

Chapter 2

Hydrogen Supply Chain Design: Key Technological Components and Sustainable Assessment

Jesus Ochoa Robles, Sofía De-León Almaraz
and Catherine Azzaro-Pantel

Laboratoire de Génie Chimique, Université de Toulouse, CNRS, Toulouse, France

ABBREVIATIONS

CCS	carbon capture and storage
FCEV	fuel cell electric vehicle
GHG	greenhouse gas
GWP	global warming potential
HAZID	hazard identification
HRS	hydrogen retail station
HSC	hydrogen supply chain
LCA	life cycle assessment
NGO	nongovernmental organization
OECD	Organisation for Economic Cooperation and Development
PEM	proton exchange membrane
PSA	pressure swing adsorption
R&D	research and development
RES	renewable energy sources
SC	supply chain
SMR	steam methane reforming
SOEC	solid oxide electrolyzer cell
SOFC	solid oxide fuel cell
WtW	well-to-wheel

2.1 INTRODUCTION

The plethora of sources for hydrogen production, along with the variety of methods for its extraction, distribution, and storage, makes hydrogen a very promising fuel in both industrialized and developing countries. This wide variety of options also makes the development of its associated supply chain a challenging task. Supply chain management (SCM) generally uses a set of approaches to efficiently integrate energy source supply, hydrogen production, conditioning, storage, and distribution, so that hydrogen is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system global cost while satisfying service level requirements (Papageorgiou, 2009) and taking into account other constraints. As previously explained in [Chapter 1](#), the path toward a hydrogen economy, and more particularly here, toward the use of hydrogen as an energy vector, must address the economic, social, and environmental pillars of sustainability. This explains why SCM models can be considered as useful to design improved business pathways, which could result in reduced environmental impacts that satisfy local regulations and international treaties for greenhouse gas emissions, while being also economically achievable (De León Almaraz, 2014). A supply chain (SC) can be defined as a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer (Mentzer et al., 2001).

A hydrogen supply chain involves:

- *Multiple echelons* from the choice of energy source, production, storage, transportation, and distribution that interact along the chain.
- *Multiple stakeholders* covering industry, academia, government, energy sector, etc. The transition to a hydrogen economy is a global issue and requires extensive consultation with industry (covering the various echelons of the HSC), energy sector, national and local Government, academia, NGOs, and the finance sector. The importance of public-private partnerships in the achievement of a hydrogen economy is emphasized in several roadmaps (Tomei, 2009). The involvement and support of local communities is also of crucial importance. The current energy system requires collaboration between countries. A review of hydrogen roadmaps also emphasizes the importance of consumer acceptance and awareness of hydrogen technologies in driving the markets for hydrogen (Tomei, 2009).
- *Multiple periods* that reflect the dynamic process from deployment to maturity and the gradual approach to infrastructure buildup, that may be initially concentrated around existing hydrogen clusters, or user centers.
- *Multiple objectives* that reflect the economic, environmental, and social pillars of sustainable development.
- *Multiple users*, including mobility, heat, and industrial applications; this aspect has been tackled in the previous chapter.

The flexibility of hydrogen systems creates many opportunities for system design. A combination of equipment can enable interactions with different sectors. The purpose of the following analysis is to establish which configurations should be considered and explored according to the desired goal. A big challenge is then to assess if hydrogen produced from renewable energy sources can be competitive with current fuels and to deploy an infrastructure of hydrogen SC (HSC) for new applications.

The remainder of this chapter is organized as follows; in [Section 2.2](#), the HSC for industrial and mobility use is introduced. The system is represented by nodes and connections, and a generic HSC framework is displayed. The different echelons (source, production, storage, transportation, etc.) involved in an HSC are then presented. Hydrogen can be produced from both fossil and renewable resources ([Section 2.3](#)). [Section 2.4](#) reviews the different technologies related to the various sources. A highlight is that hydrogen can provide storage options for intermittent renewable technologies, such as solar and wind, and might thus facilitate their large-scale introduction into the energy mix. The degree of centralization, determined by the plant capacity, is introduced, and processes, such as steam methane reforming, gasification, and electrolysis, are presented. Finally, issues related to CO₂ capture and storage are mentioned. Hydrogen conditioning and storage are the core of [Section 2.5](#). [Section 2.6](#) is devoted to transportation, with different modes, such as pipelines, tube trailers, and tanker trucks, to supply H₂ fuel to the refueling stations, which are discussed in [Section 2.7](#). These key technological components have to be integrated in an HSC, and criteria of sustainable assessment are presented in [Section 2.8](#).

2.2 HYDROGEN SUPPLY CHAINS

Because the design of the supply chain may vary according to the desired goal, there is no unique hydrogen supply chain, and thus it is difficult to embed in one generic formulation all the various possibilities that may be encountered. Several options that can be captured to build a hydrogen supply chain network framework are collected in [Fig. 2.1](#).

Two cases that may be considered are covered in the following sections.

2.2.1 H₂ Supply Chain as a Feedstock for Industrial Uses

The chemical industry is the largest producer and consumer of hydrogen (see [Tables 2.1 and 2.2](#)) as one of the key starting materials used ([Ausfelder and Bazzanella, 2016](#)). It is a fundamental building block for the manufacture of ammonia, and hence fertilizers, of methanol, used in the manufacture of many polymers, and also of the refining industry (for hydrotreatments by hydrogenation of unsaturated hydrocarbons and hydrosulfuration).

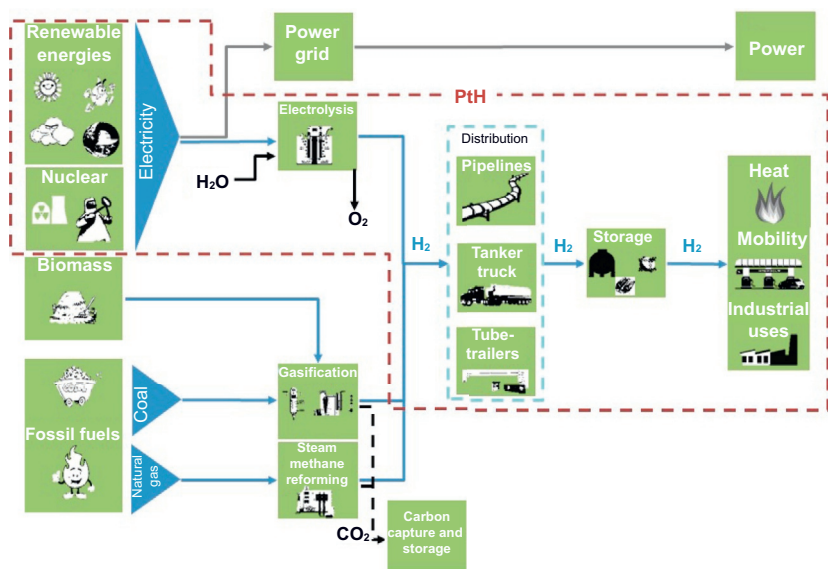


FIG. 2.1 Various pathways involved in hydrogen supply chains.

TABLE 2.1 Worldwide Hydrogen Consumption in Industry (Le Duigou and Miguet, 2010)		
Use	Consumption (Mt)	%
Refinery	26.4	44
Ammonia production	22.8	38
Other chemical products	4.8	8
Others	6	10

TABLE 2.2 Hydrogen Consumption in Industry in France (Le Duigou and Miguet, 2010)		
Use	Consumption (kt)	%
Refinery	544	59
Ammonia and fertilizers	240	26
Chemical industry (methanol)	92	10
Metal industry	9.2	1
Others	36.8	4

In the chemical industry, hydrogen is generally produced via syngas processes from fossil feedstocks, including natural gas, oil-, and coal-based sources. The syngas process variant applied depends strongly on the available feedstock and the downstream processes. Steam reforming of natural gas is by far the dominant process. Electrolytic production of hydrogen plays a minor role; it is not competitive with steam reforming and is only applied when relatively small amounts of pure hydrogen are required. Hydrogen is also produced as a significant side stream of other reactions, such as dehydrogenation processes and chlorine production.

In current schemes of industrial distribution, hydrogen is produced in centralized plants or produced onsite for captive uses. H_2 is obtained mainly from steam methane reforming (SMR) and coal gasification, and also obtained as a byproduct from chloralkali electrolysis plants. It is used onsite or transported over short distances by pipelines. The option for hydrogen to be liquefied or compressed and then transported via tube trailers or tanker trucks also exists but is less frequent. Ammonia production plants, oil processing units, and methanol and metal industries are customers with high demand volume.

As highlighted in [Ausfelder and Bazzanella \(2016\)](#) there are a lot of opportunities and challenges for the chemical industry in the face of large-scale production of renewable hydrogen.

2.2.2 H_2 Supply Chain as a Fuel

The hydrogen supply chain for H_2 as fuel is defined as a system of activities from suppliers to customers, including energy source, production, storage, transportation, and dispensation of hydrogen to refueling stations. Unlike most other fuel infrastructure, hydrogen can be produced either centrally (similar to existing gasoline supply chains) or in a distributed mode (using small-scale units that can produce H_2 close to the point of use in small quantities) at forecourt refueling stations, so that the distribution cost can be strongly reduced.

In this context, several questions arise:

- What is the environmental impact of the energy source used to produce hydrogen?
- Which production option is more cost effective?
- Is centralized production or decentralized production (small-scale production at local fueling stations) more cost-effective?
- What are the most cost-effective transportation modes and pathways to connect hydrogen demand with its supply?
- Which quantitative criteria can be used to evaluate sustainability of the hydrogen supply chain?

2.3 MULTIPLE SOURCES TO HYDROGEN

Hydrogen can be produced by two pathways, either power-to-hydrogen (from nuclear or from renewable sources, such as hydro, wind, solar, and geothermal)

or non-power-to-hydrogen options (biomass or fossil fuels associated with carbon capture and storage, for instance).

The local market conditions and availability of regional primary energy feedstock have a large impact on the selection of supply chain pathways. As previously explained, hydrogen has the benefit of improving the security of fuel supply because it can be produced from diverse primary energy sources, such as fossil fuels (natural gas, naphtha, heavy oil, and coal) and renewable energy sources (RES), such as wind, biomass, water, and solar energy. Currently, almost 95% of hydrogen is produced from fossil fuels via steam reforming, gasification, and partial oxidation processes (Heracleous, 2011). According to Murthy Konda et al. (2011), feedstock remains the biggest contributor to the cost of H₂ fuel with around 40% share.

RES are playing an ever increasing role in worldwide electricity generation (EIA, 2017); their contribution has increased from 21.5% in 1973 to 23.6% in 2015. Hydropower plays by far the most important role in electricity generation, producing 16% of the energy from RES in 2016. Nevertheless, the importance of RES other than hydro has grown considerably, generating 7.1% of the total energy in 2015. Renewables are the fastest growing source of energy for electricity generation, with average increases of 2.8% per year expected from 2015 to 2040. Renewable resources other than hydropower are the fastest-growing energy sources for new generation capacity, and this phenomenon is valid for both the OECD and non-OECD regions. Renewables other than hydropower accounted for 7% of total world generation in 2015, with an expected share in 2040 of 15% (EIA, 2017), with more than half of the growth coming from wind power. After renewable energy sources, natural gas and nuclear power are the next fastest growing sources of energy used to generate electricity (Fig. 2.2).

Several scenarios can also be found in the literature. Some of them are more optimistic in the rate projected for RES use, such as WWF (2011) and EREC (2010), that consider a 100% production rate for RES by 2050. For instance, some examples of different energy scenarios developed in French reports include the RES roadmap for 2020 and 2030 (presented by the Renewable

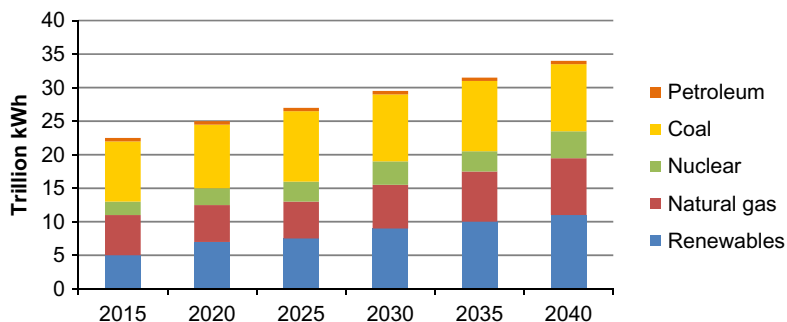


FIG. 2.2 World net electricity generation by energy source (EIA, 2017).

Energy Association) ([Syndicat des énergies renouvelables, 2012](#)) and the French energy report 2050 ([Percebois and Mandil, 2012](#)), in which some scenarios (e.g., CEA, AREVA, Global chance, RTE) regarding nuclear and RES pathways are thoroughly analyzed.

2.3.1 Coal

Coal is a sedimentary rock consisting of both organic and inorganic material. It consists of carbon, hydrogen, oxygen, and, in lower amounts, sulfur and nitrogen. Coal is the most abundant fossil fuel in the world ([Miller, 2004](#)). Coal is the world's most abundant and widely distributed fossil fuel with reserves for all types of coal estimated to be about 990 billion metric tons, enough for 150 years at current consumption ([BGR, 2009](#)). Coal makes up 42% of electricity generation and is likely to remain a key component of the fuel mix for power generation to meet electricity demand, especially the growing demand in developing countries. As pointed out by the European Directive of 2009, a key factor in reducing GHG emissions in the short term is to improve energy efficiency in end uses in different sectors: construction, transport, and industry. In this regard, using coal as an energy source is not without problems because coal combustion releases carbon dioxide and other pollutants. Coal gasification and carbon sequestration (see also [Section 2.4.6](#)) may be able to minimize pollutants and greenhouse gases while changes in mining practices can reduce the environmental concerns.

2.3.2 Natural Gas

Natural gas is a mixture of several hydrocarbon gases, including methane (between 70% and 90%), ethane, propane, butane, and pentane, as well as carbon dioxide, nitrogen, and hydrogen sulfide. The composition of natural gas can vary widely, depending on the gas field. Natural gas is produced through the decay of organic materials. Most natural gas is obtained from wells, although it can be produced from organic waste through the use of digesters ([Bartels et al., 2010](#)). A third way to obtain natural gas is by abiogenic processes. In general, extremely deep under the Earth's crust, hydrogen-rich gases and carbon molecules exist, interacting with minerals in the absence of oxygen that combined with the high pressure, form methane deposits ([Bahadori, 2014](#)).

The remaining resources of natural gas are abundant and can satisfy the projections of global demand growth included in all three of the IEA *World Energy Outlook* ([IEA, 2011](#)) scenarios to 2040 and well beyond. Proven reserves have been estimated at 216 trillion cubic meters at the end of 2014, equal to more than 60 years of production at current rates, yet proven reserves are only a fraction of the total remaining technically recoverable resources.

2.3.3 Biomass

Biomass, one of the most abundant renewable resources, is formed by fixing carbon dioxide in the atmosphere during the process of plant photosynthesis. It is therefore carbon neutral in its lifecycle. Biomass comprises any organic matter, either plant or animal in origin. Biomass energy refers to the stored energy (solar, carbon and hydrogen) that is available within organic matter and can take a variety of forms, with woody biomass being the most used (Macqueen and Korhaliller, 2011).

Biomass resources can be divided into four categories (Ni et al., 2006):

- Energy crops: herbaceous, woody industrial, agricultural, and aquatic.
- Agricultural residues and waste: crop and animal waste.
- Forestry waste and residues: mill wood, logging, trees, and shrub residues.
- Industrial and municipal wastes: municipal solid and industry waste, sewage sludge.

From the point of view of quality, biomass can be categorized according to its content of humidity, lignocellulose, sugar, starch, and oil (Orecchini and Bocci, 2007).

Much research has focused on sustainable and environmentally friendly energy from biomass to replace conventional fossil fuels. Thermochemical and biological processes are the two main pathways to obtain energy from biomass. To produce hydrogen, the most used processes are fast pyrolysis and gasification (thermochemical).

One issue with the increasing use of biomass for energy purposes (Bartels et al., 2010) is related to its impact on land use and its implications for a whole range of sustainable development issues, including social development and environmental impacts associated with land use change.

Another limitation is that the processes of hydrogen production from biomass are still in the development stage and require a strong effort in terms of R&D and demonstration activities (Balat and Balat, 2009). The characteristics of biomass are very important because they can vary greatly from location to location, and also seasonally and yearly, so that hydrogen production via the biomass route may not be competitive with hydrogen production with fossil fuels (Dagdougui, 2011a). However, the waste-to-energy application has received much attention due to its potential to become a major hydrogen source.

Bioenergy (Sawin et al., 2017) is the largest contributor to global renewable energy supply. Total primary energy supplied from biomass in 2016 was approximately 62.5 exajoules (EJ) (2.5% increase per year since 2010). The bioenergy share in total global primary energy consumption has remained relatively steady since 2005, at around 10.5%, despite a 21% increase in overall global energy demand over the last 10 years. The contribution of bioenergy to final energy demand for heat in buildings and industry far outweighs its use for

electricity and transport combined. Europe is the largest consumer of bioheat following the mandatory national targets under the Renewable Energy Directive (Sawin et al., 2017).

2.3.4 Solar Energy

The ubiquitous solar energy is a clean, renewable source with average around 120,000 TW irradiation at the Earth's surface (Hosseini and Wahid, 2016). The estimated potential of the direct capture of solar energy is enormous. When solar energy strikes the Earth's atmosphere, approximately 30% is reflected. After reflection by the atmosphere, Earth's surface receives about $3 \times 9 \times 10^{24}$ MJ incident solar energy per year, which is almost 10,000 times more than current global energy consumption. Thus, the harvesting of <1% of photonic energy would serve all human energy needs. Although solar energy is the largest energy source of the planet, it produces only 1% of all electricity used globally. However, the global installed capacity for solar-powered electricity has seen exponential growth, reaching about 227 GWe at the end of 2015 (World Energy Council, 2016).

There are two ways solar energy is used to generate electricity; photovoltaic cells directly convert sunlight to electricity, while solar thermal power plants or concentrating solar power systems focus sunlight with mirrors, heating water and producing high-pressure steam that drives turbines.

Photovoltaic cells only absorb a portion of the solar spectrum, but they can generate electricity from both direct and diffuse sunlight. Solar thermal power plants can use more wavelengths of the solar spectrum, but they can only operate in direct sunlight, limiting them to sun-rich areas. Moreover, the highest conversion efficiencies reported so far for solar thermal power plants are significantly less than those for photovoltaic cells.

2.3.5 Wind

Wind mills and horizontal- and vertical-axis turbines are used to convert the kinetic energy of the wind into electricity. Wind energy is one of the more cost-effective forms of renewable energy today. Wind turbines are typically constructed in large groups of individual wind turbines in order to form a large wind farm (Bartels et al., 2010). Onshore wind has now reached a certain maturity, even if the intermittent nature of the production makes it difficult to integrate into power grid systems, and the technical improvements are mostly incremental. However, offshore wind power has emerged recently (the first field of 500 MW in 2003 in Denmark), but faces some technical barriers, such as keeping equipment in harsh environments (saline, weather) and connection to the power grid (Direction générale de la compétitivité, de l'industrie et des services, 2011).

Wind-to-hydrogen may allow wind energy to be harnessed in areas without electrical transmission capacity, or it could provide an energy storage medium

for the intermittent wind resource in order to provide a more constant renewable electricity supply (Bartels et al., 2010).

World wind power generation capacity has reached 435 GW at the end of 2015, around 7% of total global power generation capacity (World Energy Council, 2016).

2.3.6 Hydropower

Hydropower is currently the world's largest renewable power source for electricity generation, supplying 71% of all renewable electricity. Reaching 1064 GW of installed capacity in 2016, it generated 16.4% of the world's electricity from all sources (World Energy Council, 2016). Large-scale hydropower plants store water in a reservoir behind a dam, and then regulate the flow according to electricity demand. Hydropower can provide a relatively reliable source of power on demand. The Ecofys scenario reflects a relatively small increase in hydropower. In this scenario, hydropower would provide 12% of the electricity in 2050 compared with 15% today (WWF, 2011). Nowadays, highly efficient turbines that generate electricity by spinning water are installed. Small hydropower, defined by installed capacity of up to 10 MW, is the backbone of electricity production in many countries in the European Union (EREC, 2010). Small hydropower takes advantage of the kinetic energy and pressure from falling water or rivers for instance.

Regarding the type of operation, hydropower can be classified as *run-of-river* or *pumped hydro*. Run-of-river stations have no reservoir capacity and provide a continuous supply of electricity (base load) with some flexibility of operation for daily fluctuations in demand through water flow that is regulated by the facility. Pumped hydro produces electricity to supply high peak demands by moving water between reservoirs at different elevations.

2.3.7 Geothermal

Geothermal energy for hydrogen production is considered as a sustainable option for those countries with abundant geothermal energy resources. The technologies of hydrogen production and use can be easily integrated with geothermal sources and stand-alone energy systems (Balta et al., 2010). Although many studies (e.g., Bockris and Veziroglu, 2007; Costogue and Yasui, 1977; Eisenstadt and Cox, 1975; Maack and Skulason, 2006; Yilanci et al., 2009) have been carried out on hydrogen production from solar and wind in the dedicated literature, hydrogen production from geothermal resources has received far less attention. These works highlight some demonstration projects and their technical details, feasibility studies, and planning.

Geothermal energy produces less than 1% of the world's electricity generation. There were 315 MW of new geothermal power capacity installed in 2015, raising the total capacity to 13.2 GW (World Energy Council, 2016).

2.3.8 Uranium and Nuclear

Nuclear power could produce hydrogen by either electrolysis of water, or by thermal decomposition of water using heat from high-temperature reactors (thermochemical cycles must be implemented). No greenhouse gas emissions are created directly during the generation of nuclear power. The assessments of global uranium resources show that total identified resources have grown by about 70% over the last 10 years. The total identified resources of uranium are considered sufficient for over 100 years of supply based on current requirements in 2015 ([World Energy Council, 2016](#)).

Global nuclear power capacity reached 390 GWe at the end of 2015, generating about 11% of global electricity. In 2015, 65 reactors were under construction (6 more than in July 2012) with a total generating capacity of 64 GW. The increasing need to moderate the local pollution effects of fossil fuel use means that nuclear is increasingly seen as an option in order to add large-scale baseload power generation while limiting the amount of GHG emissions.

2.4 MULTIPLE HYDROGEN PRODUCTION MODES

Three main categories of hydrogen production technologies are considered here: (1) gasification and pyrolysis from coal or biomass; (2) reforming, from natural gas, ethanol, biomass, or heavy fuel oil; and (3) electrolysis with alkaline and proton exchange membrane (PEM) and solid oxide (SOE) electrolyzers.

In this section, the centralization/decentralization level of hydrogen production is discussed and the production technologies are briefly analyzed.

The hydrogen supply chain may be classified as either centralized or decentralized (on site), depending on the degree of centralization.

2.4.1 Centralized Versus Distributed Hydrogen Production

Hydrogen can be produced: (1) at or near the site of use in distributed production, or (2) at large facilities and then delivered to the point of use in central production ([Office of Energy Efficiency and Renewable Energy, n.d.](#)).

The centralized production option (750,000 kg/day of hydrogen) would be analogous to current gasoline supply chains, for which the economies of scale are capitalized upon within an industrial context and large quantities are produced at a central site and then distributed ([Hugo et al., 2005](#); [Murthy Konda et al., 2011](#)). Centralized plants promise higher hydrogen production efficiency but require more capital investment and a substantial hydrogen transport and delivery infrastructure.

Decentralized production consists of small regional plants, or even local filling stations, that generate hydrogen. While the hydrogen generation efficiency for decentralized production is lower than that for centralized plants, losses in

hydrogen transport can make such a scheme more efficient (Kim et al., 2008; Haeseldonckx and D'haeseleer, 2011). There is a tendency in the literature to argue that decentralized production plants could overcome many of the infrastructural barriers facing a transition to hydrogen (Ball and Wietschel, 2008). Most studies consider the decentralized route as the key to bypassing the infrastructural problem (Haeseldonckx and D'haeseleer, 2011). A decentralized approach often results in higher costs as efficiencies are generally lower and because on-site production facilities are often dimensioned to cover peak demand (especially when no storage is foreseen or possible). However, a further increase in demand will require larger pipelines, and consequently additional investment costs (Haeseldonckx and D'haeseleer, 2011). Two distributed hydrogen production technologies have been identified: (1) reforming natural gas or liquid fuels, including renewable liquids, such as ethanol and bio-oil, and (2) small-scale water electrolysis.

Large hydrogen production facilities currently exist in or near petroleum refineries because hydrogen is used in petroleum processing. A small fraction of this hydrogen may be transported to nearby refueling stations during the transition phase of hydrogen deployment (Office of Energy Efficiency and Renewable Energy, n.d.).

2.4.2 Steam Reforming of Natural Gas (SMR)

Most hydrogen (97%) is produced by steam reforming of natural gas, also known as SMR (Koroneos et al., 2004). SMR is used in the chemical and petrochemical industries; it is currently the cheapest production method and has the lowest CO₂ emissions of all fossil production routes (Ball and Wietschel, 2008). This process is the most efficient in large-scale production. Fig. 2.3 presents the typical features of the SMR process.

The main steps in the production of hydrogen from natural gas are (Hajjaji, 2011): (1) production of the synthesis gas, (2) conversion of carbon monoxide to hydrogen (water shift gas); and (3) purification (Scipioni et al., 2017).

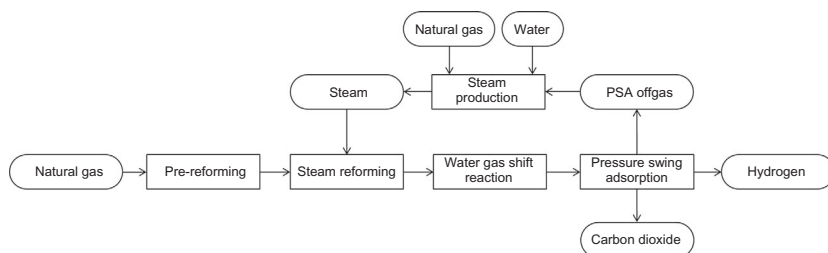
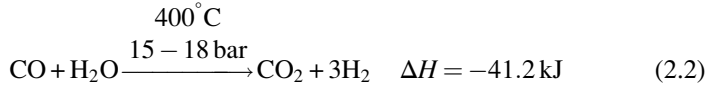
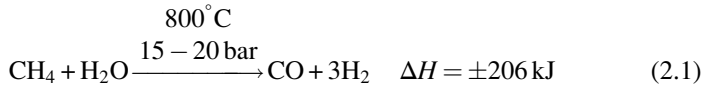
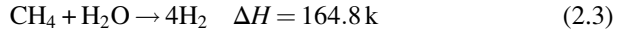


FIG. 2.3 SMR process. (From Wulf, C., Kaltschmitt, M., 2012. Life cycle assessment of hydrogen supply chain with special attention on hydrogen refuelling stations. *Int. J. Hydrogen Energy, Advances in Hydrogen Production (Selected papers from ICH2P-2011)* 37, 16711–16721. <https://doi.org/10.1016/j.ijhydene.2012.03.028>.)



Governing equation



The process starts with desulfurized natural gas below the ppm-level (the catalyst of the process is very sensitive to sulfur). Then, natural gas is reformed with the addition of water to a hydrogen- and carbon monoxide-rich gas at 800°C and 3 MPa. The gas is transformed into hydrogen by the water-gas-shift reaction, in which carbon monoxide reacts with a catalyst to produce carbon dioxide and more hydrogen. The hydrogen so produced must be cleaned by removing CO₂ by pressure swing absorption, leaving essentially pure hydrogen (Wulf and Kaltschmitt, 2012).

During hydrogen production, some heat is produced that can be recovered in an industrial furnace, making the process most efficient.

2.4.3 Electrolysis

Electrolysis is a process based on the generation of hydrogen and oxygen by applying a direct electric current to water to dissociate it. Hydrogen obtained with this technology has a high purity that can reach 99.999 vol% once hydrogen has been dried up and oxygen impurities have been removed. Electrolyzers consist of an anode and a cathode separated by an electrolyte (see Fig. 2.4).

Electrolysis needs electrical energy to convert water into oxygen and hydrogen. After hydrogen is obtained, it must be dried and purified by a deoxo dryer. Oxygen is released to the air. The governing reaction is shown in Eq. 2.4 (Scipioni et al., 2017).



The different electrolyzers, operated in slightly different ways according to the different type of electrolyte material involved, are described in the following paragraphs.

2.4.3.1 Polymer Electrolyte Membrane Electrolyzer

In a polymer electrolyte membrane (PEM) electrolyzer, the electrolyte is a solid specialty plastic material. The water reacts at the anode to form oxygen and positively charged hydrogen ions (protons). Then, the electrons flow through an external circuit and the hydrogen ions selectively move across the PEM to

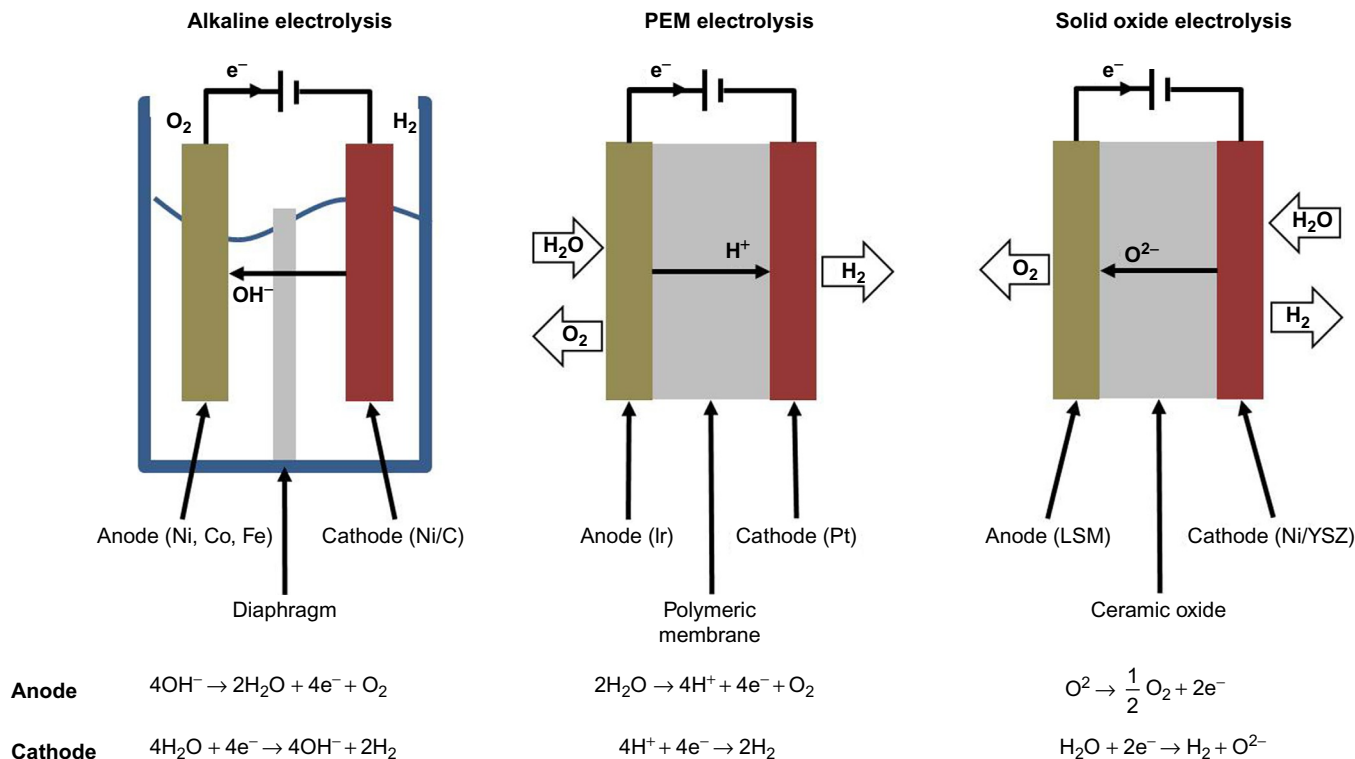
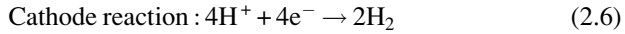
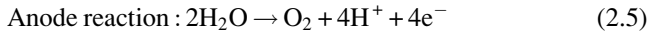


FIG. 2.4 Operation principles of an alkaline, PEM, and solid oxide electrolyzer. (From Sapountzi, F.M., Gracia, J., Weststrate, C., Fredriksson, H., Niemantsverdriet, H., 2017. Electrocatalysts for the generation of hydrogen, oxygen and synthesis gas. <https://doi.org/10.1016/j.pecs.2016.09.001>.)

the cathode. At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas, with the following reactions:



2.4.3.2 Alkaline Electrolyzers

Alkaline electrolyzers operate via transport of hydroxide ions (OH^-) through the electrolyte from the cathode to the anode with hydrogen being generated on the cathode side. Electrolyzers using a liquid alkaline solution of sodium or potassium hydroxide as the electrolyte have been commercially available for many years. Newer approaches using solid alkaline exchange membranes as the electrolyte are showing promise at the lab scale.

2.4.3.3 Solid Oxide Electrolyzers

Solid oxide electrolyzers, which use a solid ceramic material (zirconium dioxide doped with yttrium oxide) as the electrolyte that selectively conducts negatively charged oxygen ions (O^{2-}) at elevated temperatures, generate hydrogen in a slightly different way. Water at the cathode combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions. The oxygen ions pass through the solid ceramic membrane and react at the anode to form oxygen gas and generate electrons for the external circuit.

Solid oxide electrolyzers must operate at temperatures high enough for the solid oxide membranes to operate properly (about 700–800°C, compared to PEM electrolyzers, which operate at 70–90°C, and commercial alkaline electrolyzers, which operate at 100–150°C). The solid oxide electrolyzers can effectively use heat available at these elevated temperatures (from various sources, including nuclear energy) to decrease the amount of electrical energy needed to produce hydrogen from water. This system has the advantage of being reversible and able to work either as electrolyzer or as solid oxide fuel cell (SOFC). It is thus possible to operate in electrolyzer mode when the price of electricity is low and in fuel cell mode producing electricity during electrical demand peaks. This process is still in the research phase (Cueugnet et al., 2015).

An electrolysis flow diagram is shown in Fig. 2.5, although some differences may occur according to the process. For example, PEM units will not require a KOH mixing tank, as no electrolytic solution is needed for these electrolyzers. Water purification equipment may also vary, because water quality requirements differ across electrolyzers.

All systems have a hydrogen generation unit (electrolysis stack, gas purification, and heat removal). Hydrogen and oxygen are produced in the generation

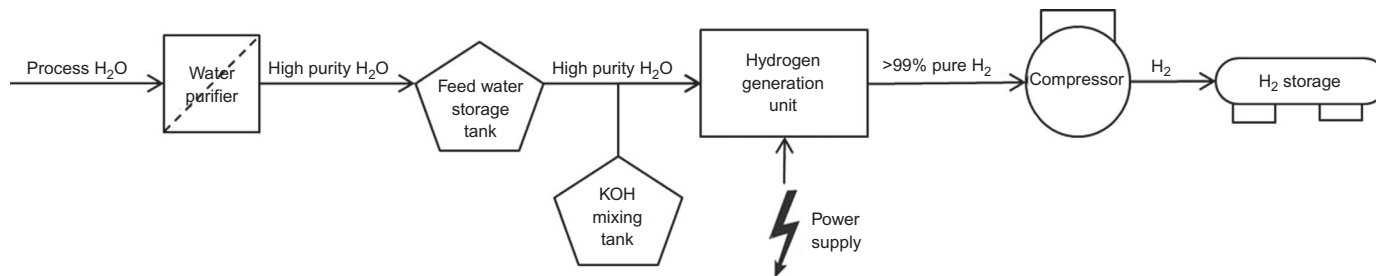


FIG. 2.5 Electrolysis flow diagram. (Adapted from Ivy, J., 2004. *Summary of electrolytic hydrogen production: milestone completion report* (No. NREL/MP-560-36734). National Renewable Energy Lab., Golden, CO (US).)

unit. At the end of the system, a compressor and hydrogen storage can be added (Ivy, 2004).

While PEM electrolysis is less proven and costlier in terms of capital expenditure (CAPEX) than alkaline electrolysis, it is more compact and suitable for dynamic load balancing of electricity grids needed with the use of intermittent renewable energy.

In a central electrolyzer, production can reach a capacity of 50,000 kg/day. The plant design capacity is 51,020 kg/day with a 98% operating efficiency (Table 2.3).

From a technological point of view, the development of alkaline electrolyzers is currently sufficiently advanced to start the production of renewable hydrogen at significant rates. However, it is generally agreed that the massive hydrogen production required by the hydrogen economy will need electrolysis units with production capacities much higher than current ones. Polymer electrolyte membrane (PEM) electrolyzers are commercially available, but their cost is high, and the technology seems more suitable for small-scale

TABLE 2.3 Specifications of the Different Types of Electrolyzers Summarized From Dincer and Acar (2015)

Specification	Alkaline	PEM	SOE
Technology maturity	State of the art	Demonstration	R&D
Cell temperature (°C)	60–80	50–80	900–1000
Cell pressure (bar)	<30	<30	<30
Current density (A/cm ²)	0.2–0.4	0.6–2.0	0.3–1.0
Cell voltage (V)	1.8–2.4	1.8–2.2	0.95–1.3
Power density (W/cm ²)	Up to 1.0	Up to 4.4	–
Specific system energy consumption (kWh/Nm ₃)	4.5–7.0	4.5–7.5	2.5–3.5
Hydrogen production (Nm ³ /h)	<760	<30	–
Stack lifetime (h)	<90,000	<20,000	<40,000
System lifetime (y)	20–30	10–20	–
Hydrogen purity (%)	>99.8	99.999	–
Cold start up time (min)	15	<15	>60

Data from Bhandari, R., Trudewind, C.A., Zapp, P., 2014. Life cycle assessment of hydrogen production via electrolysis – a review. *J. Clean. Prod., Special Volume: Making Progress Towards More Sustainable Societies through Lean and Green Initiatives* 85, 151–163. DOI: 10.1016/j.jclepro.2013.07.048.

applications. Solid oxide electrolyzers (SOEs) for hydrogen production from steam are at the R&D stage. They show enormous potential because the use of high-temperature heat reduces their electricity usage.

2.4.4 Coal Gasification

Coal gasification is economically attractive, but has significant CO₂ emissions, even if CO₂ can be captured and stored. Nowadays, hydrogen production from coal gasification is not much used, except in those places where the other sources are very expensive (Dagdougui, 2012). Fig. 2.6 shows the standard process of producing hydrogen with the coal gasification method.

The governing reaction of gasification is presented in Eq. 2.7 (Scipioni et al., 2017).



In this process, hydrogen is produced by the added water, and the coal serves merely as a reducing agent and an energy source. The first step is to pyrolyze the coal to crack carbon and obtain minuscule molecules while water is added as the synthesis gas production starts. A water-gas-shift reaction follows gasification. Depending on the ingredients of the hard coal, a pressure swing adsorption may not be enough to clean hydrogen. Hydrogen sulfide (H₂S) produced from the sulfur content of the coal must also be removed (Wulf and Kaltschmitt, 2012; Xiang et al., 2010).

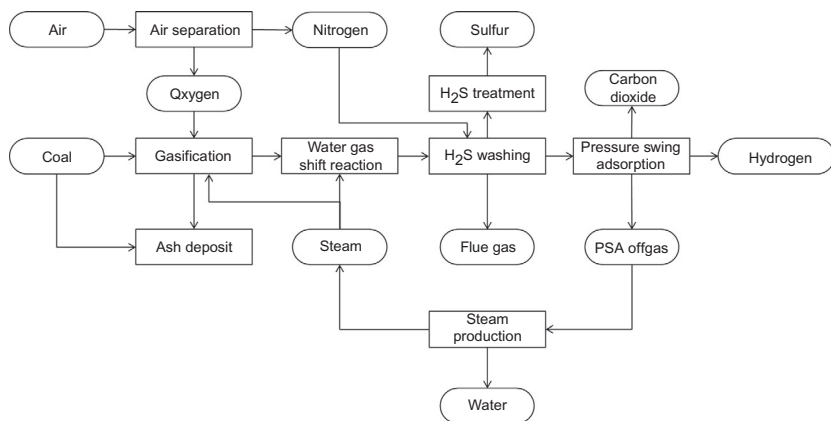


FIG. 2.6 Coal gasification to produce hydrogen. (From Wulf, C., Kaltschmitt, M., 2012. Life cycle assessment of hydrogen supply chain with special attention on hydrogen refuelling stations. *Int. J. Hydrogen Energy, Advances in Hydrogen Production (Selected papers from ICH2P-2011)* 37, 16711–16721. <https://doi.org/10.1016/j.ijhydene.2012.03.028>.)

2.4.5 Biomass

Biomass gasification is still in the development stage and competes with other uses of biomass. There are two main ways to produce hydrogen from biomass (Orecchini and Bocci, 2007), either biochemical or thermochemical. Fig. 2.7 shows a general view of the conversion from biomass to hydrogen.

Biochemical methods convert biomass into energy through the use of enzymes, mushrooms, and microorganisms formed from the biomass. Four processes can be found, namely, aerobic digestion, anaerobic digestion, oil extraction, and alcoholic fermentation (production of ethanol).

Aerobic digestion uses aerobic microorganisms, decomposing the organic matter and producing heat, CO_2 , and water. This process is used to depurate sewage and is not suitable for hydrogen production.

Anaerobic digestion produces biogas with the help of bacteria in an anaerobic environment, producing a gas mixture of 65%–70% CH_4 and 30%–35% CO_2 . The produced biogas can then be used to obtain hydrogen by the SMR method.

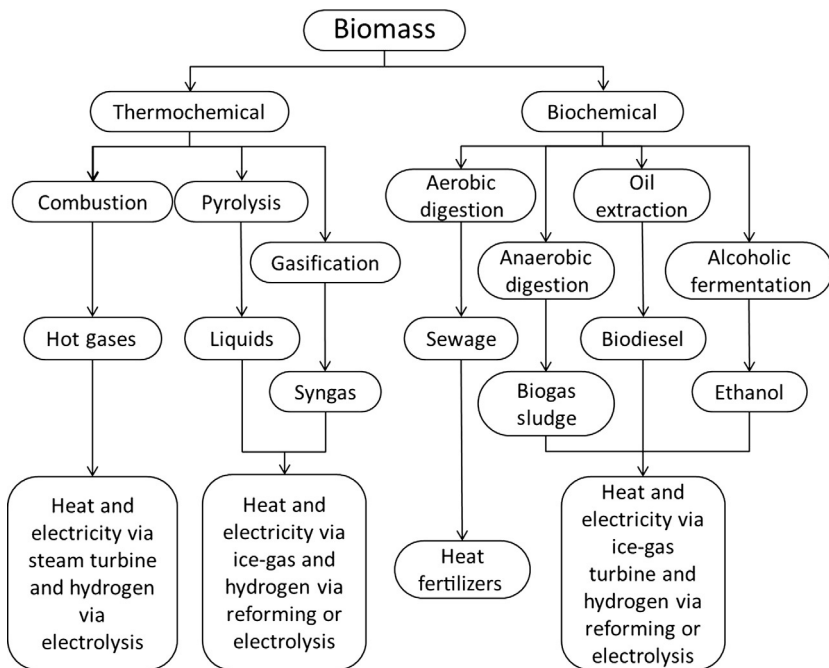


FIG. 2.7 Biomass to hydrogen processes. (From Orecchini, F., Bocci, E., 2007. Biomass to hydrogen for the realization of closed cycles of energy resources. *Energy, Third Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems* 32, 1006–1011. DOI: 10.1016/j.energy.2006.10.021.)

In the oil extraction process, oil can be extracted from biomass via pressure. Then it can be processed with alcohol through esterification, in order to obtain biodiesel and hydrogen.

Alcoholic fermentation in controlled air conditions can directly produce hydrogen or ethyl alcohol, from which hydrogen can be obtained by steam reforming, but the energetic and economic reliability of the process has not been demonstrated.

Oil extraction is a mechanical-chemical conversion process that can be used to produce oil from seeds, and that can be followed by esterification to obtain biodiesel and hydrogen. The disadvantage of this pathway is its low energy ratio (between 0.3 and 3).

On the thermochemical side, three processes can be highlighted: combustion, pyrolysis, and gasification.

Biomass combustion produces hot gases (800–1000°C), which is generally possible with a moisture level of <50%. Biomass pyrolysis generates liquid oils, solid charcoal, and gaseous compounds by heating the biomass at a temperature of 650–800 K at 0.1–0.5 MPa. It occurs in the total absence of oxygen, except in cases in which partial combustion is allowed to provide the thermal energy needed for the process (Orecchini and Bocci, 2007).

The interested reader can refer to state-of-the-art reviews of hydrogen production technologies (Dincer and Acar, 2015; Nikolaidis and Poullikkas, 2017).

2.4.6 Carbon Capture and Storage (CCS)

Hydrogen supply chains offer the possibility of capturing most of the CO₂ emissions (~90%) and sequestering them (Murthy Konda et al., 2011) because they originate mostly from point sources (production facilities using nonrenewable sources). CCS is an energy intensive and costly process involving several steps: CO₂ capture, pressurization, transportation, and final disposal into geological formations or in aquifers (Direction générale de la compétitivité, de l'industrie et des services, 2011; Haeseldonckx and D'haeseleer, 2011). There are three main technology options for CO₂ capture and storage: precombustion capture, postcombustion capture, and oxy fuel combustion.

2.4.6.1 Precombustion Capture

Precombustion capture processes can be used in coal or natural gas plants. The fuel is reacted first with oxygen and/or steam and then further processed in a shift reactor to produce a mixture of H₂ and CO₂. CO₂ is captured from a high-pressure gas mixture that contains between 15% and 40% CO₂ (Haeseldonckx and D'haeseleer, 2011; Direction générale de la compétitivité, de l'industrie et des services, 2011).

2.4.6.2 Postcombustion Capture

The postcombustion process is commercially applied to produce high-purity CO₂ from the exhaust of coal and gas fired boilers, furnaces, and turbines. CO₂ is captured typically through the use of solvents and subsequent solvent regeneration, sometimes in combination with membrane separation (Direction générale de la compétitivité, de l'industrie et des services, 2011; Haeseldonckx and D'haeseleer, 2011). The basic technology, using mono ethanolamine, has been used on an industrial scale for decades, but the challenge is the massive scaleup for power plants and to recover CO₂ with a minimum energy penalty and at acceptable cost. At present, the largest operating unit has a capacity of 800t CO₂/day. To put this into perspective, large coal-fired units produce up to roughly 10,000t CO₂/day (Haeseldonckx and D'haeseleer, 2011).

2.4.6.3 Oxygen Combustion

In this technology, the fuel is combusted using (nearly) pure oxygen, which is produced by a cryogenic ASU, although new technologies, such as ion transport membranes, are investigated. The flue gas, containing primarily CO₂, is partially recycled to the boiler to control the combustion temperature. The main advantage of oxy fuel combustion is that it enables nearly 100% CO₂ capture (Haeseldonckx and D'haeseleer, 2011).

After CO₂ is captured via physical absorption, it is compressed to supercritical pressure at 15 MPa, which permits efficient pipeline transmission of CO₂. Energy use and CO₂ emissions from CO₂ sequestration are assumed to be predominately associated with compression (Johnson et al., 2008).

2.4.7 Other Hydrogen Production Methods

Other methods exist, such as water splitting by high-temperature heat, photoelectrolysis, and biological processes. These methods have been extensively presented in some review papers (Acar and Dincer, 2014; Dincer, 2012; Hallenbeck and Benemann, 2002), and include plasma arc decomposition, water thermolysis, biological processes, thermochemical water splitting, biophotolysis, and photofermentation among others (Dincer, 2012).

Table 2.4 shows the advantages and disadvantages of the hydrogen production methods described in this chapter.

2.4.8 Key Parameters of Some Hydrogen Production Technologies

Selected hydrogen production technologies are listed in Table 2.5 with their typical features.

TABLE 2.4 Key Benefits and Critical Challenges of the Hydrogen Production Methods			
	Fossil Fuel Reforming	Coal and Biomass Gasification	Water Electrolysis
Critical challenges	High capital costs	High reactor costs	Low system efficiency
	Design	System efficiency	High capital costs
	High operation and maintenance costs	Feedstock impurities	System integration
		Carbon capture and storage	Design issues
Major R&D needs	Efficiency and cost	Low-cost and efficient purification	Durable and cheap materials
	Low-cost and efficient purification	Cofed gasifiers	Corrosive-resistant membranes
	Feedstock pretreatment	Carbon capture and storage	Durable, active, and cheap catalysts
	Optimization	Hydrogen quality	Large-scale applications
	Automated process control	Cost and feedstock preparation	Storage and production rate
	Reliability	Tolerance of impurities	Reliability
Key benefits	Most viable approach	Low-cost syngas production	No pollution with renewable energy sources
	Lowest current cost	Abundant and cheap feedstock	Existing infrastructure
	Existing infrastructure		Integration with fuel cells
Adapted from Dincer, I., Acar, C., 2015. Review and evaluation of hydrogen production methods for better sustainability. Int. J. Hydrogen Energy 40, 11094–11111. DOI: 10.1016/j.ijhydene.2014.12.035.			

TABLE 2.5 Key Parameters for Hydrogen Production in the HSC

				kg CO ₂ eq/kg (H ₂) ^a	Capital Cost	Operational Cost (\$/kg)	Capacity	Primary Energy ^a
Centralized production	LH ₂ production	Electrolysis ^a	Wind	1.03	4420–6421.05 \$/(kg/day) ^a	4.69–4.59 ^a	300–150,000 kg/day ^a	52.49 kWh/kg (H ₂)
			Solar	6.21				
			Hydro	2.07				
			Nuclear	3.10				
		SMR		10.1	903 M\$ ^b	1.12 ^b	10,000–960,000 kg/day ^b	4.02–3.16 kg (NG)/kg(H ₂)
					201.16–431.85 €/kW ^c		1530–33 MW ^c	
					29–903 M€ ^a	3.36–1.43 ^a	300–960,000 kg/day ^a	
		Coal gasification			1611 M\$ ^b	1.43 \$/kg ^b	10,000–960,000 kg/day ^b	
					462.46–573.37 €/kW ^c		1667–434 MW ^c	
		Biomass gasification		3.10	1836 M\$ ^b	2.38 ^b	10,000–960,000 kg/day ^b	
					2637.55–4101.10 €/kW ^c		33–0.7 MW ^c	
					575–1836 M€ ^a	3.52–2.15 ^a	10,000–960,000 kg/day ^a	
Distributed production	LH ₂ production	Electrolysis ^a	Wind	1.03	4.03–20.20 M€ ^a	6.24–4.94 ^a	50–2500 kg/day ^a	52.49 kWh/kg(H ₂)
			Solar	6.21				
			Hydro	2.07				
			Nuclear	3.10				

^aDe-León Almaraz et al. (2014).^bAlmansoori and Betancourt-Torcat (2016).^cSgobbi et al. (2016).

technologies in use. High-pressure hydrogen is stored in thick-walled tanks (mainly of cylindrical or quasiconformable shape) made of high-strength materials to ensure durability (Krishna et al., 2012; Tzimas et al., 2003).

According to James (2008), for stationary hydrogen storage, GH₂ also offers the advantages of simplicity and stable storage (no boil-off losses) but at a considerably greater volume than LH₂. Even accounting for compression costs, high-pressure gaseous hydrogen is cheaper than LH₂. However, except for pipeline transmission, GH₂ lacks the bulk transportability of LH₂. Consequently, GH₂ will mostly be used for storage of limited hydrogen quantities, for long term storage, or when the cost of liquefaction is prohibitive. Some issues for GH₂ are its safety perception and the high cost of the pressure vessels and hydrogen compressors.

2.5.2 Liquid Hydrogen (LH₂)

Hydrogen in liquid form has a considerably higher energy density than in gaseous form, making it an attractive storage medium (Tzimas et al., 2003). For example, the theoretical volumetric capacity of hydrogen increases from 24 or 40 g/L (for compressed H₂ at 350 or 700 bar at 300 K) to 70 g/L (for liquid H₂ at 1 atm and 20 K). When hydrogen is stored as liquid at 1 atm, it must be maintained below its boiling point (−253°C or 20 K) (Krishna et al., 2012). Effective thermal insulation is essential to maximize the efficiency of the liquid hydrogen (LH₂) tank. Typical LH₂ tanks consist of metallic double-walled containers, in which the inner and outer walls are separated by vacuum for thermal insulation purposes (Züttel, 2003).

The energy requirements of liquefaction are high, typically 30% of the hydrogen's heating value, leading to relatively high hydrogen cost as compared to gaseous hydrogen. The loss of hydrogen by evaporation effects during storage periods are further disadvantages of liquid hydrogen (LH₂) storage systems (Hake et al., 2006).

In the initial phases of hydrogen infrastructure development, the transportation of cryogenic liquid hydrogen via trucking or rail could play a significant role (James, 2008). Hydrogen is typically liquefied at the production site in large quantities (10–30 tons/day) and then trucked cross country in LH₂ tankers with no boil-off losses.

Another option is based on cryo-compressed storage; studies of physical hydrogen storage have currently shifted to cryo-compressed H₂, which combines compression and cryogenic storage (Hwang and Varma, 2014).

2.5.3 Solid Hydrogen

The storage of hydrogen in solid materials has the potential to become a safe and efficient way to store energy, both for stationary and mobile applications.

Solid hydrogen may be stored in two ways, either by metal hydrides or by carbon adsorption.

Metal hydrides store hydrogen by chemically bonding the hydrogen to metal or metalloid elements and alloys. Some hydrides can adsorb hydrogen at or below atmospheric pressure, then release the hydrogen at significantly higher pressure when heated (Tzimas et al., 2003). For example, LaNi_5H_6 can release hydrogen under PEM fuel cell operating conditions (1–10 atm and 25–100°C), but its gravimetric capacity is too low (1.4 wt%) and its cost too high for vehicle applications (Hwang and Varma, 2014).

Each alloy has different performance characteristics (cycle life, heat of reaction). Metal hydrides offer the advantages of lower pressure storage, conformable shapes, and reasonable volumetric storage efficiency. However, they suffer from weight penalties and thermal management issues. Improving resistance to gaseous contaminants and increasing system cycle life are still obstacles to overcome.

Carbon-based materials/porous structures (single-walled nanotubes and graphite nanofibers) can also be used to store significant amounts of hydrogen at room temperature due to their high surface area and abundant pore volume. There are still challenges to overcome, such as the understanding of the adsorption/desorption mechanism and the volumetric capacity of porous structures (Tzimas et al., 2003).

2.5.4 Key Factors

All the aforementioned hydrogen storage options (compressed, liquid, metal hydrides, and porous structures) have their advantages and drawbacks with respect to weight, volume, energy efficiency, refueling time, cost, and safety.

Some key parameters of the liquid and gaseous options are presented in Table 2.6.

2.6 HYDROGEN TRANSPORTATION

Conceptually, transportation is divided into two parts: transmission and distribution. Transmission refers to H_2 transportation from a plant to other regions without plant units and distribution refers to H_2 transportation to the refueling stations from a plant or regional conditioning center in any region (Murthy Konda et al., 2011).

There are various methods for transporting hydrogen, but the choice of the best transportation mode and natural state (compressed gas trucks, cryogenic liquid trucks, or gas pipelines) depends mostly on the geographic and market characteristics of the zone in which the transport occurs (market penetration, population density, demand, state of the roads, and infrastructure available) (Yang and Ogden, 2007).

TABLE 2.6 Key Parameters for Hydrogen Storage in the HSC					
	kg CO ₂ eq/kg (H ₂) ^a	Capital Cost	Operational Cost	Capacity (kg)	Efficiency ^a kWh/kg (H ₂)
Liquid H ₂	0.704	106 M€ ^b	0.0043 €/ (kg/day) ^b	540,000 ^b	8.42
		0.802–122 M€ ^a	0.064–0.005 \$/ (kg/day) ^a	50–540,000 ^a	
		122 M\$ ^c	0.005 \$/kg ^c	10,000–540,000 ^c	
Gaseous H ₂	0.349	1645 M€ ^b	0.066 €/ (kg/day) ^b	540,000 ^b	4.17
		1894 M\$ ^c	0.076 \$/kg ^c	10,000–540,000 ^c	
^a De-León Almaraz et al. (2014). ^b Sabio et al. (2010). ^c Almansoori and Betancourt-Torcat (2016).					



FIG. 2.9 Hydrogen pipelines and hydrogen tube trailers.

Hydrogen may be transported as either a gas or a liquid. Gaseous hydrogen can be transported by high-pressure pipelines or by tube trailers (see Fig. 2.9). Liquefied hydrogen can be transported in tankers (Dagdougui, 2012).

2.6.1 Hydrogen Pipelines

Pipelines are highly recommended for long distances and large quantities. They have been used for several years to deliver hydrogen to refineries and chemical plants (Ball and Weeda, 2015).

From the economic point of view, pipelines have very low operating costs, but very high capital costs due to the high-quality material that must be used in their construction that assures a lack of risk. Of course, their cost can be reduced if the natural gas infrastructure could be adapted to hydrogen (Ball and Wietschel, 2008).

Pipelines for medium and large fueling stations may become relevant once a significant market penetration of hydrogen vehicles has been achieved, but these are mostly used for local distribution in highly populated areas and for large-scale interregional energy transport according to the HyWays roadmap (European Commission, 2008). In Ball and Wietschel (2008), a pipeline network could be constructed after 2030 when the potential demand can justify the high investment.

2.6.2 Hydrogen Tube Trailers

Compressed gaseous hydrogen trailers (at 200 bar) can be a very suitable option when hydrogen must be transported over short distances, mostly up to 200 km. Recently, the pressure level for these trailers has been increased from 200 bar to 500 bar, increasing the payload from 400 kg to more than 1000 kg for distances up to 500 km (Ball and Weeda, 2015). Liquid hydrogen is recommended for smaller volumes and longer distances (Ball and Wietschel, 2009).

2.6.3 Tanker Trucks

From the liquefaction unit, LH_2 is transported by tanker trucks (cryogenic liquid hydrogen tankers) (Patay, 2008). This transportation mode is the most economic pathway for medium market penetration (Dagdougui, 2011b). Tanker trucks could transport relatively large amounts of hydrogen and reach markets located throughout large geographic areas. Forty ton trucks can carry 3500 kg of LH_2 . Thus, the transport of liquid hydrogen is limited by volume, not by weight (Bossel, 2006).

2.6.4 Key Parameters of Some Hydrogen Transportation Modes

Some key parameters of various hydrogen transportation modes are summarized in Table 2.7.

Hydrogen storage, along with distribution, is a key technology associated with the wide utilization of hydrogen. Both of these technologies represent limiting factors, currently and in the near future, to the deployment of hydrogen in the energy system

2.7 HYDROGEN REFUELING STATIONS

Hydrogen refueling stations (HRS) are not only associated with the market but also to the expectations and needs of FCEV owners. Major progress has been made in hydrogen refueling by developing equipment standards and refueling protocols for high pressure (700 bar) and fast dispensing (<3 min) in cars (Ball and Weeda, 2015).

Patay (2008) identified four types of refueling stations according to their main mode of supply, allowing the filling station vehicles equipped with tanks for hydrogen gas at high pressure to about 700 bar¹ (a priori these tanks will be dominant in the market):

- Type 1: Stations receiving liquid hydrogen require evaporation and compression facilities.
- Type 2: Stations receiving compressed hydrogen (200 bar) from tube trailers require a high-compression unit (400–700 bar).
- Type 3: Stations with a piped gaseous H_2 supply require a high-compression unit (from 100 to 400–700 bar).
- Type 4: Stations with onsite H_2 production by small electrolysis units require compression (from 15 to 400–700 bar).

1. In cases where the FCEV has 350 bar onboard storage tanks, H_2 has to be compressed up to 400 bar before being distributed (Murthy Konda et al., 2011).

TABLE 2.7 Key Parameters for Hydrogen Transportation

		g CO ₂ eq/ metric ton/ km	Capital Cost (€) ^a	Operational Cost ^a	Capacity ^a (kg/ day)	Avg Speed ^a (km/h)	Un/Loading Time ^a (h)	Efficiency (Fuel) ^a (km/L)
LH ₂	Road	62 ^b	434,236	40.56 €/h	4082–960,000	55	2	3.58
	Rail		434,236	23.62 €/h	9072–960,000	45	12	10.13
	Ship			0.00115 €/h/ kg	4082–960,000	16	48	18.75
GH ₂	Road		217,118	40.56 €/h	181–960,000	55	2	3.58
	Rail		260,541	23.62 €/h	454–960,000	45	12	10.13
	Pipeline		708,673 €/km	0.05767 €/kg/ day	10–960,000 kg/ day			

^aSabio et al. (2010).

^bDe-León Almaraz et al. (2014).

2.7.1 Key Parameters of Hydrogen Refueling Stations

The key parameters of the refueling stations are summarized in [Table 2.8](#).

The choice between central and onsite production and storage of hydrogen, and of the transport mode between sites, depends on the demand of either gaseous or liquid hydrogen. The HSC design offers multiple possibilities to explore.

2.8 MULTIPLE OBJECTIVES IN HSC SUSTAINABLE ASSESSMENT

Three categories of objectives related to economic, environmental, and social issues are of major interest for HSC design. Sustainable development usually refers to the simultaneous achievement of economic prosperity, environmental cleanness, and social responsibility, namely the so-called “triple bottom line” ([Jiménez-González and Woodley, 2010](#); [Othman et al., 2010](#)). [Table 2.9](#) presents the set of criteria that have been studied in the dedicated HSC literature.

2.8.1 Economic Assessment

The principal and the most-treated objective is the economic one ([Agnolucci et al., 2013](#); [Almansoori and Betancourt-Torcat, 2016](#); [Almansoori and Shah, 2006, 2009, 2012](#); [Gondal and Sahir, 2013](#); [Kamarudin et al., 2009](#); [Kim et al., 2008](#); [Woo et al., 2016](#)), mainly based on the total network cost.

These criteria have been generally embedded in optimization strategies for hydrogen supply chains.

[Almansoori \(2015\)](#) presents a MILP model for the optimal design and operation of an HSC under CO₂ emission constraints. This model includes carbon capture and storage (CCS) methods and a carbon tax as CO₂ mitigation strategies. The optimization objective consists of the minimization of the total network cost, both in terms of capital and operating expenditures, under techno-economic and environmental constraints, as in [Almansoori and Betancourt-Torcat \(2016\)](#). The model determines the most suitable delivered product form (gaseous or liquid) into the market.

Two scenarios were studied to determine the optimal HSC configuration of the country (with and without the application of a carbon tax). A case study of a future HSC in the United Arab Emirates (UAE) was analyzed. The production technology selected was based on steam methane reforming, as similarly in ([Almansoori and Betancourt-Torcat, 2016](#); [Agnolucci et al., 2013](#); ([Moreno-Benito et al., 2016](#)).

The total annualized cost to plan the HSC under emission constraints has also been studied in ([Almansoori and Betancourt-Torcat, 2016](#)). A case study for Germany in 2030 was treated considering CCS decisions.

Other works present techno-economic inputs and technological background information for hydrogen delivery pathways ([Bolat and Thiel, 2014a, b](#)).

TABLE 2.8 Key Parameters for Hydrogen Refueling Stations in the HSC

	Tank Pressure ^a (bar)	Storage Pressure (MP) ^a	Capacity ^a	Efficiency ^a kWh/kg(H ₂)	Refueling Time ^b (min)	Reliability ^a	Life Duration ^a (Years)
High pressure	700	85	750 kg (H ₂)/ day	3.0	<3	<95%	50 (building)
Low pressure	350	40	280 hg (H ₂) Storage				10 (comp.)

^aWulf and Kaltschmitt (2012).

^bBall and Weeda (2015).

TABLE 2.9 Sustainable Assessment Criteria for HSC

Multiobjective Assessment		
<i>Economic</i>	<i>Environmental</i>	<i>Social</i>
Total network cost (Agnolucci et al., 2013; Almansoori and Betancourt-Torcat, 2016; Almansoori and Shah, 2006, 2009, 2012; Kim et al., 2008)	Global warming potential (De-León Almaraz et al., 2013)	Hazard identification (HAZID) (Oyama et al., 2016)
Total investment cost (Woo et al., 2016)	Life cycle assessment (LCA): Eco-Indicator99 (EI-99) (Guillén-Gosálbez et al., 2010)	Total relative risk (Han et al., 2013; Kim and Moon, 2008)
	Cumulative WtW (well-to-wheel) life cycle GHG emissions (Hugo et al., 2005; Li et al., 2008)	Social effects (Cantuarias-Villesuzanne et al., 2016; Creti et al., 2015)

2.8.2 Environmental Assessment

Life cycle assessment (LCA) has been extensively used for energy supply chain environmental assessment (Curran, 2000). LCA is an established and internationally accepted method that is defined in the ISO standards ISO 14040 and ISO 14044. Even if hydrogen is considered to be a clean fuel in its use phase, its production still has impacts on the environment. Examining resource consumption, energy requirements, and emissions from a life cycle point of view (production to distribution) gives a complete picture of the environmental burdens associated with the hydrogen supply chain. Some LCA-based approaches for hydrogen production processes are listed in Table 2.10.

To limit the global mean temperature increase to 2 °C by the middle of this century, roughly 80% of the global greenhouse gas (GHG) emissions must be reduced by 2050 using the 1990 baseline. This explains why the global warming potential (GWP) is perhaps the most used indicator for energy supply chains, and for hydrogen ones in particular.

De-León Almaraz et al. (2013) uses the GWP as an indicator of the overall effect of the process related to the heat radiation absorption of the atmosphere due to emissions of greenhouse gases (CO₂-equiv) of the network. The total GWP is the cumulative value of the GWP associated with the different echelons of the supply chain, namely, production, storage, and distribution.

TABLE 2.10 Reviews of the LCA of Hydrogen Production	
Authors	Title
Boyano et al. (2011)	Exergo-environmental analysis of a steam methane reforming process for hydrogen production
Cetinkaya et al. (2012)	Life cycle assessment of various hydrogen production methods
Dufour et al. (2012)	Life cycle assessment of alternatives for hydrogen production from renewable and fossil sources
Hacatoglu et al. (2012)	Comparative life cycle assessment of hydrogen and other selected fuels
Koroneos et al. (2008)	Hydrogen production via biomass gasification. A life cycle assessment approach
Lee et al. (2010)	Life cycle environmental and economic analyses of a hydrogen station with wind energy
Ozbilen et al. (2011)	A comparative life cycle analysis of hydrogen production via thermochemical water splitting
Spath and Mann (2004)	Life cycle assessment of renewable hydrogen production via wind/electrolysis
Utgikar and Thiesen (2006)	Life cycle assessment of high-temperature electrolysis for hydrogen production via nuclear energy
Wulf and Kaltschmitt (2012)	Life cycle assessment of hydrogen supply chain with special attention on hydrogen refueling stations
Based on Bhandari, R., Trudewind, C.A., Zapp, P., 2012. Life cycle assessment of hydrogen production methods—a review, STE research report. Forschungszentrum Jülich, Institute of Energy and Climate Research.	

Guillén-Gosálbez et al. (2010) uses the Eco-indicator 99 framework, focusing their attention on only one of its impact categories, that is, damage to human health caused by climate change. The units of this metric are disability adjusted life years (DALYs).

Hugo et al. (2005) and Li et al. (2008) propose the analysis and reduction of the environmental performance of the competing hydrogen infrastructures using the cumulative WtW (well-to-wheel) life cycle GHG emissions that result from delivering hydrogen to the FCEV consumer.

2.8.3 Social Assessment

Social aspects are perhaps the most difficult to formalize. The social aspects involved in the development of the hydrogen economy have been addressed

from different perspectives and at different levels. Firstly, several studies have been conducted to evaluate hydrogen sustainability (Afgan et al., 2007; Chang et al., 2011; Hsu, 2013; Markert et al., 2016; Ren et al., 2013a, 2013b). Secondly, other works have focused on the analysis of strategies to narrow the gap toward a hydrogen economy (Keles et al., 2008; Moliner et al., 2016; Qadrdan et al., 2008). Lastly, several assessments have been performed to evaluate the potential of a hydrogen economy compared with other sustainable alternatives, and its acceptance in the future (Ball and Weeda, 2015; Ricci et al., 2008; Sgobbi et al., 2016).

One approach from a social point of view is the real case presented by Oyama et al. (2016) and developed by Kawasaki Heavy Industries, Ltd., focused on inexpensive Australian brown coal, which boasts tremendous reserves. Oyama et al. (2016) have developed the concept of the “CO₂-Free Hydrogen Chain” in which a large amount of hydrogen is imported into Japan by liquefied hydrogen carriers after gasifying and refining the brown coal to produce hydrogen. This model takes safety into account using Hazard Identification (HAZID) for safety design.

Han et al. (2013) have proposed an HSC model optimizing a risk safety objective considering the cumulative risk of production sites, storage sites, and of transportation.

In addition to economic objectives, Kim and Moon (2008) have also considered a risk index. The index is based on three subrisk indexes according to the types of hydrogen activities: hydrogen production, storage, and transportation. In addition, the index takes into account the characteristics of the regions (e.g., the population density) in which hydrogen activities are performed.

More recently, other studies (Cantuarias-Villessuzanne et al., 2016; Creti et al., 2015) have also investigated the social effects of developing a hydrogen economy, for electromobility applications. Cantuarias-Villessuzanne et al. (2016) have quantified the societal benefits for the reduction of greenhouse gas emissions and social costs for the increase of platinum consumption in the manufacture of fuel cells. According to their study, the social balance is positive, including also platinum depletion, generating net savings for Europe.

2.9 CONCLUSIONS

In this chapter, the key components of an HSC have been presented. An HSC involves a variety of energy sources, production, storage, transportation options, and supply of hydrogen to the refueling stations. These individual components constitute the building blocks that need to be integrated to form the global supply chain. The resulting network will heavily depend on country- and region-specific conditions.

HSC deployment and design are clearly a problem with multiple objectives, in a context of energy transition with multiple stakeholders and multiple end users.

Even though most of the aspects of the HSC infrastructure have been covered in the literature, an open question that remains is how the hydrogen infrastructure will back the transition toward long-term sustainable hydrogen economies while guaranteeing short- and mid-term system economic acceptability, starting from the current carbon-based economy.

This issue has been tackled in several roadmaps, but the formulation for optimizing simultaneously the range of production technologies, scales, transportation modes, and CCS elements across time and space for solving the transition toward a low-carbon energy system, and in particular toward a hydrogen economy remains. Such an approach will be required to manage a gradual penetration of hydrogen demand.

All these activities need to be integrated in a systematic modeling framework that allows a more precise approach than roadmaps and planning scenarios (as previously explained in [Chapter 1](#)). This analysis emphasizes that achieving the potential benefits of a hydrogen system requires careful integration of production, storage, and end-use components with minimized cost and maximized efficiency, and a strong understanding of the environmental impact, reliability, and opportunities, positioning this book in a system modeling approach based on a multiobjective optimization framework.

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