Chapter 1

Hydrogen as a Pillar of the Energy Transition

Jesus Ochoa Robles, Sofía De-León Almaraz and Catherine Azzaro-Pantel
Laboratoire de Génie Chimique, Université de Toulouse, CNRS, Toulouse, France

ACRONYMS

ADEME	Agency for Environment and Energy Management (Agence de l'environnement et de la maîtrise de l'énergie)
BEV	battery electric vehicle
CaFCP	California Fuel Cell Partnership
CCS	carbon capture and storage
CCU	carbon capture and utilization
CHP	combined heat/power
FC	fuel cell
FCEV	fuel cell electric vehicle
GHG	greenhouse gas
HHV	high heating value
HRS	hydrogen refueling station
ICE	internal combustion engine
IEA	International Energy Agency
LHV	low heating value
METI	Ministry of Economy, Trade, and Industry (Japan)
OPECTS	Parliamentary Office for the Evaluation of Scientific and Technological Options (Office Parlementaire d'Evaluation, des Choix Scientifiques et Technologiques)
PHEV	plug-in hybrid electric vehicle
PtG	Power-to-Gas
PtH	Power-to-Hydrogen
PtM	Power-to-Methane
SMR	steam methane reforming

Hydrogen Supply Chain. https://doi.org/10.1016/B978-0-12-811197-0.00001-4

SNG synthetic natural gas
TPES total primary energy supply
WtW Well-to-Wheel

1.1 INTRODUCTION

The global demand for energy production and environmental concerns are among the most significant issues in the 21st century (Dincer and Acar, 2015). One of the biggest challenges is to meet growing energy demand in an environmentally benign and sustainable manner, as highlighted in the Paris Climate Agreement, which aims to keep global average temperatures from rising by 2°C above preindustrial levels, and to pursue efforts to limit the temperature increase even further to 1.5°C (United Nations, 2015).

Fig. 1.1 shows the world fuel shares of total primary energy, electricity generation, and CO_2 emissions in 2015. According to the International Energy Agency (IEA, 2017a), in 2015, global total primary energy supply (TPES) was 13,649 Mtoe, electricity generation was 24.2 billion MWh, and final consumption was 9384 Mtoe. These numbers are expected to increase with continuing consumption and population increases. In 2050, according to (World Energy Council, 2013), global electricity generation is expected to increase to 53.6

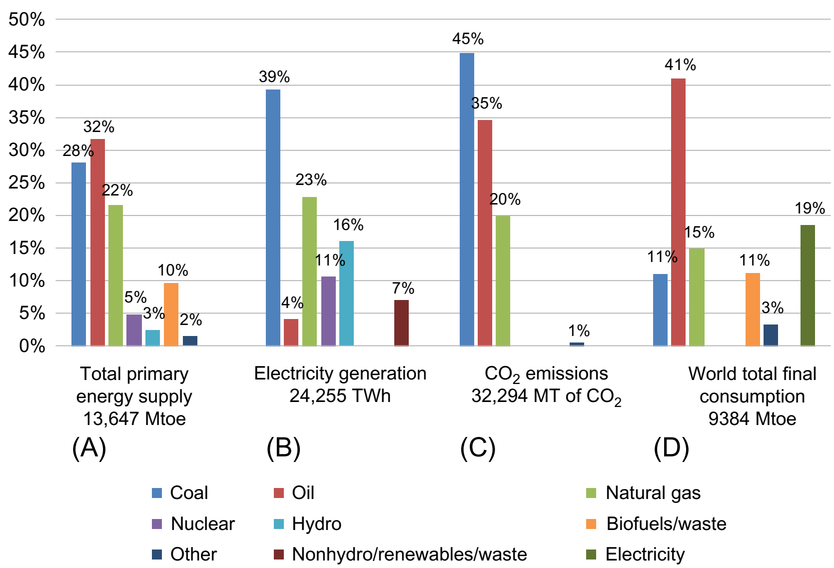


FIG. 1.1 World fuel shares of (A) total primary energy supply, (B) electricity generation, (C) CO_2 emissions in 2015, and (D) world total final consumption by fuel. *(Adapted from IEA, 2017a. International Energy Agency Technical Report. Key world energy statistics [WWW Document]. https://www.iea.org/publications/freepublications/publication/KeyWorld2017.pdf (Accessed 29 December 2017).)*

billion MWh (scenario Jazz) and to 47.9 billion MWh by 2050 (scenario Symphony). More than 80% of the global energy supply comes from fossil fuels (World Energy Council, 2013).

The massive utilization of fossil fuels causes economic and technical issues because they derive from resources that are finite and unequally distributed across the globe. This, in turn, may create a dependency of some countries on others, and thus generate tension. Another issue is that fossil fuel reserves are becoming less accessible as the easily accessible sources are consumed, so that an increase in the price of fossil fuels can be expected. In addition to the economic and technical issues, most of the emissions of human-caused (anthropogenic) greenhouse gases (GHG), mainly CO_2 emissions, come primarily from burning fossil fuels (coal, hydrocarbon gas liquids, natural gas, and petroleum) for energy use. Fig. 1.1 also shows that 99% of global GHG emissions were caused by fossil fuels. If emissions follow a commonly used business-as-usual scenario, there is a 93% chance that global warming will exceed 4°C by the end of this century, as recently highlighted in Brown and Caldeira (2017).

The development of clean energy solutions is, then, a key prerequisite to pave the way for the energy transition in which there is a switch from a system fueled primarily by nonrenewable, carbon-based energy sources to one fueled by clean, low-carbon energy sources. Four main levers are available to decarbonize the energy system: improving energy efficiency, promoting renewable energy sources, switching to low- or zero-carbon energy carriers, and developing carbon capture and storage (CCS) as well as utilization (CCU).

In that context, the concept of mitigating climate change by transitioning to an energy system with fewer greenhouse gas emissions, and more sustainable, even circular, consumption and production, is particularly attractive.

For that, hydrogen, as a near zero-emission energy carrier if produced from renewable energy sources, is viewed as an attractive candidate to overcome the challenges surrounding the energy transition. Some of the advantages have been listed in Dincer and Acar (2015): (i) high energy conversion efficiencies; (ii) production from water with no emission; (iii) abundance; (iv) different forms of storage (e.g., gaseous, liquid, or in together with metal hydrides); (v) long distance transportation; (vi) ease of conversion to other forms of energy; (vii) higher HHV (high heating value) and LHV (low heating value) than most of the conventional fossil fuels.

This introductory chapter is devoted to exploring the potential of hydrogen to fulfill these objectives and to presenting the barriers that must be overcome. The remainder of this chapter is organized as follows. Section 1.2 is dedicated to the major roles that hydrogen is likely to play in the economy, with a specific focus on decarbonization. The concepts of Power-to-Gas and hydrogen supply chains are then presented. The vision that is laid out is based on a systemic view of the potential of hydrogen in the energy system. Section 1.3 illustrates hydrogen supply chains for mobility purposes. Section 1.4 then presents the barriers that must be overcome and the roadmaps that have been reported for hydrogen deployment. They are often used by international organizations, businesses, and industry to address the challenges of hydrogen scaleup. This section also discusses transition plan scenarios. This chapter concludes that more precise analyses are necessary to design the hydrogen supply chain.

1.2 MAJOR ROLES OF H_2 IN THE ECONOMY

1.2.1 Decarbonization of Key Sectors of the Economy

Hydrogen is likely to play a major role in decarbonizing key sectors of the economy. Seven actions have been identified in Hydrogen Council (2017a), as illustrated in Fig. 1.2:

- *Favoring large-scale, efficient renewable energy integration*. Hydrogen offers valuable advantages, as it avoids CO_2 and particle emission if produced from renewables, can be deployed at large scale, and can be made available everywhere. Hydrogen can improve the efficiency and flexibility of an energy system in two ways: (1) the excess of electricity can be converted by electrolysis into hydrogen and be used in other sectors, such as transport, industry, and buildings; and (2) it can be used as a carbon-free storage medium as a way to store energy for long periods. Three modes of storage can be considered for hydrogen, namely, as a compressed gas, as a liquid, or as solid absorbing metals (Florida Solar Energy Center, n.d.).

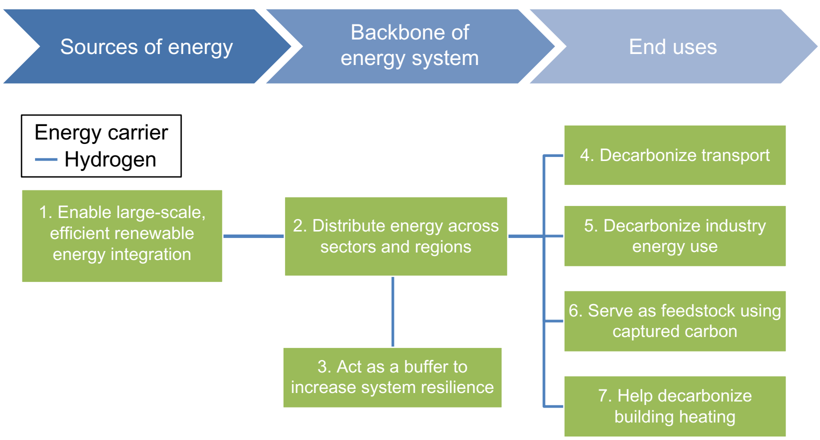


FIG. 1.2 Roles of hydrogen in decarbonizing major sectors of the economy. *(Adapted from Hydrogen Council, 2017a. How hydrogen empowers the energy transition [WWW Document]. Rep. January. http://hydrogeneurope.eu/wp-content/uploads/2017/01/20170109-HYDROGEN-COUNCIL-Vision-document-FINAL-HR.pdf (Accessed 29 December 2017).)*

- *Energy distribution across sectors and regions*. Some countries are not well positioned to generate energy with wind or solar power alone. For other countries, time may be needed to raise the necessary investment. As hydrogen has a high energy density and can be easily transported, it can (re)distribute energy effectively and flexibly. Hydrogen may be transported as a pressurized gas or as a cryogenic liquid. Gaseous hydrogen can be transported by highly pressurized pipelines or by tube trailers. Liquefied hydrogen can be transported in tankers (Dagdougui, 2012).
- *Acting as a buffer to increase system resilience*. Hydrogen can help align global energy storage with changing energy demand. Its physical characteristics make it well suited to serve as an energy buffer and strategic reserve. By 2030, 250–300 TWh of surplus renewable electricity are expected to be stored in the form of hydrogen for use in other segments (Hydrogen Council, 2017a).
- *Transport decarbonization*. Nowadays, battery electric vehicles (BEV) are already used to reduce CO_2 emissions. However, fully decarbonizing transport will require deployment of fuel cell electric vehicles (FCEVs), having the same performance as gasoline vehicles. FCEVs have several advantages: they actually zero emissions, have a good autonomy (500 km), and refuel quickly (from 3 to 5 min) (Ball and Weeda, 2015). Decarbonizing transport is particularly challenging because it represents a large share of total energy and more than 30% of hydrogen's total CO_2 abatement potential is expected in this sector (Hydrogen Council, 2017a).
- *Decarbonization of industry energy use*. Fossil fuels are the most used energy sources for industrial processes. Hydrogen can be an alternative when it is available as a byproduct of the chemical industry or when a specific industry needs an uninterruptable power supply. As hydrogen can be burnt in hydrogen burners or be used in fuel cells, it offers a zero-emission alternative for heating. Nowadays, hydrogen is only used in industry for low-grade heat applications (process heating and drying), but is expected to be used with fuel cells in the future for not only low-grade, but also high-grade heat needs (Hydrogen Council, 2017a).
- *Serve as feedstock using captured carbon*. Hydrogen could be used to convert captured carbon into usable chemicals, such as methanol, methane, formic acid, or urea. This technology is still in the research phase, and it is expected to be developed in the next 15 years. For example, in Iceland, geothermal CO_2 is used to generate electricity to produce hydrogen and ethanol, by two thermophilic bacteria (Koskinen et al., 2008). By 2030, 10–15 million tons of chemicals may be produced from such renewable feedstock (Hydrogen Council, 2017a).
- *Contribution to the decarbonization of building heating*. Heat generation in buildings and industry accounts for more than half of global final energy consumption and a third of global energy-related carbon dioxide (CO_2)

emissions (Dodds et al., 2015; IEA, 2014). Hydrogen technologies, such as fuel cell micro CHPs (combined heat/power units), serve as energy converters. Possible roles for hydrogen and fuel cell products include the substitution of hydrogen for natural gas in some processes, and the use of CHP technologies. For the purpose of illustration, about 190,000 buildings are already heated with hydrogen-based fuel cell micro CHPs, mainly in Japan.

1.2.2 Hydrogen Supply Chains and the Power-to-Gas (PtG)/Power-to-Hydrogen (PtH) Concept

The hydrogen supply chain is a concept in the life cycle perspective, consisting of several echelons, including selection of energy source, hydrogen production, hydrogen transportation, hydrogen refueling, and hydrogen utilization subsystems (see Fig. 1.3). Of course, there is not a unique hydrogen supply chain. Even if there is clear evidence for the use of renewable sources, as already highlighted from an environmental viewpoint, the switch to a 100% renewable scheme can only be gradual, in order to satisfy both economic and environmental concerns as well as to take into account the availability of the energy source.

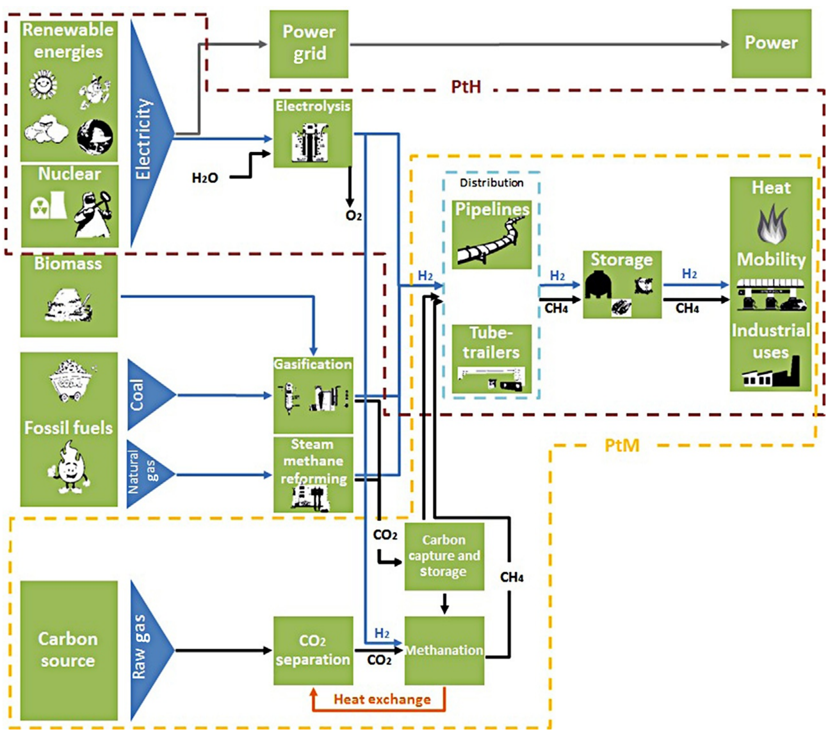


FIG. 1.3 Power-to-Gas supply chains.

Hydrogen can thus be produced using different energy sources (renewables or fossil fuels) and with different technologies (mainly steam methane reforming (SMR), electrolysis, and gasification) and distributed via pipelines or tube trailers. Fig. 1.3 also embeds other options that may be encountered.

The key roles of hydrogen in the future energy system emphasize the PtG concept, in particular the PtH one (brown dotted line in Fig. 1.3). PtG refers to the process in which electrical energy is converted into chemical energy via gas production. The main purpose is to store surplus electricity from fluctuating renewable sources by generating hydrogen (H_2) via water electrolysis, with optional methane (CH_4) synthesis from carbon dioxide (CO_2) and H_2 (methanation process, yellow dotted line). This "green hydrogen" produced by renewable resources without pollution allows for the storage, transportation, and reuse of the energy when needed.

The production of synthetic methane (synthetic natural gas, SNG) results in lower total efficiency but could be advantageous in terms of feeding the produced energy carrier into the gas distribution grid. In contrast to the case of pure H_2, the injection of SNG is not limited in amount. The SNG or H_2 can be used not only in electricity production, but also in other applications, such as mobility via fuel cells or natural gas vehicles (Fig. 1.3).

A Power-to-Gas supply chain, as shown in Fig. 1.3, is ultimately a network of integrated facilities, or nodes, that are interconnected and work together in a specific way. The network begins with primary energy sources and terminates with end uses. A supply chain is not unique, and one typical feature of a PtG supply chain, as a segment of a hydrogen supply chain, is the large number of configurations that can be encountered from energy sources, production, distribution, and storage to final uses.

The conversion to hydrogen and methane makes the transport of renewable energy outside the power grid possible, also allowing large-scale, long-term storage. The chemical energy carriers can also be converted to electricity and a multitude of other pathways are possible, resulting in different efficiencies of the total system.

As highlighted in Lehner et al. (2014), hydrogen is the first possible end product of the Power-to-Gas process chain. The efficiency of the conversion of methanation is reported to be 70%–85% in the case of the chemical path, and greater than 95% for the biological path (Grond et al., 2013). The main asset of SNG is its unrestricted compatibility with the natural gas grid. The so-called "repowering" of methane to electricity in combined cycle plants opens the possibility of producing electric power in areas far away from the renewable power sources, connected by an already existing gas grid. However, the efficiency of this option is the lowest of all possibilities (see Table 1.1).

Slightly better conversion efficiencies can be achieved by producing electricity from hydrogen. Gas turbines, fuel cells, or reverse fuels cells can be utilized for this purpose. The efficiency for PtG systems is increased with recovery of the released heat of the system, for example in district heating or

TABLE 1.1 Efficiencies for Different Power-to-Gas Process Chains (Sterner et al., 2011)

Path	Efficiency	Boundary Conditions
Electricity to gas		
Electricity → Hydrogen	54–72	Including compression to 200 bar (underground storage working pres.)
Electricity → Methane (SNG)	49–64	
Electricity → Hydrogen	57–73	Including compression to 80 bar (feed in gas grid for transportation)
Electricity → Methane (SNG)	50–64	
Electricity → Hydrogen	64–77	Without compression
Electricity → Methane (SNG)	51–65	
Electricity to gas to electricity		
Electricity → Hydrogen → Electricity	34–44	Conversion to electricity: 60%, compression to 80 bar
Electricity → Methane → Electricity	30–38	
Electricity to gas to combined heat and power (CHP)		
Electricity → Hydrogen → CHP	48–68	40% electricity and 45% heat, compression to 80 bar
Electricity → Methane → CHP	43–54	

in industrial plants nearby (Table 1.1). The pressure level has a significant influence on the global efficiency.

A thorough investigation of PtG systems is particularly interesting from a systemic viewpoint in the context of the energy transition and the different pathways should not be considered in isolation. Some recent investigations have highlighted that the PtG (Götz et al., 2016) might play an important role in the future energy system. However, technical and economic barriers must be solved and a critical aspect of the PtG process is the availability of CO_2 sources. Concerning methanation, biological and thermochemical methanation processes have potential for integration into the PtG process chain. Biological methanation is a simple process that tolerates gas impurities but induces slower reaction times and has higher power requirements, leading to a lower process efficiency than for thermochemical methanation. Thermochemical methanation is attractive for its high reaction rates and the high temperature level of thermochemical methanation results in more options for process integration, yielding more efficient processes. Due to the higher process temperature and the resulting higher reaction velocity, thermochemical methanation requires much lower reactor volumes for a certain feed gas flow than biochemical methanation. However, full CO_2-conversion in a single step thermochemical methanation reactor cannot be achieved due to thermodynamic equilibrium limitations (Götz et al., 2014).

In this chapter, specific attention is given to hydrogen supply chains for which many of the required technologies are already available today (Hydrogen Council, 2017a).

1.3 HYDROGEN SUPPLY CHAINS FOR MOBILITY PURPOSE

Hydrogen infrastructure and technologies are seen as an important part of the future energy mix, due to their advantages in terms of CO_2 reduction potentials in the transport sector, which has been shown to be one of the hardest to decarbonize (IEA, 2017a).

1.3.1 Environmental and Energy Benefit

Fig. 1.4A presents GHG emissions in the European Union (EU) and shows that energy use is the main source of GHG. Among the various sectors, the energy industry (29%) and transport (21%) are the most polluting. It can be observed that the decrease in GHG emissions is mainly due to significant declines in the energy industry (−7%) and residential-tertiary (−15%) sectors (Institute for Climate Economics and Ministère de l'Environnement, de l'Énergie et de la Mer, 2016).

As GHG emissions are declining in the industrial sector, the transport sector remains as one of the challenges to be tackled. Hydrogen thus represents an interesting fuel alternative in the transportation sector because this sector contributes approximately 836 Mt. CO_2 eq emissions in Europe and 14 Mt. CO_2 in France (Fig. 1.4B), and technologies related to FCVs are being developed rapidly (Institute for Climate Economics and Ministère de l'Environnement, de l'Énergie et de la Mer, 2016).

In France, as in most countries worldwide, there is a dependency on fossil fuels. Fig. 1.4B shows the contribution of GHG emissions by sector. The transport sector contributes significantly so that special attention must be paid to it. To more effectively reduce pollution, the transportation sector requires the development of both new vehicular technologies and new fuels (Cipriani et al., 2014). Hydrogen, which can be used in vehicles equipped with the

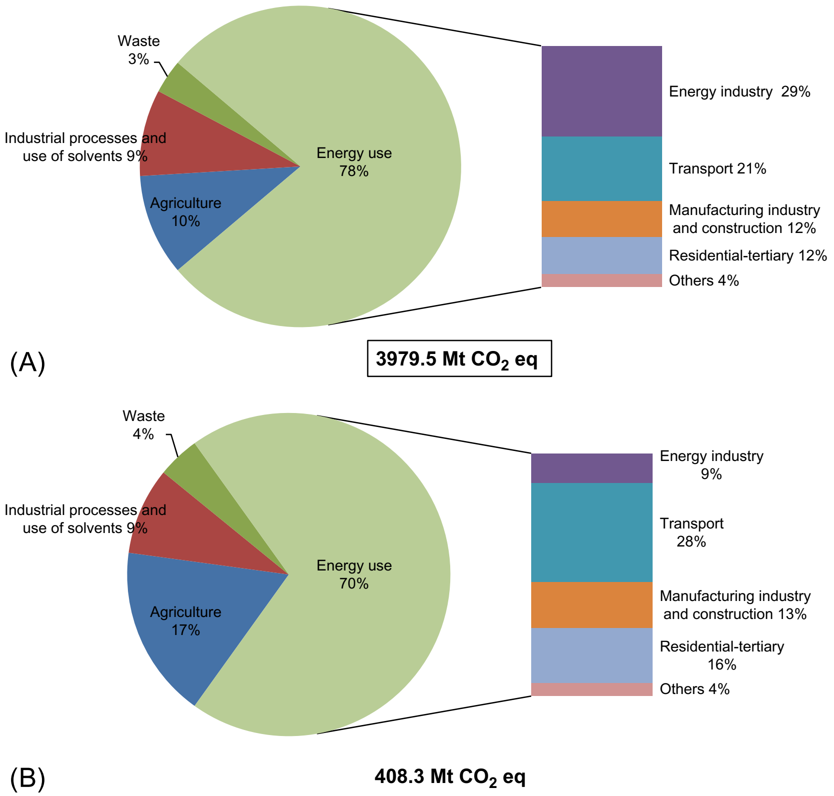
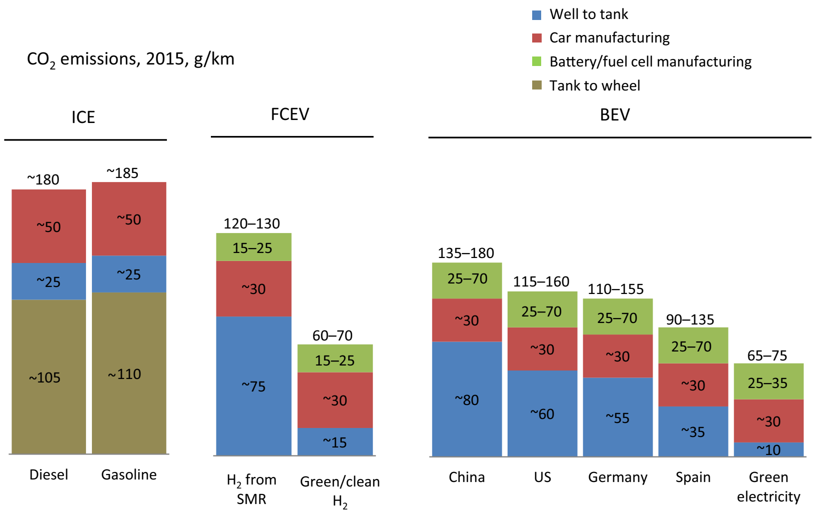


FIG. 1.4 Greenhouse gas emissions by sector in (A) Europe and in (B) France in 2014. *(Adapted from Institute for Climate Economics, Ministère de l'Environnement, de l'Énergie et de la Mer, 2016. Chiffres clés du climat France et Monde ÉDITION 2017.)*

technology for converting hydrogen into electricity, is thus particularly attractive because the carbon emissions of FCEVs are very low when the whole life-cycle is considered. Even if hydrogen is entirely produced from natural gas through steam methane reforming (SMR) without the use of carbon capture, FCEV emissions are 20%–30% lower than those of ICEs. In total, an FCEV powered by green or clean hydrogen in our example could achieve combined CO_2 emissions of 60–70 g per km (Fig. 1.5) (Hydrogen Council, 2017b).

Local air emissions, responsible for particulate matter, ozone, and acid rain, as well as noise, could be significantly reduced by the introduction of hydrogen fuel cell vehicles. Emissions of NOx, SO_2, and particulates can be reduced by 70%–80% compared to a case without hydrogen (Ball and Wietschel, 2009). Due to the growing number of megacities worldwide, the importance of improving urban air quality is of major importance. According to (Mobilité Hydrogène France, 2016), the societal cost savings are about 500 M€ over the 2015–30



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

FIG. 1.5 CO_2 emissions for the ICE, FCEV, and BEV vehicles. *(Adapted from Hydrogen Council, 2017b. Hydrogen scaling up. A sustainable pathway for the global energy transition [WWW Document]. http://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf (Accessed 4 January 2018).)*

period; in particular, the societal cost of the CO_2 emissions, noise, and pollutants evaluated for an ICE (internal combustion engine) vehicle, which came to 510 € per year, is reduced to 160 € for an FCEV.

These elements contribute to make hydrogen an accepted clean energy carrier worldwide, because it is source independent and has a very high energy content per mass compared to petroleum or the actual fuels (120 MJ/kg versus 46 MJ/kg, respectively) (Dutta, 2014). Also, liquid hydrogen possesses a very low density of 0.07 g/cm^3, one-tenth that of gasoline. These properties provide some advantages and disadvantages. On the one hand, an advantage is that hydrogen stores around twice the energy of gasoline/diesel, being energetically more efficient than gasoline. On the other hand, it requires a storage volume four times greater than gasoline (Sharma and Ghoshal, 2015).

(Ball and Weeda, 2015) developed a study describing the process and use of hydrogen in transportation. Currently, in order to achieve a deep decarbonization of road transport, three options exist:

- battery electric vehicles (BEV), using electricity as fuel;
- fuel cell electric vehicles (FCEVs), using hydrogen as fuel; and
- plug-in hybrid electric vehicles (PHEV), combining a battery system with a fuel cell system.

Nowadays, approximately 500,000 electric vehicles (PHEVs and BEVs) are used globally (mainly in the United States, Europe, and China), and in the coming years, most of these vehicles will come from China (Ball and Weeda, 2015).

The main advantage of this kind of vehicle is that the distribution infrastructure of the energy source or fuel (the electric energy) is available, and thus, automatically, the costs are reduced in comparison with alternatives that are in the development phase.

The market for hydrogen is expected to increase in the future. In France, the demand for 2030 is expected to reach 90,000 t of hydrogen, versus only 3,000 t in 2016 (Fig. 1.6). Obviously, electricity demand will also increase, reaching 3 TWh in 2030. In the transport sector, almost 800,000 FCEVs are expected to be found in 2030, requiring the installation of 600 hydrogen refueling stations (HRS) to satisfy the automotive demand. This situation contrasts with the current one, with only 23,000 FCV and 96 HRS to cover vehicle refueling needs.

1.3.2 Hydrogen FCEV

Hydrogen is one of the principal alternatives in the future of road transport (Ball and Weeda, 2015):

- FCEVs using hydrogen as fuel are real zero-emission vehicles, and in the last years, the efficiency of hydrogen has increased (50%–60%).
- As FCEVs are basically electric vehicles, they combine the benefits of electric driving (silence and smoothness) with the power of using hydrogen as a fuel (autonomy of 500 km and 3–5 min of refueling time). Their autonomy is two or three times an electric car (Bettayeb, 2017).
- Because of more favorable energy density characteristics compared to batteries, hydrogen and fuel cells are better suited to electrify a wide range of road vehicles, ranging from small cars to buses and light-duty trucks.
- Hydrogen can be produced from many different energy sources, from CO_2-free and renewable energy sources (wind, water, sun, etc.) to fossil fuels (natural gas, coal). Clearly, the use of renewable energy sources is the priority in order to make hydrogen a real and totally CO_2-free fuel.

Fig. 1.7 presents FCEV vehicles that are available in the market, with the emblematic Toyota Mirai. In the United States, a Toyota Mirai is available for sale at $57,500 USD and for lease at $349/month (IEA, 2017b).

Fuel cells (with a capacity of 10–30 L) are composed of an electrode sandwiched between two electrodes (anode and cathode), as seen in Fig. 1.8. The bipolar plates at the extreme sides of the cell help to distribute and collect the gases. Then, hydrogen flows through the labels to the anode, where the hydrogen molecules are separated into protons and electrons. The electrons follow a circuit until the cathode (they are electricity ready to be used). The oxygen gas, obtained from the air, flows to the cathode. After the electrons are used and

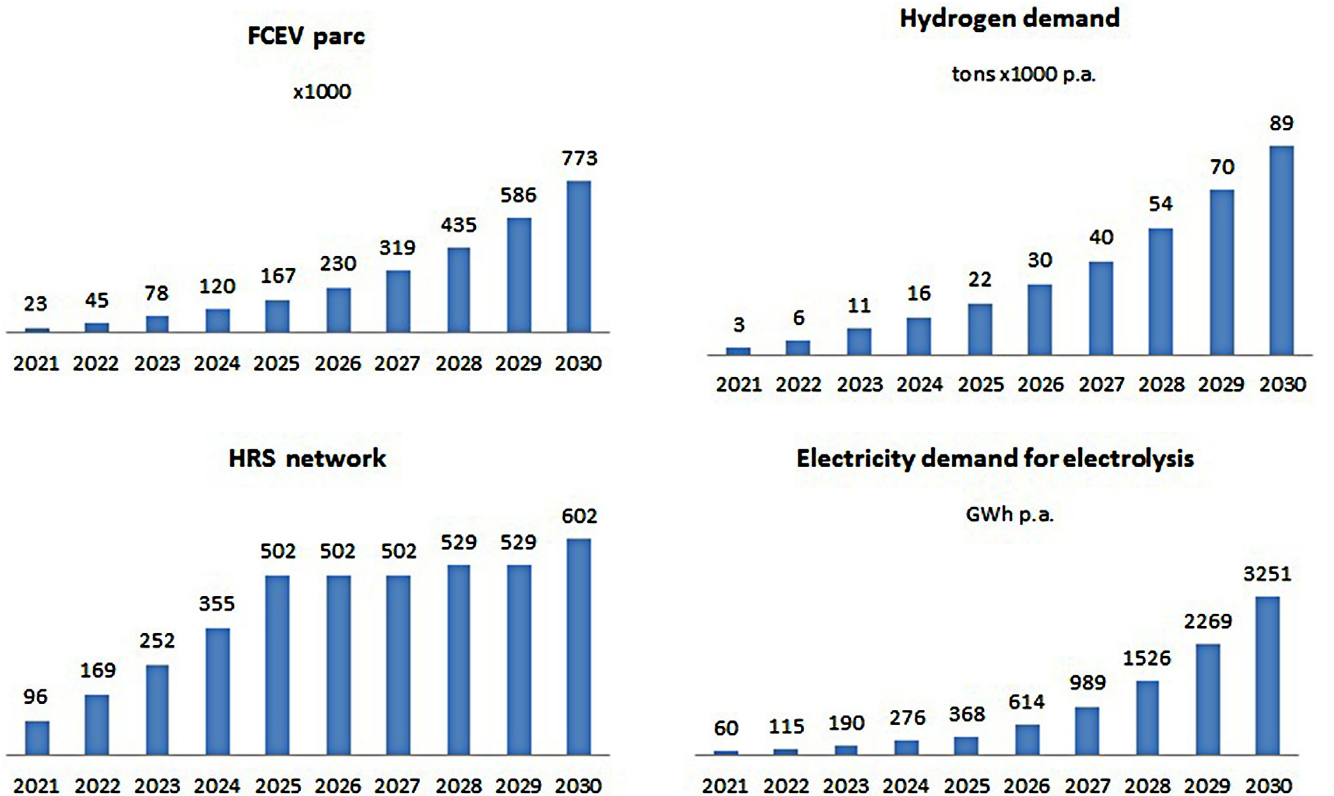


FIG. 1.6 FCEV market evolution in France. *(Adapted from Mobilité Hydrogène France, 2016. H2 MOBILITÉ FRANCE. Study for a Fuel Cell Electric Vehicle National Deployment Plan [WWW Document]. http://www.fch.europa.eu/sites/default/files/Smart%20Spec%20Fabio%20Ferrari%20%28ID%202436338%29%20%28ID%202497336%29.pdf (Accessed 31 December 2017).)*

FIG. 1.7 FCEV vehicles (IEA, 2017b).

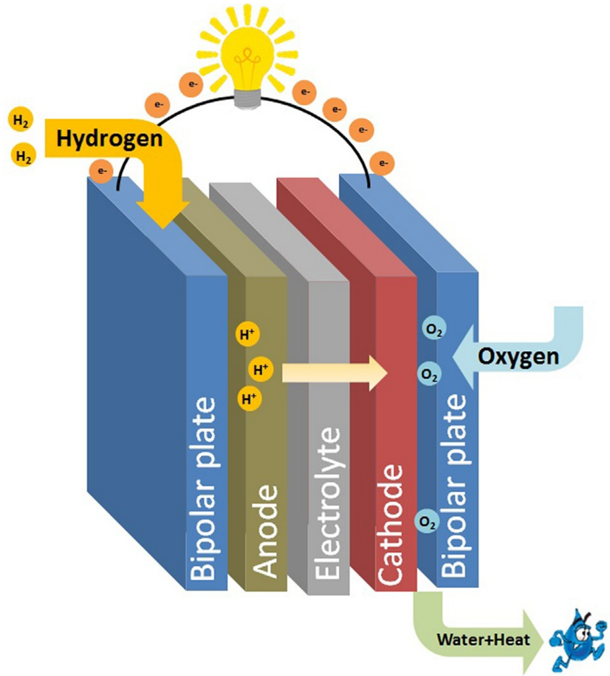


FIG. 1.8 A single fuel cell. *(Adapted from DOE Hydrogen Program, 2006. Hydrogen Fuel Cells.)*

return, they react with oxygen and the hydrogen protons at the cathode and form water that is released from the fuel cell (DOE Hydrogen Program, 2006).

1.3.3 Hydrogen Safety

Hydrogen is a flammable gas with a wide flammability range (4%–75% by volume) and relatively low ignition energy (0.02 mJ) (McCarty et al., 1981). It has a very low density and therefore must be stored at high pressure to achieve enough mass for practical use. The ease of ignition and high storage pressure of hydrogen are responsible for a large portion of the risk associated with hydrogen usage.

Hydrogen also has the ability to attack—and damage to the point of leakage—certain materials that are used for the construction of storage

TABLE 1.2 Autoignition Temperature of Comparable Fuels (Mazloomi and Gomes, 2012)

Fuel	Autoignition Temperature (°C)
Hydrogen	585
Methane	540
Propane	490
Butane	405
Methanol	358
Gasoline	246–280
Diesel	210

containers, piping, valves, etc., referred to as hydrogen embrittlement (Cramer and Covino, 2003).

To ensure the safe use of hydrogen, leakage must be prevented, because hydrogen is flammable and explosive, and any "confined" situation can be dangerous, requiring the use of appropriate safety devices[1] (fans, sensors, etc.). A good knowledge of these dangers and their consequences is needed in order to implement safe designs for systems using hydrogen. Besides, hydrogen is nontoxic and is very volatile.

The low density and high diffusion coefficient of hydrogen are safer than other fuels. Generally, wider ignition limits, lower energies, and lower temperatures for ignition make a fuel less safe, as they increase the beginning and extent of fire. One of the most important safety parameters is the autoignition temperature, that means, the temperature at which the material will ignite without any external ignition source. As seen in Table 1.2, hydrogen has the highest autoignition temperature, and this is a positive safety characteristic among various fuels.

A fuel is considered to be less safe if it possesses higher flame temperature, explosion energy, and flame emissivity, because its fire would be more damaging. When comparing hydrogen, gasoline, and methane, hydrogen turns out to be the safest fuel with a safety factor of 1, compared with 0.8 and 0.53 for methane and gasoline, respectively (Sharma and Ghoshal, 2015).

Hydrogen is nontoxic, yet extremely flammable. However, the flame temperature is almost the same as the others fuels, and its fire lasts 0.1–0.2 times that of a hydrocarbon consuming fire with the same volume, and the inhalation

1. It is difficult to detect without appropriate sensors because it is both colorless and odorless, and airborne flame is almost invisible.

of its smoke is absolutely harmless (Mazloomi and Gomes, 2012). Because of its nontoxicity, a hydrogen leak cannot cause environmental damage, and cannot be detected by simple smell.

In 1990, the International Standard Organization (ISO) established a technical committee to develop standards in the field of production, storage, transport, and various applications of hydrogen as, for example, the European Integrated Hydrogen Project (EIHP), which makes proposals for the regulation of FCEVs and hydrogen activities (Devillers et al., 2000). Another project concerned with safety issues on a technical level is the European Network of Excellence, HySafe (HySafe—Safety of Hydrogen as an Energy Carrier, 2007). Placing hydrogen at public fueling stations and using it in vehicles has created a need for new safety requirements. Hydrogen storage is regarded as one of the most critical issues that must be solved before a technically and economically viable hydrogen infrastructure can be implemented. In fact, without effective storage systems, a hydrogen economy will be difficult to achieve (Dagdougui, 2012).

1.4 DEPLOYMENT STRATEGIES OF HYDROGEN SUPPLY CHAIN

Many of the required technologies are already available today and a current challenge is to deploy hydrogen infrastructure and scale up manufacturing capacities so as to achieve competitive cost and mass market acceptance. The hydrogen contribution to the energy transition has accelerated over the last years, following the phases of precommercialization in all sectors. Several improvements along the entire value chain of hydrogen need yet to be made, mainly in the field of cost and performance (Fig. 1.9) (Hydrogen Council, 2017a).

1.4.1 Barriers to be Overcome for Hydrogen Supply Chain Deployment

A key point in the development of hydrogen supply chains is the demonstration of the feasibility of the infrastructure while economic and social obstacles must be overcome.

1.4.1.1 Economic Barriers

Economic obstacles include the cost of FCs and of hydrogen and the lack of cash flow and of a supply base during the first phase of deployment. The main institutional hurdles are difficulties of policy and regulatory frameworks for disruptive technologies moving from demonstration to large-scale deployment across the "valley of death" (Fig. 1.10). Societal barriers include insufficient coverage of FCs and hydrogen technologies (Cantuarias-Villessuzanne et al., 2016; Creti et al., 2015), such as the lack of recognition of hydrogen and its benefits in

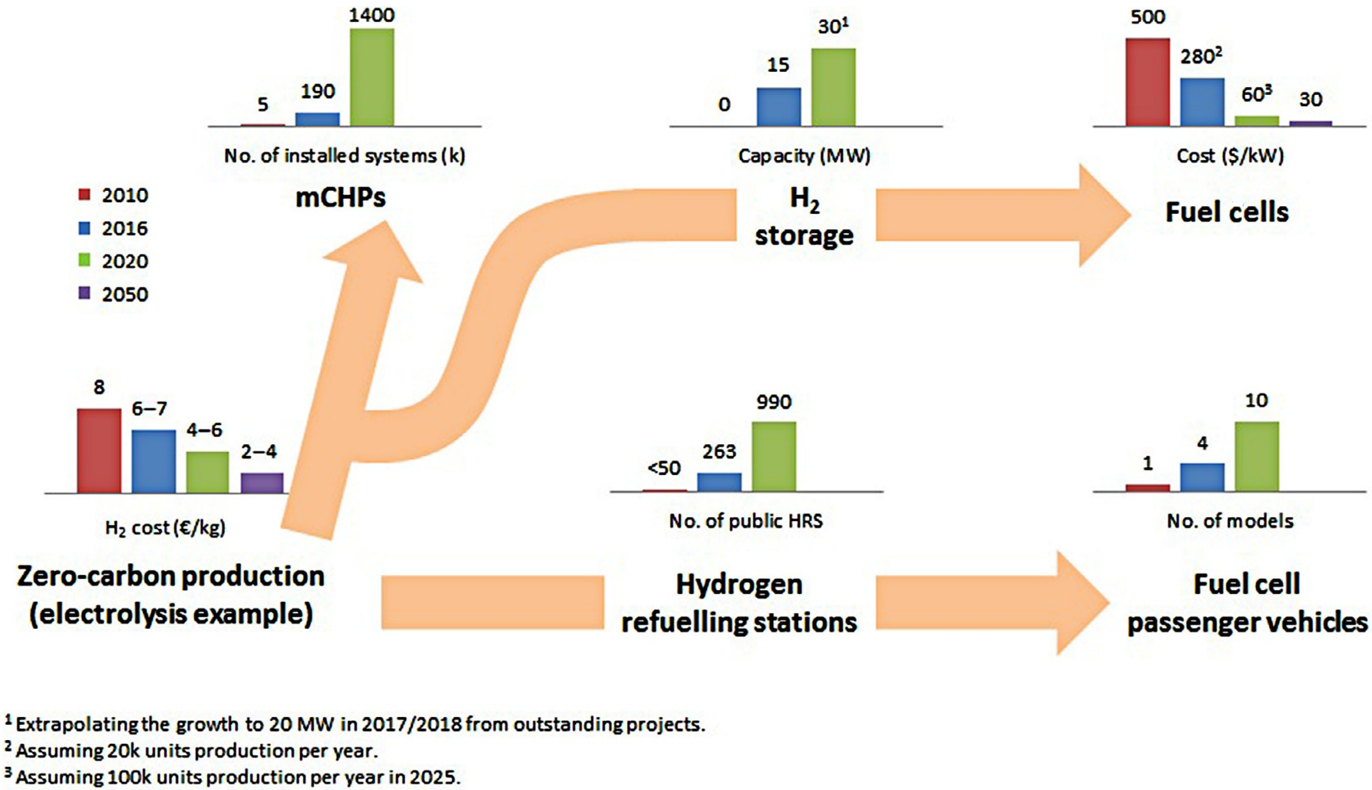


FIG. 1.9 Examples of hydrogen technologies and the continuous improvements along the entire value chain. *(Adapted from Hydrogen Council, 2017a. How hydrogen empowers the energy transition [WWW Document]. Rep. January. http://hydrogeneurope.eu/wp-content/uploads/2017/01/20170109-HYDROGEN-COUNCIL-Vision-document-FINAL-HR.pdf (Accessed 29 December 2017).)*

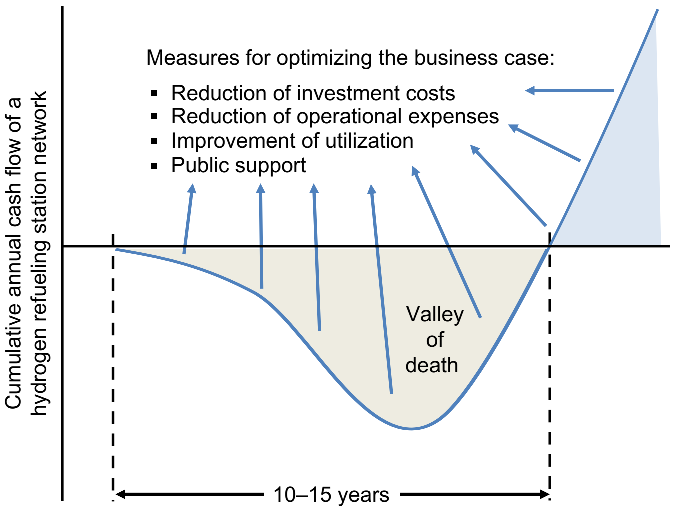


FIG. 1.10 Valley of death in hydrogen deployment from IEA (2015).

the energy transition, the absence of mechanisms to mitigate and share the long-term risks of the initial 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 (Hydrogen Council, 2017a).

As highlighted in many investigations, the deployment of the hydrogen infrastructure is expected to be gradual. The main problem lies in its chicken-and-egg dilemma. Without a convenient hydrogen refueling infrastructure, there is a lack of interest in buying FCEVs, and the car manufacturers are not motivated to produce these vehicles. If there are no options for FCEVs to create a demand and market conditions, there is no interest in building a network of hydrogen refueling stations (HRS) (Ball et al., 2015). For that to occur, both sides of the network must be developed simultaneously and gradually. During the first decade of developing a hydrogen supply infrastructure for mobility, the costs are highest, exceeding 10 €/kg, mainly caused by the low rate of utilization of the HRS and the small number of FCEVs on the road. Over time, hydrogen costs are expected to fall. In the next 5 years, in the early commercial phase, the number of HRS and FCEVs is expected to increase, reducing the delivery cost to 7–9 €/kg, thus making hydrogen competitive with fossil fuels for the first time. With the arrival of the commercial phase, with a mature market, a well-developed HRS network and the current use of FCEVs, the hydrogen cost is expected to be in the range 4–5 €/kg. In fact, in 2030, 800,000 FCEVs (including large, mid-size and light commercial vehicles), 600 HRS and a demand of 90,000 t of hydrogen are expected to be reached in France, versus only 45 FCEVs, 96 HRS and a hydrogen demand of 6 t in 2022 (Mobilité Hydrogène France, 2016).

Risk mitigation hinges upon close collaboration among many stakeholders involved in the hydrogen supply chain, such as the different actors directly involved in the various echelons of the supply chain, power grid providers, car manufacturers, as well as local, regional, and national authorities.

1.4.1.2 Barriers Related to Social Acceptance and Safety

Effective public education will be necessary to achieve the widespread social acceptance of hydrogen technologies. Yet, as aforementioned, H_2 is commonly used in industry and is actually no more dangerous than other flammable fuels, such as gasoline and natural gas. Nevertheless, under specific conditions, hydrogen can behave dangerously. The burning or explosion of hydrogen causes most fatal accidents, so that the development of hydrogen infrastructure requires stringent safety considerations (Kim and Moon, 2008; Hake et al., 2006).

In the transition to a hydrogen economy, the public perception of safety is a critical issue. Although the public view on hydrogen is in general positive, an early large accident could change this perception quickly.

Convincing the consumer that FCEVs are safe will be one of the major tasks during the early market introduction phase. International hydrogen technology-related training programs are the core of the European HySafe project that will be further developed (IEA, 2017b).

The social perception of the use of hydrogen in FCEVs has been investigated (Bellaby et al., 2016). This research combines a quota sampling survey of 1003 adults across three disparate "travel-to-work areas" in England with representative focus groups. According to this study, "participants highlighted the benefits in hydrogen energy, not presenting any issues for its safety, discussing their risks, although the costs were considered a problem."

The study AIDHY/CEA (Le Duigou, 2010) conducted in 2010 was a decision support for the identification of societal changes brought by new hydrogen technologies. It analyzed the acceptability among users and experts. According to this presentation, the public was not worried by safety issues surrounding the use of hydrogen. Potentially 77% of people said they would be interested in this fuel, and strong acceptance appeared in highly urban areas.

The organization of public debates is also of tremendous importance (e.g., BEV vs. FCEV); one of the challenges is to demonstrate that they are part of a long-term vision. In France, the National Debate for the Energy Transition (Débat national sur la transition énergétique, 2013) allows for the discussion of some issues. How can France move toward energy efficiency and energy conservation? How to achieve the energy mix targets? Which renewable energies should France rely on? These issues have been discussed by civil society and experts. The Regional Innovation Agency MPI (Midi-Pyrénées Innovation) organized this debate on June 3, 2013 in Toulouse, treating the "hydrogen as fuel" topic based on the results obtained in a case study of the Midi-Pyrénées region (De León Almaraz, 2014).

Communication efforts will always be important in the transition phase, because each stakeholder has its own "language" and a large quantity of analysis about potential scenarios regarding the H_2 economy is mandatory.

1.4.2 Initiatives for Infrastructure Development and Roadmaps

Hydrogen supply chains have been the subject of various roadmaps and scenarios that have been developed at regional, national, and multinational levels. These roadmaps identify the steps needed to accelerate the implementation of radical technology changes, in order to help enable governments, industry, and financial partners to make the right choices (De León Almaraz, 2014). Their main objective is to evaluate some industrial, technological, environmental, and social issues and to identify the main obstacles associated with the hydrogen economy. They all agree that a key point in the development of the hydrogen supply chain is the demonstration of the feasibility of its infrastructure, though many technical, economic, and social obstacles must be overcome (Hydrogen Council, 2017b; IEA, 2017b).

This assessment agrees with the observation made from a literature review of recent scientific publications that emphasizes the need to develop systemic studies in order to demonstrate the feasibility of the sector and to validate the technical and economic interest in the production and recovery of hydrogen produced from renewable sources. The use of hydrogen for transport applications has generated the most interest and, subsequently, has been studied more extensively than stationary applications. Very few of the national roadmaps and hydrogen scenarios reviewed here consider both of these applications.

A factual and well-documented report entitled "A portfolio of power-trains for Europe: a fact-based analysis" (McKinsey & Company, 2010) provided a comparison of four different powertrains—BEVs, FCEVs, PHEVs and ICEs—on economics, sustainability, and performance across the entire supply chain (Wheel to Wheel, WtW) between 2010 and 2050, based on confidential and proprietary industry data. Various scenarios with different potential hydrogen demand behaviors (three scenarios: 5%, 25%, and 50% in 2050) were built. The study was conducted at a continental level. This study considered the interconnection with many stakeholders of the HSC, including vehicle producers (BMW AG, Daimler AG, Ford, General Motors LLC, Honda R&D, Hyundai Motor Company, Kia Motors Corporation, Nissan, Renault, and Toyota Motor Corporation) and industrial gas companies (Linde and Air Liquide). From 2010 to 2020, all cost and performance projections are based on proprietary industry data and on projected learning and annual improvement rates after 2020.

Some significant initiatives undertaken at the worldwide, European, and national levels are discussed below, although the list is not exhaustive.

1.4.2.1 Worldwide Level

The Technology Roadmap "Hydrogen and Fuel Cells," developed by the IEA, 2015 has as its purpose to lay out the potential of hydrogen and its limitations in different energy sectors, aiming to provide extensive information about the function and cost of hydrogen technologies, to identify the sectors in which hydrogen can offer the maximum added value, and also the actions required to deploy hydrogen technologies (IEA, 2015).

According to the different scenarios that have been evaluated, the adoption of renewable hydrogen, as opposed to fossil-derived hydrogen (with or without CCS), strongly depends on its economic competitiveness. The relationships between natural gas price, electricity price, annual full-load hours, carbon price, and the resulting cost of hydrogen have been studied in depth. Even under optimistic assumptions with regard to the techno-economic parameters of the electrolyzer, electrolytic hydrogen remains more expensive than hydrogen from natural gas reforming, unless very low-cost renewable electricity is available and carbon or natural gas prices are high.

1.4.2.2 European Level

In the *HyWays project* (2007–08), over 50 member-state (MS) workshops were conducted with key stakeholders. The HyWays project combines technology databases and socio-techno-economic analyses to evaluate selected stakeholder scenarios for future sustainable hydrogen energy systems. In this project, market scenarios for hydrogen end-use applications were also developed. Each country outlined its own preferences (Finland, France, Germany, Greece, Italy, the Netherlands, Norway, Poland, Spain, and the United Kingdom). The HyWays project differs from other road mapping exercises because it integrates stakeholder preferences, obtained from multiple member state workshops, with extensive modeling in an iterative way. The stakeholder validation process, which takes into account country specific conditions, is a key element of the road mapping process. In Europe, the prospect of the hydrogen economy plays a major role, especially because of the aggregation of many countries that have various specific institutions, opportunities, conditions, and territorial and socio-economic barriers (Dagdougui, 2012). Another well-known roadmap is *H_2 Mobility* (2010), which outlines a plan to introduce the use of FCEVs in Europe, starting in Germany and the United Kingdom (Williamson, 2010) with others following in 2013. In this program, the main car manufacturers and gas producers are involved.

Hydrogen Mobility Europe 2 (H2ME 2) is a six-year project that runs to the end of June 2022, and which brings together 37 partners from eight European countries. It includes the deployment and operation of 1230 FCEVs and the addition of 20 new hydrogen refueling stations (HRS), and it will test the ability of electrolyzers to simultaneously feed hydrogen stations and help balance the electrical grid (H2ME 2 launched in Europe to grow hydrogen fueling infrastructure network and vehicle fleet, 2016).

The HYRREG project, founded by the Program of Cooperation of Southwest Europe (SUDOE) has the objective of developing a platform to generate hydrogen-related programs and a roadmap between the countries of the southeast of Europe, namely, France, Portugal, and Spain. The HYRREG roadmap, mainly based on a qualitative analysis, is focused on stakeholder preferences and region-specific conditions, highlighting the importance of hydrogen in the transport sector and its production from renewable sources.

1.4.2.3 Some National Levels

Iceland can be identified as the first hydrogen economy in the world. *The Icelandic New Energy* is a partnership that was established between the Icelandic government, Shell, Norsk Hydro, Ford, and the University of Reykjavik. It was a pioneering initiative to create the first hydrogen economy in the world by 2040 (Dunn, 2000). The project aims to promote energy independence by exploiting the vast renewable resources of the island, such as geothermal and hydropower (Dutta, 2014). In 2003, the country inaugurated the first hydrogen station in the world to supply the three hydrogen buses that ran through the ECTOS program until the end of 2006. In 2007, a new demonstration phase began with 13 SMART-H_2 model cars and boats (Bento, 2010).

With very few natural resources, Japan has been a pioneer in investment in hydrogen. The world's largest national hydrogen program (WE-NET) was established in 2003 in Japan with market penetration targets on FCVs and hydrogen energy. More recently, the Ministry of Economy, Trade, and Industry (METI) in Japan established in 2014 the Strategic Road Map for Hydrogen and Fuel Cells in order to formulate a Roadmap toward the implementation of a "hydrogen society" (Agency for Natural Resources and Energy, 2014). The METI proposed three phases to achieve this goal: first, the expansion of the scope of application for fuel cell technology, such as fuel cells for households and for vehicles, scheduled to begin in 2014; second, the development of a system for supplying the hydrogen using energy resources imported from other countries, while introducing hydrogen power generation with a time frame in the late 2020s; third, establishment of a carbon-dioxide-free hydrogen supply system using renewable and other energy around 2040.

In Germany, the National Innovation Program for Hydrogen and Fuel Cell Technology NIP (2006–16) has contributed significantly to fostering the market development of hydrogen technology. It was founded in 2006 as a joint effort of German policymakers, industry leaders, and the research community. Germany covers the length of the supply chain with 20 manufacturers and 12 distributors of fuel cells and components.

Various studies have been conducted to estimate the development of a hydrogen economy in the United States and its implications in terms of emissions as well as infrastructure requirements. The *US* Department of Energy

(*DOE)* has developed a hydrogen program in cooperation with industry, national laboratories, universities, and government agencies since 1980 (Bento, 2010; Patay, 2008).

One of the most famous H_2 plans can be found in California. Since 1999 demonstration projects have been managed by the *California Fuel Cell Partnership* (CaFCP). This partnership was established between Ballard Power Systems, Daimler Chrysler, Ford Motor Company, Shell Hydrogen, and Chevron (formerly ARCO), and the California agencies (California Air Resources Board and California Energy Commission). Its mission is to facilitate the commercialization of fuel cells for transportation. The CaFCP has supported the establishment of stations and had experience with more than 170 hydrogen vehicles. Stations are normally financed by the state government (Bento, 2010). More recently, two programs, the California Fuel Cell Partnership and the *California Energy Commission and Air Resources Board* are in effect. The former is a roadmap for fuel cell vehicles and hydrogen stations and the latter is a program of incentives for vehicles and fueling infrastructure from state agencies.

In France, HyFrance3 is a project to support the HyWays project. This project was launched to focus on the competitiveness of different steps of the hydrogen chain, from production to end use, with a time horizon of 2030 (Le Duigou et al., 2013). The roadmap describes and analyzes the French hydrogen industrial markets, including different scenarios. The infrastructure to distribute hydrogen in France for automotive applications up to 2050 is also studied, taking into account hydrogen storage to balance the supply and demand characteristics.

The "Office Parlementaire d'Evaluation des Choix Scientifiques et Technologiques" (OPECTS) in France has also presented a roadmap to implement a national hydrogen network, promoting the use of FCEV via tax elimination (AFHYPAC, 2012).

The French Association for Hydrogen and Fuel Cells (Association Française pour l'Hydrogène et les Piles à Combustible*: AFHYPAC*) started a French study on H_2 power and mobility in May 2013. "Mobilité Hydrogène France" is a consortium of private and public stakeholders formed by the French Association for Hydrogen and Fuel Cells (AFHYPAC). The consortium spans the gamut from energy companies to end customers.

A first analysis of market segments highlighted the role of clusters of captive fleets. Under the 2015 FCH-JU call, the deployment started in 2015 with 10 hydrogen stations and a first wave of fuel cell vehicles. The consortium members continue to develop the next phase of the rollout strategy for hydrogen mobility in France, to support the introduction of fuel cell passenger cars for fleets and private citizens.

A Hydrogen Territory initiative was launched in France in 2016, which aims to demonstrate, on the scale of a particular territory, the technical and economic feasibility as well as the environmental benefits of deploying hydrogen in energy networks or local energy applications. The Occitania region has been awarded the metaproject HyPort, which combines advanced innovation in hydrogen fuel cell applications for aeronautics, green hydrogen production, and H_2 mobility deployment for the Toulouse International Airport, Tarbes-Lourdes-Pyrénées regional airport, and the vast urban, rural, and tourist perimeters connected to them.

Table 1.3 summarizes some roadmaps. The advantage of these plan scenarios is the potential to use the information generated in other scenarios, and also the demonstration of the potential of hydrogen in automobile applications.

1.4.3 Implementation Steps

Transition plan scenarios can be taken as an important basis for more precise studies in which the different potential activities of the network can be measured and analyzed to design the hydrogen supply chain.

The different roadmaps and transition plan scenarios that already exist and that have been presented constitute necessary information and can be considered as the starting point to launch more detailed analyses. They highlight general targets as well as coordination and communication efforts from which valuable information is shared. The principal limitations of these macro studies are the difficulty in generating specific results on the location, size, and number of production, storage, or transport units, and also the lack of interconnection between the different objectives. Their main advantage is that they provide valuable information that can be used to implement scenarios of interest, thus demonstrating or not the potential of hydrogen infrastructure.

According to these roadmaps, hydrogen demand for road transport is assumed to be a major parameter and likely to grow in three phases according to Energy Trends 2030 scenario (Ozkan, 2009):

- *Infrastructure phase I*: the demonstration phase during which a few large-scale first user centers are situated across Europe.
- *Infrastructure phase II*: the early commercialization phase with 3–6 user centers per country, possibly including a network of transit roads connecting these centers.
- *Infrastructure phase III*: the full commercialization phase, which encompasses existing user centers as well as newly developed regions, and a dense, long-distance road network. Phase III is assumed to develop in three subphases.

These large-scale deployment initiatives must be supported by long-term policy frameworks in countries that are early adopters. These deployment initiatives should use current activities as a platform to scale their successes up to a national level (Hydrogen Council, 2017b).

A common assumption in all roadmaps is that hydrogen use will take off in densely populated urban areas at first and then gradually expand outward through

TABLE 1.3 Plan Scenarios of Various Roadmaps

Roadmap	Scale	Year	Description
IEA Hydrogen Council	Worldwide	2017	Evaluation of some industrial, technological, environmental, and social issues, and identification of the main obstacles associated with the hydrogen economy
IEA Hydrogen Technology Roadmap		2015	This roadmap details the steps governments, industry, and researchers need to take to foster and to track the deployment of hydrogen technology
The Technology Roadmap. Hydrogen and Fuel Cells			Description of the potential of hydrogen and its limitations in different energy sectors
H2ME	Europe	2016	Largest EU-funded project for hydrogen mobility and FCEV deployment Integrated in Mobility Europe project (now called H2ME 1) Involves Germany, Scandinavia, France, and the United Kingdom Plans for 300 FCEVs and 29 hydrogen refueling stations in 2020 and the operation of 1230 FCEVs and 20 more HRS in 2022
HYRREG	France, Portugal, and Spain	2013	Development of a platform to generate hydrogen-related programs and a roadmap between the countries of the southeast of Europe through the HyFrance3, HiPo, and EDEN projects
HyWays	Finland, France, Germany, Greece, Italy, Netherlands, Norway, Poland, Spain, and the United Kingdom	2008	Compilation of all pivotal technological and socioeconomic factors related to a future hydrogen infrastructure, providing a number of scenarios under different assumptions. Some market scenarios for hydrogen end-use applications are developed (Finland, France, Germany, Greece, Italy, the Netherlands, Norway, Poland, Spain, and the United Kingdom)

Continued

TABLE 1.3 Plan Scenarios of Various Roadmaps—cont'd

Roadmap	Scale	Year	Description
Australian National Hydrogen Study	Australia	2003	Assessment of the necessary steps to use hydrogen to meet its future energy requirements Three potential uses were addressed: road transport, portable electrical appliances, and generation. Three scenarios based on the demand (low, medium, and high) are described within the timeline 2020–50
Joint Research Centre Ispra of the European Communities and the Government of Quebec	Canada	2002	The idea of this project is to provide renewable primary energy from the already available hydroelectricity in Quebec for hydrogen production via electrolysis. Hydrogen will be shipped to Europe to be stored and used in different applications (Momirlan and Veziroglu, 2002)
H2 Mobilité France	France	2016	Creation of hydrogen clusters that could provide nationwide coverage by 2030
HyFrance3		2013	Description and assessment of the French hydrogen industrial markets, including different scenarios
OPECTS		2012	Proposes that hydrogen be tax free for a transition period, except for the hydrogen produced from fossil fuels
Roadmap on hydrogen energy (ADEME)		2011	Four scenarios for hydrogen energy in 2050, in which each one represents specific infrastructures and interactions with other energy industries

National Innovation Programme for Hydrogen and Fuel Cell Technology NIP (2006–16)	Germany	2017	Three objectives are involved: (1) Secure Germany's position as a technology leader in hydrogen and fuel cells; (2) Accelerate the development of the hydrogen and fuel cell markets; and (3) Strengthen the industry along the whole hydrogen and fuel cell value chain
Icelandic New Energy Ltd.	Iceland	1999	Development of feasibility studies to produce hydrogen locally from hydro and geothermal power
National Hydrogen Energy Roadmap	India	2014	Production of hydrogen through biological and biomass routes, using renewables sources (Dutta, 2014)
METI	Japan	2014	Establishment of a carbon-dioxide-free hydrogen supply system using renewable and other energy in different steps until 2040
California Fuel Cell Partnership	United States	2012	Implementation of FCEVs in California, concluding that the refueling stations must precede the vehicles, must have free access, and must be easy to use

so-called "hydrogen corridors." For the sake of illustration, the Hydrogen Corridor between Spain, France, and Andorra (H2PiyR Initiative) aims to develop a cross-border corridor of refueling stations for hydrogen vehicles connecting Spain (Catalonia and Aragon), France, and Andorra with central and northern Europe, where the deployment of infrastructure with this type of mobility is more advanced, through the installation of 10 hydro generators (ABC.es, 2017). The corridor will include the Spanish cities of Zaragoza, Huesca, Fraga and Tarragona, as well as Andorra (city) and Pamiers (France). They will join the already existing stations in Huesca and Zaragoza, and the French ones in Rodez and Albi (Afhypac - Newsletter Hynovations - #62, 2016). The project includes 16 FCVs (Fuel Cell Vehicles) (6 passenger cars, 8 commercial vehicles, and 2 buses) (L'hydrogène, de Rodez à Sarragosse, 2016).

Some studies assume that hydrogen can also be used for stationary applications between the commercialization and mass use phases.

The economic viability of hydrogen mobility from an infrastructure or retail operator's perspective can be helped with a fast rollout of FCEVs. The introduction of hydrogen-fueled captive fleets could further help hydrogen development (Ball et al., 2015). A captive fleet can be defined as a fleet of vehicles with predictable driving and refueling patterns that make regular visits to a parking lot or depot. A cluster is based on multiple fleets of customers in a defined area (Mobilité Hydrogène France, 2016). At least one HRS must be founded in each cluster. The development via clusters maximizes the utilization of the HSR installed. The next steps in the development of the hydrogen infrastructure consist of analyzing consumer behavior and developing a widespread network for passenger car drivers (Fig. 1.11).

Post offices in Audincourt (Doubs) and Périgny (Jura) in France have distributed letters since 2013 by small FCVs (Fig. 1.12), developed under the auspices of the project MobyPost (Bettayeb, 2017).

A total of 50 FCVs (in 2017) have been sold to different companies under the framework of the Hyway project. The end of phase 1 consists in building two hydrogen refueling stations (in Grenoble and Lyon). For the second phase, the objective is to produce "green" hydrogen, from renewable energy (solar, wind).

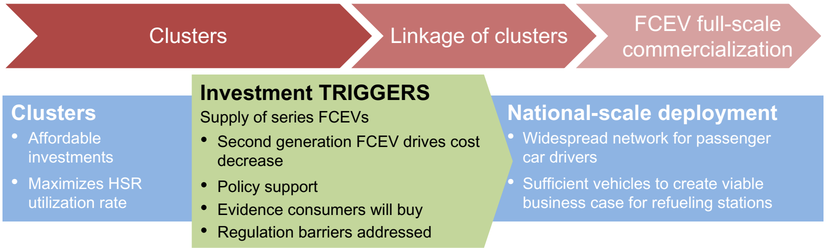


FIG. 1.11 Captive fleet approach: A 3 phase national roll-out (Mobilité Hydrogène France, 2016).

FIG. 1.12 The small FCVs used by the post offices.

The projects in Corsica with the Myrte platform (Mission renewable hydrogen for the integration to the electrical) and Jupiter 1000 in Fos-sur-Mer are perfect examples of this second stage (HyWay, 2017).

1.5 CONCLUSIONS

This chapter aims to shed some light on the challenges and opportunities that lie ahead for the development of hydrogen energy policies and for the deployment of hydrogen infrastructure. Hydrogen produced from renewable sources and used in fuel cells, both for mobile and stationary applications, constitutes a very promising energy carrier in the context of sustainable development. Hydrogen and fuel cell technologies have significant potential to improve energy security and mitigate the effects of climate change and other harmful environmental impacts, thus effecting a switch toward a clean, low-carbon energy system.

Yet hydrogen should not be seen as the unique solution to the world's energy problems and in particular not as the unique answer to the challenges that the transport sector has to cope with. The energy challenge will probably be solved by a much more diversified portfolio of fuels in the future.

Many energy sources, production processes, transportation modalities, storage modes, and end uses exist for hydrogen, so that the way that the hydrogen economy could be developed is very flexible. The concept of Power-to-Gas considered in isolation for hydrogen or extended to its coupling with methanation constitutes an attractive perspective.

Nowadays, the cost of hydrogen is considered prohibitive compared to the fossil fuels currently used in the transportation system, but the development of some technologies associated with hydrogen, coupled with high oil prices, has improved its competitiveness.

Some strategic roadmaps have been published about the potential of hydrogen at the continental, national, and regional levels. Their main objective has been to evaluate some of the industrial, technological, environmental, and social issues, and to identify the main obstacles in the development of the hydrogen economy. These roadmaps are particularly useful for accelerating the deployment of hydrogen technologies, with the support of policymakers, the private sector, and society; according to these studies, although many of the required technologies are already available today, the deployment of a hydrogen infrastructure constitutes a challenging task for the development of a hydrogen economy that is cost competitive and accepted by the mass market.

In this context, methodologies for the deployment and design of hydrogen supply chains need to be addressed, taking into account the variety of energy sources, production and storage technologies, transportation modes, and stakeholders, to link hydrogen demand to its supply with economic, environmental, and societal considerations.

REFERENCES

ABC.es, 2017. España tendrá 20 estaciones de servicio para hidrógeno antes de 2020 [WWW Document]. abc. http://www.abc.es/motor/reportajes/abci-espana-tendra-20-estaciones-servicio-para-hidrogeno-antes-2020-201703021822_noticia.html. (Accessed 5 September 2017).

AFHYPAC, 2012. Rapport d'activité de la France sur l'Hydrogène et les Piles à Combustible, période juin 2012 à novembre 2014 [WWW Document]. http://www.afhypac.org/documents/publications/rapports/AFHYPAC_RA_bd.pdf.

Afhypac - Newsletter Hynovations - #62, 2016. (WWW Document). http://www.afhypac.org/newsletter/62/actualites-internationales-81/. (Accessed 5 September 2017).

Agency for Natural Resources and Energy, 2014. Summary of the Strategic Road Map for Hydrogen and Fuel Cells. Ministry of Economy, Trade and Industry, Japan.

Ball, M., Weeda, M., 2015. The hydrogen economy—vision or reality? Int. J. Hydrog. Energy 40, 7903–7919. https://doi.org/10.1016/j.ijhydene.2015.04.032.

Ball, M., Wietschel, M., 2009. The future of hydrogen—opportunities and challenges. Int. J. Hydrog. Energy 34, 615–627. https://doi.org/10.1016/j.ijhydene.2008.11.014.

Ball, M., Basile, A., Veziroglu, T.N., 2015. Compendium of Hydrogen Energy: Hydrogen Use, Safety and the Hydrogen Economy. Woodhead Publishing, Oxford. https://doi.org/10.1016/B978-1-78242-364-5.09987-5.

Bellaby, P., Upham, P., Flynn, R., Ricci, M., 2016. Unfamiliar fuel: how the UK public views the infrastructure required to supply hydrogen for road transport. Int. J. Hydrog. Energy 41, 6534–6543. https://doi.org/10.1016/j.ijhydene.2016.03.024.

Bento, N., 2010. The Transition to a Hydrogen Economy: Infrastructure and Technological Change. Université de Grenoble, France.

Bettayeb, K., 2017. Les défis de la voiture à hydrogène. CNRS J. [WWW Document]. https://lejournal.cnrs.fr/articles/les-defis-de-la-voiture-a-hydrogene. (Accessed 5 September 2017).

Brown, P.T., Caldeira, K., 2017. Greater future global warming inferred from Earth's recent energy budget. Nature 552, 45. https://doi.org/10.1038/nature24672.

Cantuarias-Villessuzanne, C., Weinberger, B., Roses, L., Vignes, A., Brignon, J.-M., 2016. Social cost-benefit analysis of hydrogen mobility in Europe. Int. J. Hydrog. Energy 41, 19304–19311.

Cipriani, G., Di Dio, V., Genduso, F., La Cascia, D., Liga, R., Miceli, R., Ricco Galluzzo, G., 2014. Perspective on hydrogen energy carrier and its automotive applications. Int. J. Hydrog. Energy 39, 8482–8494. https://doi.org/10.1016/j.ijhydene.2014.03.174.

Cramer, S.D., Covino, B.S., 2003. Corrosion: Fundamentals, Testing and Protection. ASM International, Ohio, USA.

Creti, A., Kotelnikova, A., Meunier, G., Ponssard, J.-P., 2015. A cost benefit analysis of fuel cell electric vehicles, Research Report, Report 1: 1–41.

Dagdougui, H., 2012. Models, methods and approaches for the planning and design of the future hydrogen supply chain. Int. J. Hydrog. Energy 37, 5318–5327. Optimization approaches to hydrogen logistics. https://doi.org/10.1016/j.ijhydene.2011.08.041.

De León Almaraz, S., 2014. Multi-Objective Optimisation of a Hydrogen Supply Chain. INPT, Toulouse.

Débat national sur la transition énergétique, 2013. (WWW Document). http://www.transition-energetique.gouv.fr/liste-des-debats-en-france. (Accessed 25 November 2013).

Devillers, C., Pehr, K., Stoll, D., Wetzel, F., Duffield, J., Grubel, H., Zisler, S., Vandenborre, H., Driessens, T., Gonzalez, A., Vegas, G., Wurster, R., Kesten, M., Machel, M., Michel, F., Heurtaux, F., Adams, P., 2000. European integrated hydrogen project (EIHP). In: Proceedings of the Hydrogen Energy Progress Xiii.Vols. 1 and 2. pp. 139–149.

Dincer, I., Acar, C., 2015. Review and evaluation of hydrogen production methods for better sustainability. Int. J. Hydrog. Energy 40, 11094–11111. https://doi.org/10.1016/j.ijhydene.2014.12.035.

Dodds, P.E., Staffell, I., Hawkes, A.D., Li, F., Grünewald, P., McDowall, W., Ekins, P., 2015. Hydrogen and fuel cell technologies for heating: a review. Int. J. Hydrog. Energy 40, 2065–2083. https://doi.org/10.1016/j.ijhydene.2014.11.059.

DOE Hydrogen Program, 2006. Hydrogen Fuel Cells. U.S. Department of Energy Hydrogen Program. https://www.hydrogen.energy.gov/pdfs/doe_fuelcell_factsheet.pdf.

Dunn, S., 2000. The Hydrogen Experiment. World Watch Institute, Washington, DC.

Dutta, S., 2014. A review on production, storage of hydrogen and its utilization as an energy resource. J. Ind. Eng. Chem. 20, 1148–1156. https://doi.org/10.1016/j.jiec.2013.07.037.

Florida Solar Energy Center, n.d. Hydrogen Basics—Storage [WWW Document]. http://www.fsec.ucf.edu/en/consumer/hydrogen/basics/storage.htm (Accessed 3 October 2017).

Götz, M., Koch, A.M., Graf, F., 2014. State of the art and perspectives of CO2 methanation process concepts for power-to-gas applications.International Gas Union Research Conference, Copenhagen.

Götz, M., Lefebvre, J., Mörs, F., McDaniel Koch, A., Graf, F., Bajohr, S., Reimert, R., Kolb, T., 2016. Renewable power-to-gas: a technological and economic review. Renew. Energy 85, 1371–1390. https://doi.org/10.1016/j.renene.2015.07.066.

Grond, L., Schulze, P., Holstein, J., 2013. Systems Analyses Power to Gas: Deliverable 1: Technology Review. DNV KEMA Energy & Sustainability, Groningen.

H2ME 2 launched in Europe to grow hydrogen fueling infrastructure network and vehicle fleet, 2016. Fuel Cells Bull. 2016, 1. https://doi.org/10.1016/S1464-2859(16)30131-6.

Hake, J.-F., Linssen, J., Walbeck, M., 2006. Prospects for hydrogen in the German energy system. Energy Policy 34, 1271–1283. https://doi.org/10.1016/j.enpol.2005.12.015.

Hydrogen Council, 2017a. How Hydrogen Empowers the Energy Transition [WWW Document]. Rep. January. http://hydrogeneurope.eu/wp-content/uploads/2017/01/20170109-HYDROGEN-COUNCIL-Vision-document-FINAL-HR.pdf. (Accessed 29 December 2017).

Hydrogen Council, 2017b. Hydrogen Scaling Up. A Sustainable Pathway for the Global Energy Transition [WWW Document]. http://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf. (Accessed 4 January 2018).

HySafe—Safety of Hydrogen as an Energy Carrier, 2007. (WWW Document). http://www.hysafe.org. (Accessed 8 February 2018).

HyWay, 2017. Tenerrdis [WWW Document]. https://www.tenerrdis.fr/fr/projets/hyway/. (Accessed 8 February 2018).

IEA, 2014. Heating Without Global Warming: Market Developments and Policy Considerations for Renewable Heat. International Energy Agency, Paris.

IEA, 2015. Technology Roadmap. Hydrogen and Fuel Cells [WWW Document]. https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapHydrogenandFuelCells.pdf. (Accessed 31 December 2017).

IEA, 2017a. International Energy Agency Technical Report. Key World Energy Statistics [WWW Document]. https://www.iea.org/publications/freepublications/publication/KeyWorld2017.pdf. (Accessed 29 December 2017).

IEA, 2017b. Global Trends and Outlook for Hydrogen [WWW Document]. http://ieahydrogen.org/pdfs/Global-Outlook-and-Trends-for-Hydrogen_Dec2017_WEB.aspx.

Institute for Climate Economics, Ministère de l'Environnement, de l'Énergie et de la Mer, 2016. Chiffres clés du climat France et Monde ÉDITION 2017. .

Kim, J., Moon, I., 2008. Strategic design of hydrogen infrastructure considering cost and safety using multiobjective optimization. Int. J. Hydrog. Energy 33, 5887–5896. https://doi.org/10.1016/j.ijhydene.2008.07.028.

Koskinen, P.E.P., Beck, S.R., Örlygsson, J., Puhakka, J.A., 2008. Ethanol and hydrogen production by two thermophilic, anaerobic bacteria isolated from Icelandic geothermal areas. Biotechnol. Bioeng. 101, 679–690. https://doi.org/10.1002/bit.21942.

L'hydrogène, de Rodez à Sarragosse, 2016. Media12 [WWW Document]. http://www.media12.fr/lhydrogene-de-rodez-a-sarragosse/. (Accessed 5 September 2017).

Le Duigou, A., 2010. Témoignage sur le projet AIDHY. CEA, I-tésé, France.

Le Duigou, A., Quéméré, M.-M., Marion, P., Menanteau, P., Decarre, S., Sinegre, L., Nadau, L., Rastetter, A., Cuni, A., Mulard, P., Antoine, L., Alleau, T., 2013. Hydrogen pathways in France: results of the HyFrance3 project. Energy Policy 62, 1562–1569. https://doi.org/10.1016/j.enpol.2013.06.094.

Lehner, M., Tichler, R., Steinmüller, H., Koppe, M., 2014. Power-to-Gas: Technology and Business Models. Springer Briefs in Energy. https://doi.org/10.1007/978-3-319-03995-4_2.

Mazloomi, K., Gomes, C., 2012. Hydrogen as an energy carrier: prospects and challenges. Renew. Sust. Energ. Rev. 16, 3024–3033. https://doi.org/10.1016/j.rser.2012.02.028.

McCarty, R.D., Hord, J., Roder, H.M., 1981. Selected properties of hydrogen (engineering design data). Final report (No. PB-81-211492). National Engineering Lab. (NBS), Boulder, CO.

McKinsey & Company, 2010. A Portfolio of Power-Trains for Europe: A Fact-Based Analysis. The Role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles [WWW Document]. 2010.

Mobilité Hydrogène France, 2016. H2 Mobilité France. Study for a Fuel Cell Electric Vehicle National Deployment Plan [WWW Document]. http://www.fch.europa.eu/sites/default/files/Smart%20Spec%20Fabio%20Ferrari%20%28ID%202436338%29%20%28ID%202497336%29.pdf. (Accessed 31 December 2017).

Momirlan, M., Veziroglu, T.N., 2002. Current status of hydrogen energy. Renew. Sust. Energ. Rev. 6, 141–179. https://doi.org/10.1016/S1364-0321(02)00004-7.

Ozkan, N., 2009, UKSHEC Working Paper No. 3. A Review of Hydrogen Demands in National Roadmaps. Policy Studies Institute.

Patay, E., 2008. Déploiement de la chaîne logistique de l'hydrogène pour le marché des carburants en 2050: Conception et développement d'un outil d'aide à la décision pour l'analyse de scénarios. Ecole Centrale Paris-Laboratoire Génie Industriel, Paris.

Sharma, S., Ghoshal, S.K., 2015. Hydrogen the future transportation fuel: from production to applications. Renew. Sust. Energ. Rev. 43, 1151–1158. https://doi.org/10.1016/j.rser.2014.11.093.

Sterner, M., Jentsch, M., Holzhammer, U., 2011. Energiewirtschaftliche und ökologische Bewertung eines Windgas-Angebotes. Gutachten für Greenpeace Energy. Fraunhofer IWES, Kassel.

United Nations, 2015. Paris Agreement [WWW Document]. http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf. (Accessed 29 December 2017).

Williamson, I., 2010. H2-Mobility—Towards Commercialisation of Fuel Cell Vehicles. Presentation to US HTAC. https://www.hydrogen.energy.gov/pdfs/4_williamson_0610.pdf.

World Energy Council, 2013. World Energy Scenarios. Composing Energy Futures to 2050. PSI, United Kingdom.

FURTHER READING

Dagdougui, H., 2011a. Decision Support Systems for Sustainable Renewable Energy Systems and Hydrogen Logistics: Modelling, Control and Risk Analysis. UNIGE; CRC, MINES ParisTech, Italy; Paris.