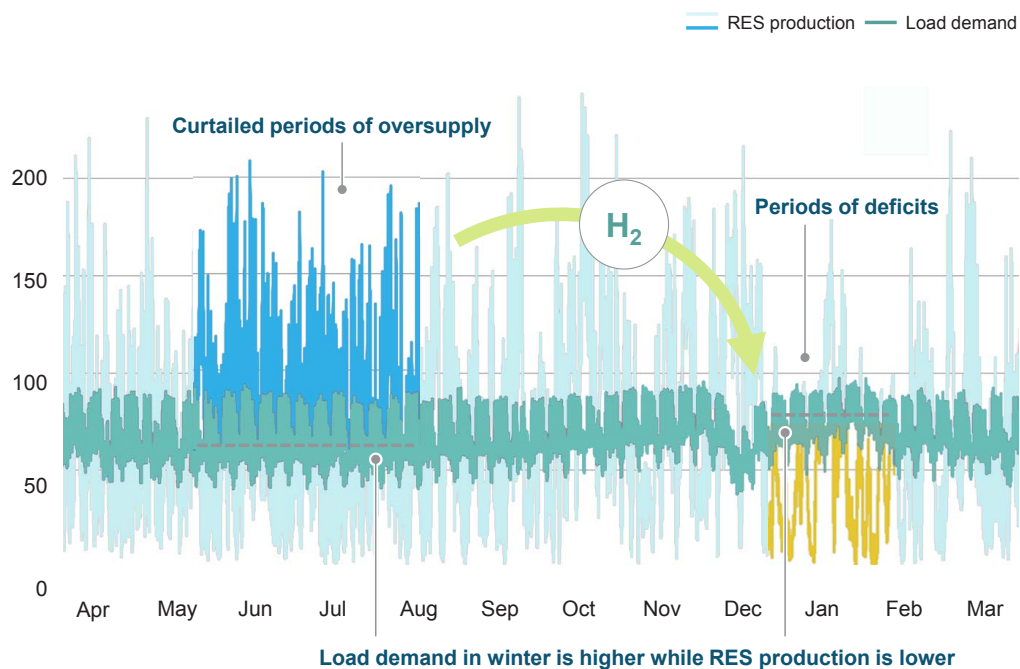
In the power sector, the timing of variable electricity supply and demand is not well matched (neither over the day nor between seasons). Integration of an increasing share of intermittent sources up to targeted levels (above 40% of the electricity mix) will enhance the need for operational flexibility. Increased electrification and limited storability of electricity will require adequate storage solutions. Various options exist to resolve the various issues, such as grid infrastructure upgrades or technologies for short- or longer-term balancing of supply and demand, e.g., flexible back-up generation, demand-side management, or energy storage technologies.

Hydrogen offers valuable advantages in this context, as it avoids CO₂ and particles emission, can be deployed at large scale, and can be made available everywhere. There are two ways in which hydrogen improves the efficiency and flexibility of the energy system (Figure 3):

- i. Electrolysis can convert excess electricity into hydrogen during times of oversupply. The produced hydrogen can then be used **to provide back-up power during power deficits** or can be **used in other sectors such as transport, industry or residential**. It thus valorizes excess electricity.

The potential of valorization of otherwise curtailed renewable energy is considerable. For instance, in Germany alone, in a scenario with 90% renewables, curtailment of more than 170 TWh/year is projected for 2050, equivalent to about half the energy needed to fuel the German passenger car fleet with hydrogen. This would create an opportunity for around 60 GW of electrolysis capacity to operate economically (depending on improvements in grid interconnectivity).

Figure 3: Excess power can be used to produce hydrogen for seasonal energy storage
Simulation for Germany 2050, in GW



Source: EC 2050 scenario, McKinsey analysis

Hydrogen offers a centralized or decentralized source of primary or backup power. Like gas, power from hydrogen (or one of its compounds) is switched on and off quickly. Thus, hydrogen helps deal with sudden drops in renewable energy supply, e.g., during adverse weather events). In addition, electrolysers may provide ancillary services to the grid, such as frequency regulation.

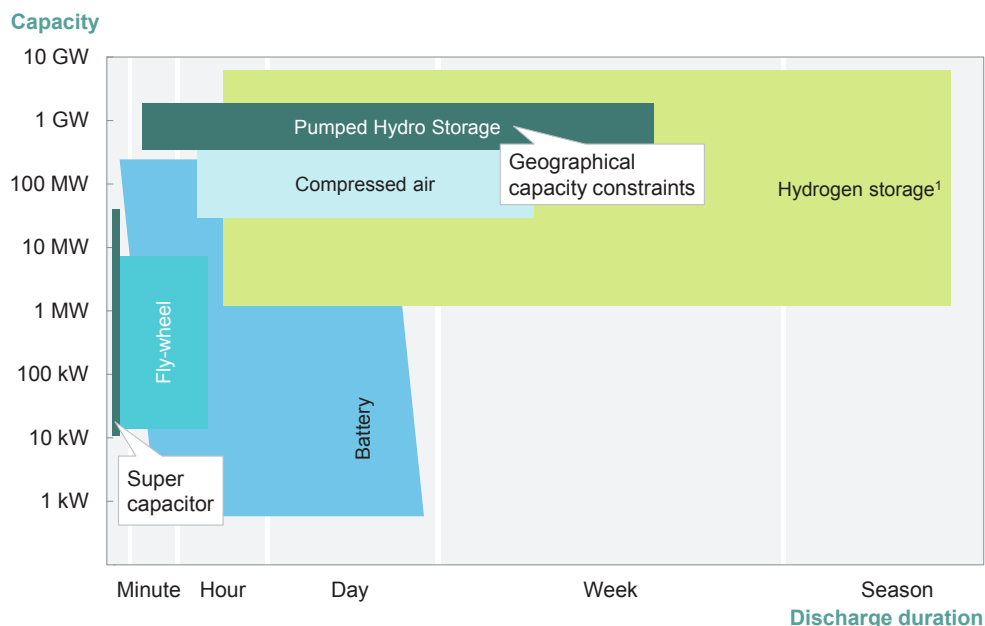
Hydrogen can also be used in specific fuel cell CHPs in industry and buildings, linking heat and power generation. This enhances the efficiency of generated electricity and heat for these sectors and improves flexibility of the energy system as a whole. Its potential is discussed in the following sections.

ii. Hydrogen can serve as long-term carbon-free **seasonal storage medium**.

Hydrogen represents the optimal overall solution for long-term, carbon-free seasonal storage. While batteries, super-capacitors, and compressed air can also support balancing, they lack either the power capacity or the storage timespan needed to address seasonal imbalances (Figure 4). Pumped hydro offers an alternative to hydrogen for large-scale, long-term energy storage; it currently accounts for more than 95% of global power storage (162 GW worldwide). However, its remaining untapped potential is subject to local geographic conditions and limited to about 1% of annual global energy demand (0.3 EJ). This is not enough to handle seasonal demand differences. For instance in Germany energy demand is about 30% higher in winter than in summer, while renewable generation is typically 50% lower in winter than in summer (Figure 3).

At this point in time, hydrogen remains a novel way to store energy, but more and more large, hydrogen-based storage demonstration projects are being planned, announced, or launched around the world – e.g., in Denmark, Canada, Japan, and the Asia-Pacific region. In addition, underground storage of large volumes of hydrogen is a well-established industry practice and does not present a major technological barrier. With an increasing share of renewable energy sources, the deployment of hydrogen as a long-term storage solution is expected to accelerate. As that happens, the cost of hydrogen storage is

Figure 4: Hydrogen is most promising for long-term carbon-free seasonal storage
 Technology overview of carbon-free energy storage technologies



1 IEA data updated due to recent developments in building numerous 1MW hydrogen storage tanks
 Source: IEA Energy Technology Roadmap Hydrogen and Fuel Cells, JRC Scientific and Policy Report 2013

projected to decrease to €140/MWh (power to power) in 2030 for hydrogen stored in salt caverns. This is even less than the projected cost for pumped hydro storage (about €400/ MWh in 2030). In Germany the constrained potential for storage in caverns is about 37 billion cubic meters. This would be sufficient to store 110 TWhth hydrogen, covering the projected full seasonal storage need.

All in all, hydrogen permits to integrate more economically large amounts of intermittent energy sources in the system and provides the much needed flexibility to maintain the resilience of the system.

2. Distribute energy across sectors and regions

The power system will require distribution of renewable energy for several reasons. Some countries, such as Japan, are not well positioned to generate energy with wind or solar power alone. Other countries may need time to raise the necessary investments. In some cases, importing renewable energy might be more economical, e.g., bringing low-cost solar energy from sun-belt countries to less sunny regions. As hydrogen and its compounds have a high energy density and are easily transported, they will help to (re)distribute energy effectively and flexibly.

While transporting electricity over long distances can cause energy losses, pipeline transportation of hydrogen reaches almost 100% efficiency. This benefit makes hydrogen an economically attractive option when transporting renewable energy at scale and over large distances, e.g., from areas with a high potential for renewable power generation, such as the Middle East, to areas with high energy demand like Europe.² Import of hydrogen might serve as a long-term strategy, aimed at handling the ramp-up period for renewables or ensuring adequate energy supply during the winter, when renewable energy sources produce less electricity.

Japan is planning to launch the first technical demonstration of a liquefied hydrogen carrier ship to enter

² Assuming double production costs for solar and wind electricity in the Netherlands compared with solar in the sun-belt regions, 2 ct/kWh electrolysis cost without electricity and 2.5 ct/kWh for the liquefaction and transport of hydrogen

international trade in 2020. Today, hydrogen pipelines and gaseous or liquefied tube trailers are the most common modes of transport. As the flow of hydrogen increases, the costs for liquefaction and transport are expected to drop by 30 to 40% in the next 15 years. Use of existing gas grids to transport hydrogen has been tested but not applied at large scale. Leeds is the first city that has proposed to convert its gas grid into a hydrogen grid by 2026.

3. Act as a buffer to increase system resilience

Hydrogen can help align global energy storage with changing energy demand. Its high energy density, long storage capacity, and variable uses make hydrogen well suited to serve as an energy buffer and strategic reserve.

Today, the energy system has backup capacity of about 90 EJ (24% of final annual energy consumption), held almost exclusively by fossil energy carriers. The council sees no indication that the amount of buffering need could decrease significantly in the future.

But, as consumers and the power sector switch to alternative energy carriers, the use of fossil fuels as backup might shrink, since this buffer serves only applications that consume fossil fuels. The most efficient buffer would mix energy carriers that reflect (or could transform into) end-use applications. This mix would include fossil fuels, biofuels/biomass/synthetic fuels, and hydrogen.

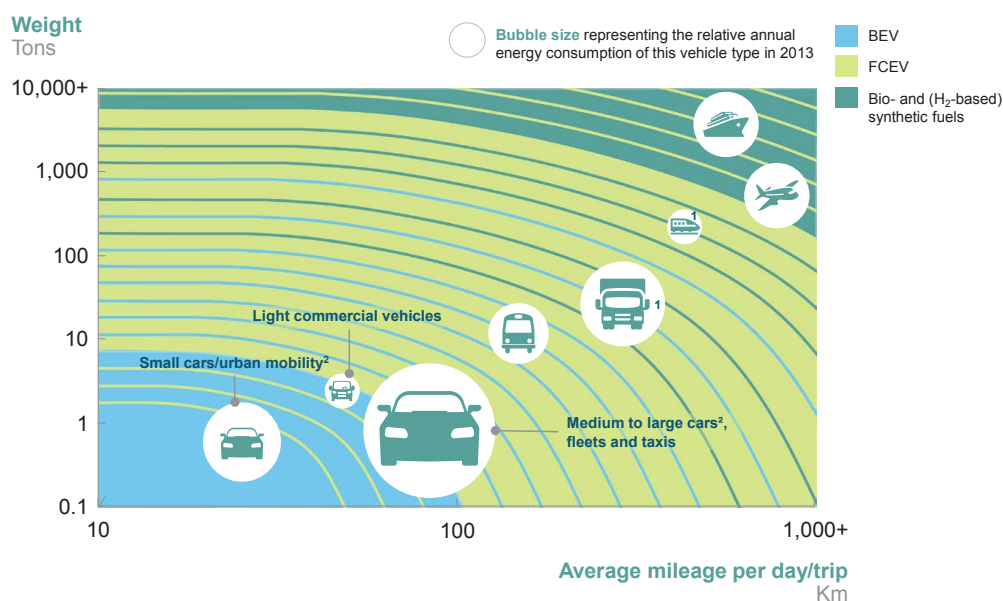
4. Decarbonize transport

Fuel cell electric vehicles (FCEVs) have an important role to play in decarbonizing transport. Today oil dominates the fuel mix that meets the world's transport needs. Gasoline and diesel account for 96% of total fuel consumption and 21% of global carbon emissions (Figure 5).

Efficient hybrid vehicles like hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) are already reducing vehicle emissions. However, fully decarbonizing transport will require deployment

Figure 5: FCEVs will play an essential role in decarbonizing transport

Projected economic attractiveness



Source: Toyota, Hyundai, Daimler

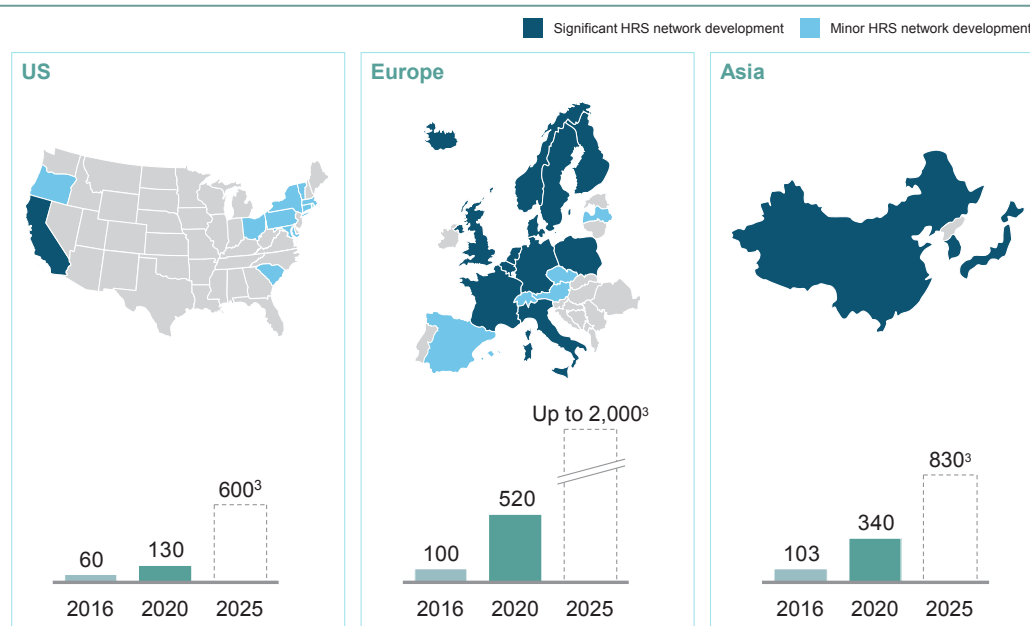
of zero-emission vehicles like hydrogen-powered FCEVs and battery electric vehicles (BEVs), or hybrid combinations thereof. Advances in technology and new trends in mobility (e.g., connected cars, autonomous driving technology, and shared mobility) will influence relative levels of deployment and the transition speed. Both electric vehicle types make use of similar and complementary technologies and are specifically suited to serve different segments and customers. Besides lowering CO₂ emissions, both also support local air quality improvements and noise reductions.

FCEVs offer several significant benefits. Firstly, they can drive long distances without needing to refuel (already more than 500 km), a feature highly valued by consumers. Secondly, they refuel quickly (3 to 5 minutes), similar to current gasoline/diesel cars, which adds to consumer convenience. Thirdly, thanks to a much higher energy density of the hydrogen storage system (compared to batteries), the sensitivity of the FCEV powertrain cost and weight to the amount of energy stored (kWh) is low. This increases its attractiveness and likelihood of adoption of vehicles that require significant energy storage (e.g., heavy load capacity and/or long range/heavy use). Lastly, FCEV infrastructure can build on existing gasoline distribution and retail infrastructure, creating cost advantages and preserving local jobs and capital assets.

FCEVs will emerge in all segments. Considering the above indicated benefits, they will be especially important in decarbonizing passenger cars (e.g., medium to large cars, fleets, and taxis), heavy-duty transportation, buses, and nonelectrified trains. Application of synthetic fuels made out of hydrogen to shipping and aviation is also being explored (Figure 6).

For passenger cars, total cost of ownership (TCO) for FCEVs is currently higher than for internal combustion engine (ICE) vehicles, while travel cost (hydrogen price per kilometer traveled) is already similar to the cost of HEVs in Japan. When FCEVs reach at-scale commercialization, we are confident that cost parity (from a TCO perspective) can be reached by 2025 for medium to large passenger cars.

Figure 6: Leading Western and Asian countries plan to roll out a significant hydrogen infrastructure over the coming decade. Number of hydrogen refueling stations (HRS)¹



¹ Publicly available HRS from countries with a significant HRS network development

² Countries or states with no major HRS outlook as of today

³ Depending on the number of FCEVs on the road

Source: H₂ Mobility, US DOE, Hydrogen Europe, Air Liquide

Selected car fleets and buses will reach cost parity even sooner, as their infrastructure rollout tends to be simpler and thus cheaper.

Major automotive players are pursuing a dual solution for zero-emission products. Three leading manufacturers already offer commercially available FCEVs, while many others have announced the intention to launch their own FCEVs soon. FCEVs are starting to become commercially available, with more than a thousand vehicles already on the road in Japan and the US, and a few hundred in Europe. Several OEMs have FCEV production lines that can produce thousands of FCEVs a year. By the early 2020s, a significant ramp-up is expected and OEMs will have the capacity to produce tens of thousands of commercially available passenger FCEVs a year. This is in line with several countries' ambitious FCEV deployment targets. China, for example, has set the goal of having 50,000 FCEVs on the road by 2025 and 1 million by 2030. Japan plans to deploy 200,000 FCEVs by 2025 and 0.8 million by 2030.

FCEVs start to penetrate mass and goods transport. While the current market share of FCEV buses is still small (~ 500 on roads around the world), recent investments show increasing momentum to shift mass transit to FCEV solutions. For example, Lianyungang Haitong Public Transport (China) plans for 1,500 FCEV buses, Europe has announced to deploy in total 600 to 1,000 FCEV buses by 2020 and South Korea plans to replace 27,000 CNG buses with FCEVs by 2030. The development of commercial heavy-duty vehicles is currently targeted by several OEMs. Germany announced recently that its first hydrogen trains will start running in 2017. FCEV trains are already cost competitive with diesel trains (from a TCO perspective).

Leading Western and Asian countries are planning to roll out significant hydrogen infrastructure over the coming decade. In Europe the number of stations is expected to double biannually, with up to 400 stations in Germany alone by 2023, and California has set the goal of having 100 stations by 2020. Japan already has more than 80 stations operating, and South Korea and China are planning to setup a hydrogen network, together aiming for 830 stations by 2025. The total targeted number of more than 3,000 stations in 2025 will be sufficient to provide hydrogen for about 2 million FCEVs. After this initial development phase, refueling infrastructure will be self-sustained.

5. Decarbonize industry energy use

Today, natural gas, coal, and oil provide energy for industrial processes and thus generate about 20% of global emissions. Industry needs to improve energy efficiency (including waste heat recovery), thus reducing the need for energy. Steam electrolysis technologies can help valorize waste heat into hydrogen. Industry also needs to decarbonize the sources of process heat, for both low- and high-grade heat.

Industry has many options for decarbonizing low-grade heat. While heat pumps and electric resistance heating offer advantages in certain geographic locations, hydrogen is clearly advantageous when it is available as a by-product of the chemical industry or when a specific industry needs an uninterrupted power supply (as provided by a fuel cell), along with heat. As hydrogen can be combusted in hydrogen burners or be used in fuel cells, it offers a zero-emission alternative for heating.

High-grade heat - above 400°C - is harder to decarbonize. Hydrogen burners can complement electric heating to generate high-grade heat, depending on local conditions: some regions might favor industrial use of hydrogen technologies instead of electricity, given the constraints they have in the design of their energy system.

Today, industry uses hydrogen in low-grade heat applications, such as process heating and drying. In the future, industry might also use a mix of hydrogen burners and fuel cells to meet their low- and high-grade heat needs. Fuel cells have a higher efficiency than burners and simultaneously provide heat and power, but their deployment still requires significant investment. Burners, on their side, require only adjustments of existing equipment.

6. Serve as feedstock using captured carbon

Hydrogen-based chemistry could serve as a carbon sink and complement or decarbonize parts of the petrochemical value chain. Today, crude oil (derivatives) are used as feedstock in the production of industrial chemicals, fuels, plastics, and pharmaceutical goods. Almost all of these products contain both carbon and hydrogen. If the application of carbon capture and utilization (CCU) technology takes off (as part of a circular economy or an alternative to carbon storage), the technology will need (green) hydrogen to convert the captured carbon into usable chemicals like methanol, methane, formic acid, or urea. This use of hydrogen would make CCU a viable alternative for other hard-to-decarbonize sectors like cement and steel production, and would contribute to the decarbonization of part of the petrochemical value chain.

The use of hydrogen and captured carbon to produce chemical feedstocks is in the research and development phase, with initial pilot projects being launched. Iceland has an operational geothermal plant that uses geothermal CO₂ and generated electricity to produce hydrogen and then methanol. This methanol production is stated to be cost-competitive with an electricity price of EUR 30/MWh; other local conditions might produce different results. Sweden has planned a similar project that will use carbon captured from iron ore processing. Germany is combining carbon from steel production emissions with hydrogen from excess electricity to produce chemicals. The project is still in the concept phase and is expected to reach scale in 15 years.

7. Help decarbonize building heating

Heating and warm water supply account for about 80% of residential energy consumption. About 50 EJ of energy is used for residential heating, responsible for 12% of global emissions. Hydrogen will be part of a portfolio of solutions for decarbonizing building heating. Local conditions will dictate the choice of options.

Building heating can use hydrogen as a fuel or leverage hydrogen technologies, or ideally a combination of both: hydrogen technologies such as fuel cell micro CHPs serve as energy converters. They offer high efficiency for heat and power generation (> 90%). Hydrogen itself can serve as a fuel (either pure or blended with gas, partially decarbonizing the gas grid). For houses connected to a natural gas grid, switching to hydrogen-combustion-based heating offers an opportunity to keep using the existing gas grid. With relatively small adjustments and investments, the grid can safely transport a mixture of hydrogen and natural gas. Full decarbonization requires a total switch to hydrogen, as contemplated by UK gas grid operators in Leeds.

On a global scale, about 190,000 buildings are already heated with hydrogen-based fuel cell micro CHPs. Most micro-CHPs (> 95%) are located in Japan, where about half run on methane combined with a reformer to produce hydrogen. The project has shown the ability of micro CHPs to meet heating requirements and supplement the electricity balance. By 2030, some 5.3 million Japanese households will use micro CHPs. Economies of scale have already cut prices more than 50%, from 2.4 USD/W installed in 2009 to 1 USD/W installed in 2014.

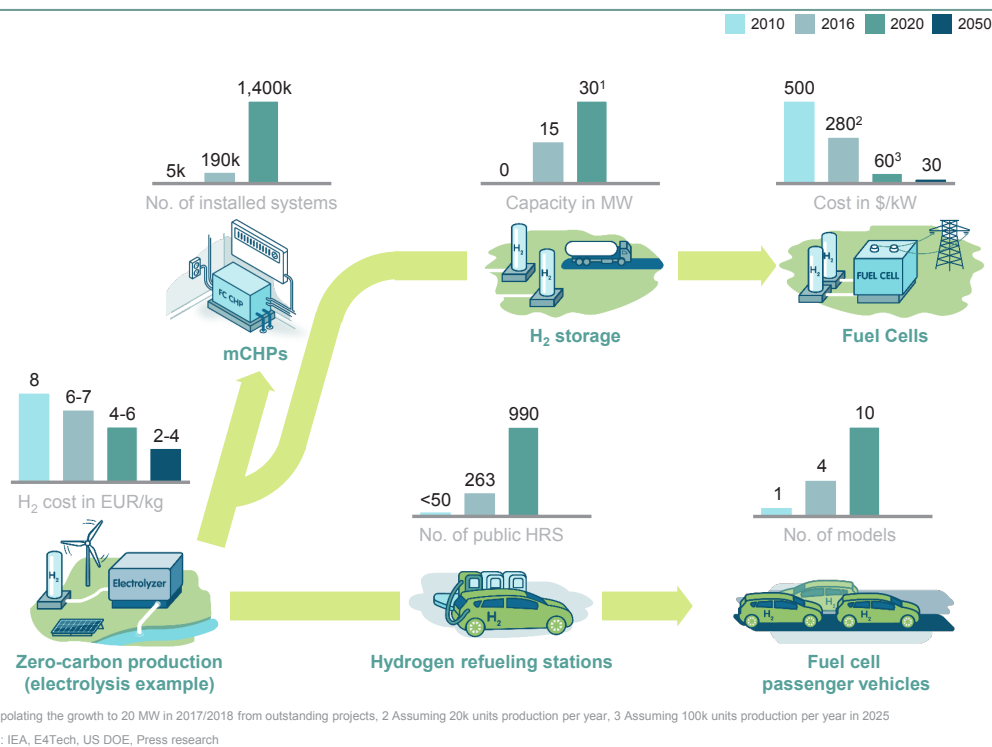
Chapter 3



Existing barriers and enablers to fully unlock the potential of hydrogen

The long-term benefits of hydrogen are compelling, and it provides a promising pathway for the energy transition, with a clear acceleration over the past 3 years, coming from commercialization of products in all sectors. Continuous improvements in cost and performance of hydrogen related technologies are being made along the entire value chain (Figure 7).

Figure 7: Continuous improvements are being made along the entire value chain
Selected examples of hydrogen technologies



Nevertheless, a number of obstacles need to be overcome before the full benefit of hydrogen in the energy transition can materialize. Among these obstacles are an insufficient recognition of its importance for the energy transition, the absence of mechanisms to mitigate and share the long-term risks of the initial large-scale investments, a lack of coordinated action across stakeholders, a lack of fair economic treatment of a developing technology, and limited technology standards to drive economies of scale.

Many **investments in hydrogen require a long horizon** of 10 to 20 years. Especially in the early years, infrastructure investments are needed before consumer demand increases. The lack of clear and binding emission reduction targets or stimuli for specific sectors discourages potential investors from taking on the long-term risk. Japan has forged a path to mitigating these risks. The government and industrial companies share a long-term roadmap for creating the “hydrogen society.”

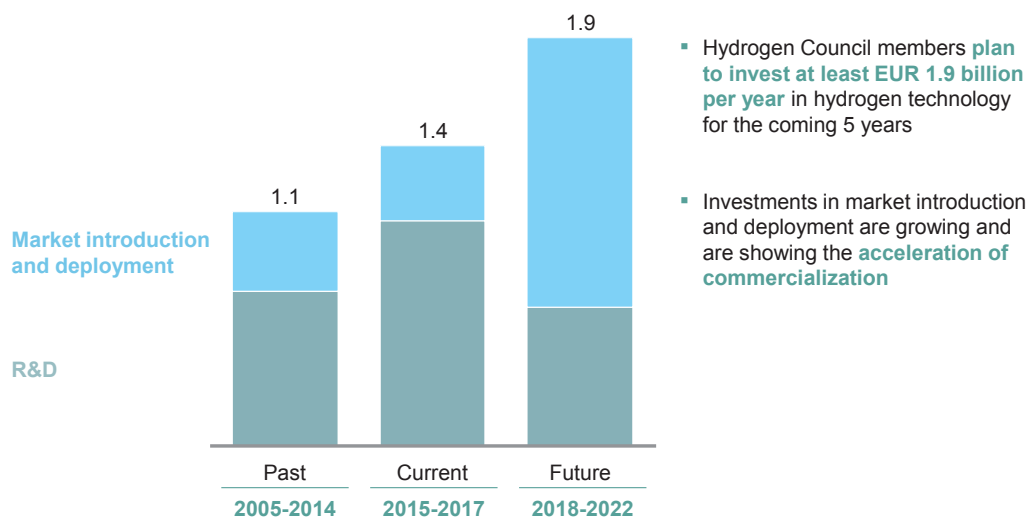
Mobility applications **require a coordinated effort across industries** to resolve the market mismatch between infrastructure deployment (stations) and demand for hydrogen (FCEVs). H2 Mobility Germany is such an effort. Together with government, this industry coalition planned to invest EUR 350 million to build up to 400 refueling stations for FCEVs by 2023. Another example is the California Fuel Cell Partnership,

which is a collaboration of auto manufacturers, energy companies, fuel cell technology companies, and government agencies, striving to commercialize FCEVs and hydrogen in California. Despite such pockets of progress, full adoption of hydrogen requires similar coordinated initiatives around the world.

Many emerging technologies have benefited from **clear regulatory guidelines** on preferential financial stimuli, such as feed-in tariffs and Renewable Obligation Certificates (ROCs) for renewables, combined with penetration targets, e.g., by EU member states. However, regulations have not yet recognized the benefits of hydrogen in an integrated way. For example, regulations in Germany impose a double tax on in- and out-flow of electricity when hydrogen is used for energy storage, and power generators have limited incentives to optimize curtailed electricity.

While the cost and performance of fuel cells and hydrogen production systems have improved in recent years (e.g., fuel cell cost fell more than 50%), performance improvement is not capturing its full potential as **industry standards** have been set for specific applications but remain limited overall. Advancing the energy transition requires harmonized regional and sector-specific fuel cell and hydrogen standards that will allow for economies of scale in research, development and deployment (R, D & D) and manufacturing. The Hydrogen Council members plan to shift investment from R, D & D to commercialization (Figure 8)

Figure 8: Hydrogen Council members plan to orient their increasing annual investments in hydrogen on market development. Investments planned by Hydrogen Council members, in EUR billions per year



Source: Hydrogen Council

Policy recommendations to unlock the potential of hydrogen

We, the members of the Hydrogen Council, are convinced that hydrogen has a key role to play in the energy transition. Technologies and products have been developed and are market ready.

We recognize that more investment is needed to deploy hydrogen-related products. Investments planned over the next five years by Council members alone are already in the order of EUR 10 billion.

We invite governments to join us in acknowledging the contribution of hydrogen to the energy transition, and to support the Hydrogen Council and other stakeholders on hydrogen's development.

We recommend the following actions to policy makers to unlock the contribution of hydrogen to the energy transition:

- 1. Provide long-term and stable policy frameworks** to guide the energy transition in all sectors (energy, transport, industry, and residential). We will bring in our expertise on the feasibility of decarbonization solutions in each sector.
- 2. Develop coordination and incentive policies** to encourage early deployment of hydrogen solutions and sufficient private-sector investments. These policies should complement sector policies and provide tools to capture the benefits of hydrogen.
 - In the transport sector, ensure strong coordination among governments (to give direction), car manufacturers (to produce and commercialize FCEVs), infrastructure providers (to invest in supply and distribution infrastructure), and consumers (to purchase FCEVs).
 - Ensure the energy market reforms effectively in terms of feed-in tariffs, curtailment management, seasonal balancing capacity remuneration and taxation, while taking into account the benefits hydrogen can deliver to the energy system.
 - Provide financial instruments to leverage private investment with the support of public guarantees, to mitigate risk for early movers.
- 3. Facilitate harmonization of industry standards** across regions and sectors to enable hydrogen technologies and take advantage of scale effects and decrease costs.

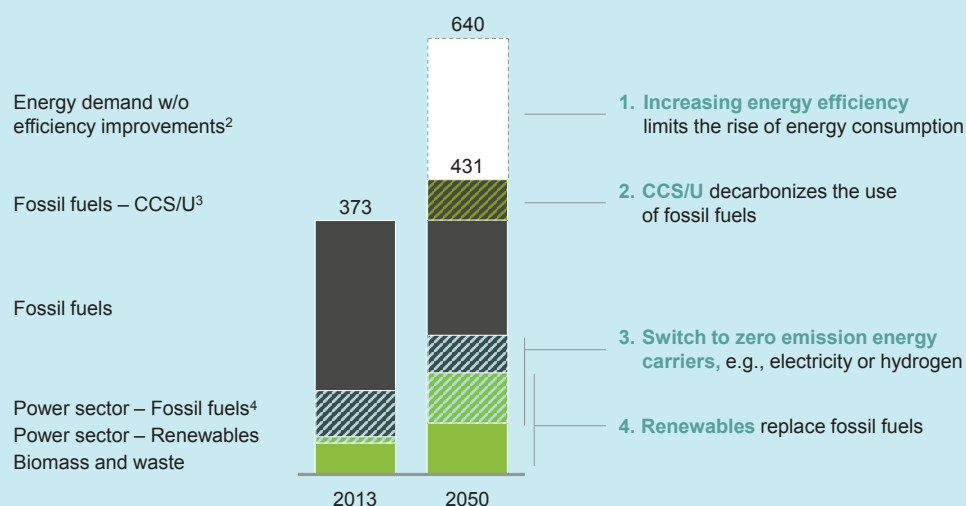
As a council, we invite you to discuss concrete next steps with us.

Appendix I – The energy transition will require changes throughout the energy system

There are several pathways to keep global warming well below 2°C. They all lead to deep changes in the energy system, but all build on common major levers (Figure 9).

Figure 9: Four major levers to decarbonize the energy system

Final energy consumption¹, 2013 and 2050, in EJ



¹ Final energy consumption within the 2°C scenario of the IEA

² Increase of energy demand is determined via the relative increase of CO₂ emissions w/o energy efficiencies

³ The fossil fuels amount processed using CCS/U was determined to be 25% of the total amount of fossil fuels by relating the CO₂ emission reduction compared for the 2DS and 6DS scenario

⁴ The fossil fuel power sector also includes nuclear energy

Source: IEA ETP 2016

Signs of change are emerging. Renewable power supply, electrification, and energy efficiency measures are appearing across sectors. Over the past ten years, global investments in renewable energy sources have been spurred with 16% per year to USD 286 billion in 2015, amplifying price drops: solar power costs have dropped by 70%, and wind power costs have fallen by 50%.

The primary energy supply will shift from fossil fuels to renewables. Today, fossil fuels account for 82% of primary energy consumption; renewable energy sources contribute only 14%, and nuclear 6%. By 2050, renewables are expected to provide 3 to 5 times that amount, and the power sector in particular will move towards zero emission power generation. Fossil sources will still comprise a large part of the energy mix (partially using carbon capture and storage or reuse), at least in the 2°C scenarios. When striving to limit warming to 1.5°C, even more radical changes are needed, including creating negative emissions.

Growth in population and GDP will increase energy demand, even with the planned large effort of energy efficiency measures. Demand for electricity will grow in all three demand sectors – transport, buildings, and industry (e.g., IEA ETP/WEO 2016: electricity + 75%, total energy + 15%). Most scenarios also project increasing demand for other low emission energy carriers (such as other low-emission fuels like hydrogen).

The infrastructure will shift away from transporting, storing, and distributing almost exclusively fossil fuels. By 2050, demand for new power infrastructure will increase. Interconnection capacity in European markets needs to double its throughput by 2030. Incorporating the growing share of renewable energy sources into the European grid will require a total investment of EUR 150 billion, thereof more than EUR 80 billion by 2030. Demand for fossil fuel storage and transport will likely decrease, while storage requirements for biofuels and renewable fuels (hydrogen, ammonia, etc.) will increase to maintain energy security.

Appendix II – Hydrogen essentials

Hydrogen is a well-known, versatile, and clean energy carrier. Hydrogen is widely used in industry (55 Mt global hydrogen consumption in 2015), and most of the related technologies have a long history. The industry track record using hydrogen as well as the current use of hydrogen for buses, warehouses (fork lifts), vehicles, or residential heating (in Japan) shows its safety. Hydrogen usage could be expanded safely to broader public and private end users.

Hydrogen is very versatile and offers several options for production, distribution and use.

There are three main pathways to produce zero-emission hydrogen. Through steam methane reforming (SMR), using bio-methane, or combined with carbon capture and storage or utilization (CCS/U); through electrolysis using electricity generated by renewables; and through gasification of biomass. While SMR and electrolysis are mature technologies, gasification and SMR with CCS/U are pilot phase.

Today, 99% of hydrogen is produced through fossil fuel reforming, as this is currently the most economic pathway. Decarbonization of the current hydrogen production is challenging, but will have a positive impact on CO₂ emissions and can play an important role in realizing cost declines. At the same time, hydrogen production costs from electrolysis of renewables is expected to decrease by 50% as electrolysis capex decreases with increasing application (from 700 - 850 USD/kW chemical energy delivered to 450 - 550 USD/kW by 2050).

Hydrogen can be stored and distributed in various ways. Hydrogen or its compounds have a high (gravimetric) energy density. Transport options are comparable to those of fossil energy carriers and include gaseous/liquefied truck transport, ship transport, and pumping of gaseous hydrogen through pipelines. Blending into the existing natural gas grid is also possible, and might become important, especially during the transition period. Storage options include pressurized tank storage (to reduce volume) and underground storage in salt caverns. Aquifer storage might become possible but is still in the R&D phase. Another alternative is using liquid organic hydrogen carriers for transport and storage, with hydrogen stored chemically in a liquid.

Hydrogen can be used in many ways. To date, hydrogen has been almost entirely (99%) used as feedstock for industrial applications (> 50% in ammonia/fertilizer production, with the rest in refining of (bio)fuels, methanol production, and processing). The use of hydrogen as an energy carrier is beginning to accelerate; in recent years, fuel cell sales have increased more than 30% a year, reaching 60,000 units last year, with over 300 MW of capacity. Costs of fuel cells fell almost 50% during the last 10 years and are projected to drop drastically, with the transition to mass production over the next 10 to 15 years.

Hydrogen can be used safely. Over the past decades hydrogen has been widely used in industry ensuring safe production, storage, transport and utilization. Hydrogen is flammable fuel, and has similar flammable properties as gasoline and natural gas. Hence, similar to other flammable fuels, hydrogen can be used safely when simple guidelines are observed and the consumer has knowledge of its characteristics.

List of abbreviations

BEV	Battery electric vehicle
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CHP	Combined heat/power units
CNG	Compressed natural gas
COP21	Conference of the Parties in Paris in December 2015
FCEV	Fuel cell electric vehicle
GDP	Gross domestic product
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
INDC	Intended Nationally Determined Contributions
OEM	Original equipment manufacturer
PHEV	Plug-in hybrid electric vehicle
R&D	Research and development
R, D & D	Research, development and deployment
ROC	Renewable Obligation Certificate
SDG	Sustainability Development Goals
SMR	Steam methane reforming
TCO	Total cost of ownership



List of sources



- D** Department of Energy, US: *Global energy storage database*, 2016
Department of Energy and Climate Change, UK: *The Future of Heating: A strategic framework for low carbon heat in the UK*, 2012
- E** E4Tech: *Fuel Cell Industry Review*, 2016
E4Tech: *Hydrogen and Fuel Cells: Opportunities for Growth*, 2016
Element Energy: *Strategies for joint procurement of fuel cell buses*, 2016
Enerdata: *Global Energy Statistical Yearbook*, 2016
Energy Information Administration: *Monthly Energy Review*, November 2016
Energy Technologies Institute: *Hydrogen The role of hydrogen storage in a clean responsive power system*, 2015
The European Wind Energy Association: *Wind Energy Scenarios*, 2015
- F** Fuel Cells and Hydrogen Joint Undertaking: *Commercialisation of energy storage in Europe*, 2015
- G** Greenpeace: *PowE[R] 2030*, 2014
- H** Hydrogen Science and Engineering: *Materials, Processes, Systems and Technology Volume 2*, D. Stolten and B. Emonts, 2016
- I** International Energy Agency: *Energy technology perspectives*, 2016
International Energy Agency: *World energy outlook*, 2016
International Energy Agency: *Technology Roadmap Hydrogen and Fuel Cells*, 2015
International Gas Union: *World LNG Report*, 2016
International Renewable Energy Agency: *The Power to Change: solar and wind cost reduction potential to 2025*, 2016
- J** Joint Research Centre: *Scientific and policy report*, 2013
- M** McKinsey & Company: *A portfolio of power-trains for Europe: a fact-based analysis*, 2012
- N** The National Hydrogen Association: *Hydrogen safety*, 2016
- P** Praxair: *Advanced Hydrogen Liquefaction Process*, 2011
- S** SBC Energy Institute: *Hydrogen based energy conversion*, 2014
- U** Umwelt Bundesamt: *Energy target 2050: 100% renewable electricity supply*, 2010
US Department of Energy: *Fuel Cell Technologies Market Report*, 2015
- W** The World Bank: *Annual report*, 2014
World Health Organization: *World Health Statistics*, 2014

Contact and Acknowledgements



Contact

Hydrogen Council

secretariat@hydrogencouncil.com

www.hydrogencouncil.com

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