Chapter 7

Hydrogen Applications: Overview of the Key Economic Issues and Perspectives

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7.1 OVERVIEW OF HYDROGEN APPLICATIONS

Despite the fact that hydrogen is mainly advertised as a promising energy carrier, especially for mobile applications, hydrogen can address a wide range of applications. This section aims at clarifying the diverse uses at stake and proposing an assessment of the related volumes, today and in the future.

7.1.1 Hydrogen: A Chemical Product and an Energy Carrier

What is hydrogen? From the market perspective, hydrogen is both an energy carrier that needs to be produced, even if "natural" hydrogen is a rising topic (Prinzhofer and Deville, 2015), and a chemical product involved in a range of industrial processes. To offer a relevant overview of hydrogen applications, both standpoints must be considered. This is what is intended the following text. Overall, as depicted by Fig. 7.1, hydrogen can be produced from any energy source, whether fossil, nuclear, or renewable, and involved in any use (or almost any).

7.1.1.1 Industry Applications

Hydrogen is required as a chemical input in a variety of industry chemical processes. The first application, in quantitative terms, is *the refining industry*. It uses 26.4 million tons of hydrogen per year worldwide (Alphéa Hydrogène, 2014).

Hydrogen Supply Chain. https://doi.org/10.1016/B978-0-12-811197-0.00007-5

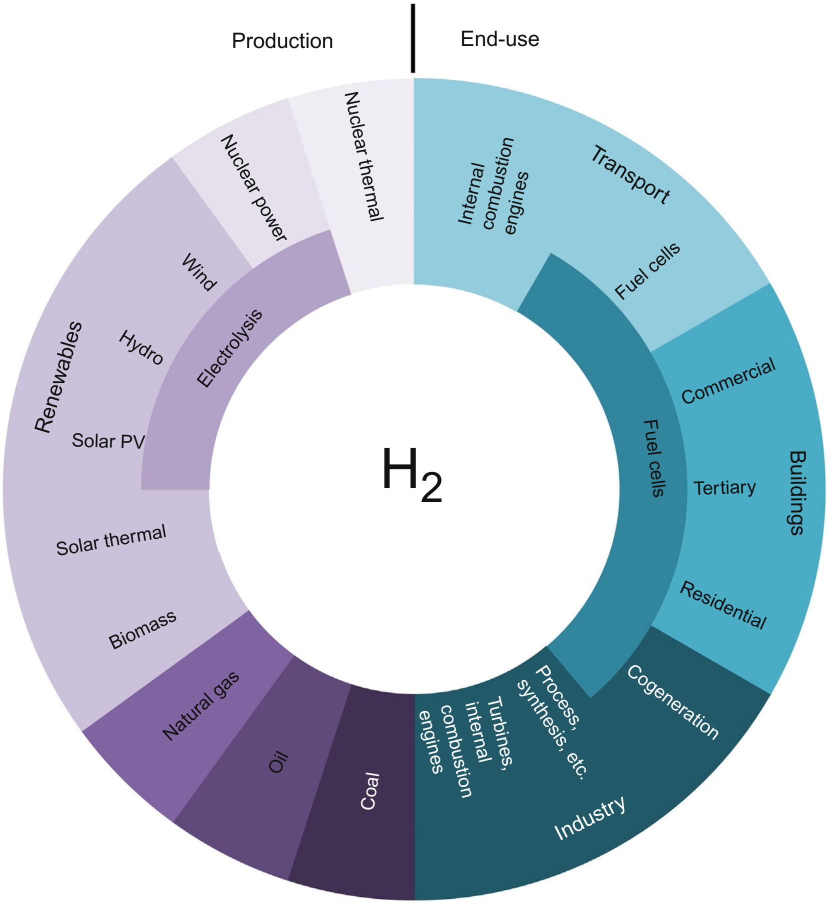

FIG. 7.1 Hydrogen production and uses *Adapted from 2011 connaissancedesenergies.com, from AFHYPAC—UE.*

Refining is a very complex process that involves a series of chemical reactions. Some require hydrogen as an input (e.g., hydrocracking, hydrotreating, desulphurization); others generate hydrogen as a byproduct (e.g., catalytic or thermal cracking, catalytic reforming). The global balance between these steps is negative; hydrogen must be produced to feed the refining process. Lately, the refining industry faces an increasing need for hydrogen due to two main factors: (1) fuel specifications have become more demanding (to be saleable, products must meet the standards), and (2) resources have become heavier.

The second major sector today is the *fertilizer industry* (ammonia production, NH_3), with demands similar to those of the refinery industry: 22.8 million tons per year.

Other applications also exist in a range of sectors more marginal in terms of hydrogen demand, and very diverse in terms of applications: methanol production, metallurgy, glass industry, semiconductor industry, food industry (for the well-known hydrogenated fats), and fuel for space rockets. Together, they represent 18% of the current hydrogen needs worldwide.

Finally, another category of industry applications is the production of *"new" fuels* that require hydrogen as an input. They include synthetic fuels and biofuels. We categorize these applications as a demand for industry because hydrogen is not directly used as an energy carrier but as a chemical input to generate energy carriers. These "new" fuels could be an attractive step toward a more sustainable energy system because they can be used directly (or almost directly) in classical internal combustion engines (drop-in fuels for either road or aviation, without major engine modification) (Imbach, 2012). The hydrogen input is also very valuable to generate these fuels because it helps enhance biomass use (Imbach, 2012), and production of fuels from carbon dioxide (Ademe, 2010). An overview of carbon dioxide hydrogenation routes is provided in Fig. 7.2. A variety of products could be generated from carbon dioxide emissions, together with a hydrogen input.

With regard to biofuels, second-generation biodiesel (also called BtL, for "biomass-to-liquid") can be produced without competing with food resources, as they are generated from lignocellulosic biomass (non-staple crops), primary resources of agriculture and forests including dedicated crops, or secondary resources (waste products and byproducts). The process requires adjusting the hydrogen-to-carbon-monoxide ratio from one to two, thereby necessitating an additional hydrogen feed. If supplied by another process (such as water electrolysis), the mass efficiency can be improved from 15% to 45%, resulting in a better use of the limited biomass feedstock.

7.1.1.2 "Green" Gas Applications

Hydrogen is also contemplated as an energy carrier, to be substituted—at least partially—for natural gas. This can be achieved through two different routes. The first option is to directly inject hydrogen into the natural gas network. A few percent in volume do not raise any difficulty, and diverse projects examine the possibility of injecting up to 20% (Florisson, 2010). Another option is to go from hydrogen to synthetic methane, through a methanation step (see Fig. 7.3). This would overcome any barrier in terms of injection limits, and also provide an additional sink for carbon dioxide emissions (provided that the carbon release is not delayed).

These options are often called "power-to-gas." However, they are very rarely properly and precisely defined. As a matter of fact, power-to-gas can refer to power to hydrogen, or to power to synthetic methane, for injection in the natural gas network, or for a range of different applications (including mobility, for instance). Besides, power-to-gas can rely on renewable power (exclusively),

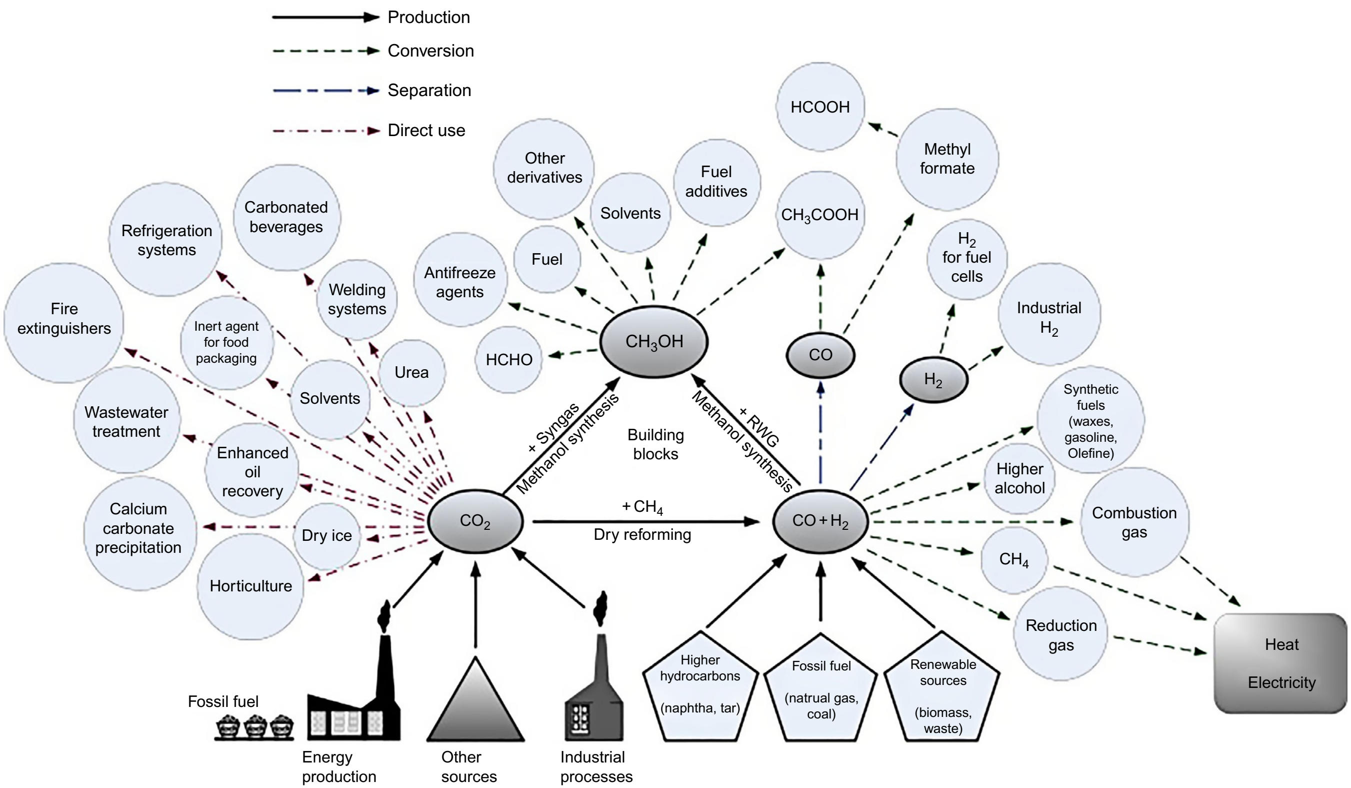

FIG. 7.2 CO_2 hydrogenation routes (Ademe, 2010). *From DiaMilani, R.K., Gholamreza, Z., Ali, A., 2015. A model-based analysis of CO_2 utilization in methanol synthesis plant. J. CO_2 Utilization 10, 12–22.*

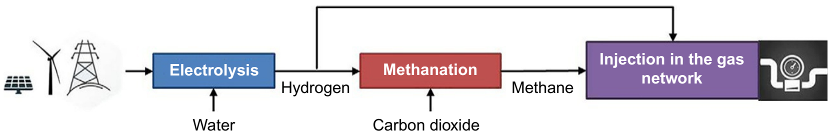

FIG. 7.3 "Green gas" pathways.

TABLE 7.1 Global Warming Potential of Methane vs. Carbon Dioxide (Climate Change, 1995)

	Global Warming Potential (Time Horizon)		
	20 Years	*100 Years*	*500 Years*
Carbon dioxide	1	1	1
Methane	56	21	6.5

sometimes only "excess" or "surplus" power, or simply power, disregarding the way it is produced (also trying to keep it low-carbon).

Overall, to promote this application as "green," several issues should be carefully examined:

– What is the life-cycle environmental footprint of the power-to-gas system?
– What is the alternative it will replace?

Indeed, such systems could improve the environmental footprint of pre-existing natural gas applications, but they could damage the global system environmental footprint if they lead to create brand new applications for natural gas (not replacing already existing ones, which are more carbon-intensive), as natural gas has a much greater global-warming potential than carbon dioxide (cf. Table 7.1). Moreover, losses during production and transportation steps due to unintentional methane equipment or pipeline leaks accentuate the impact (Robinson et al., 2003 in Camuzeaux, 2012). According to the French gas operator, losses amount to 0.6% (GRDF, 2009).

As a result, today, almost 3% of greenhouse gas emissions (all emissions included) are due to leakages and venting in natural gas and oil systems (Camuzeaux, 2012).

7.1.1.3 Mobility Applications

Hydrogen mobility is often understood as full-hydrogen mobility for passenger cars. However, it covers a range of diverse vehicles in land, maritime, and aeronautic mobility: light duty vehicles (LDV) such as cars and vans, commercial vehicles, buses, and trucks, two- and three-wheeled vehicles such as scooters and bicycles (cf. Fig. 7.4), forklift trucks, trains and trams, ferries and smaller

FIG. 7.4 Hydrogen bicycle. *Used with permission from Pragma-Industries*

boats. For aeronautics, applications include manned light aircraft, unmanned aerial vehicles (UAV), and unmanned underwater vehicles (UUV), for example, for recognition purposes. Aeronautics companies are also developing alternative power sources for non-propulsive aircraft systems such as a galley in a commercial aircraft, or to be used as a secondary power source onboard business jets, as an auxiliary power unit or last-resort turbine.

The market maturity is, of course, different depending on the market segments, from demonstration to products available on the market. For example, buses in California have been on the road for over 20,000h now (White, 2016). One spectacular example of market development is forklift trucks. As a matter of fact, they demonstrated their qualities in real conditions, in terms of charging time, autonomy, and costs. A number of companies implemented hydrogen forklift trucks in their warehouses. Among them are global brands like Walmart, FedEx, Sysco, IKEA, and Coca Cola (Denhoff, 2016).

Hydrogen vehicles have begun entering the market. Toyota, Hyundai, Honda, and BMW include hydrogen cars in their product portfolios. As an example, Toyota released the “MIRAI” in December 2014, at the price of 7.23 million yen (i.e., approximately 50,000 euros). They plan to sell 30,000 vehicles by 2020 (Ohira, 2016) (cf. Fig. 7.5).

With regard to passenger vehicles, hydrogen mobility may appear competitive with electric mobility. However, hydrogen mobility can also be realized via range-extenders, thus combining the advantages of hydrogen and electric mobility, with autonomy and recharge times similar to classical vehicles, smaller hydrogen storage and fuel cell capacity requirements as compared to full-hydrogen vehicles, and a smaller battery capacity requirement than a fully-electric vehicle.

As a result, hydrogen mobility should take part in the sustainable mobility panel, offering alternatives to electric vehicles and biofuels. In this respect, the way hydrogen is produced is of paramount importance, so that the life-cycle balance of hydrogen vehicles may be improved beyond that of diesel and

FIG. 7.5 Hydrogen car—example of the Toyota Mirai.

gasoline vehicles. As shown in, beyond comparison with gasoline or hybrid vehicles, it should be highlighted that the way hydrogen is produced dramatically impacts the environmental footprint of hydrogen vehicles.

Overall, the interest for hydrogen mobility also arises from the fact that, with regard to electric mobility, significant local benefits are realized in terms of air pollution and noise. In this respect, diffuse CO_2 emissions are avoided, whatever the hydrogen production process.

7.1.1.4 Stationary Applications

Stationary applications refer to the use of fuel cells to generate electricity from hydrogen. Fuel cells may be fed directly by natural gas, though (Hashimoto, 2015). Hydrogen is used as an energy carrier, and the market segment is clearly energy storage. It may also be named re-electrification, if hydrogen is initially produced from electricity. This kind of application is being developed for off-grid sites, for back-up power (complementary to renewable sources, for instance, and other kinds of storage such as batteries, instead of diesel gensets), and recently, for microgrids.

Stationary applications also refer to the coproduction of heat and electricity (i.e., CHP, or combined heat and power) that is useful for households, or buildings in general. In Japan, there is a massive development program of micro-CHP for households called Ene-Farm. The systems implemented are fueled by natural gas (Hashimoto, 2015). Over 154,000 units have already been installed, and 1.4 million units are planned by 2020, with an additional 5.3 million by 2030 (Ohira, 2016).

7.1.2 The Hydrogen Demand: Today and Tomorrow

7.1.2.1 Today

From the current hydrogen markets that were listed in the previous section, the global balance can be assessed. Today, the world's hydrogen consumption is

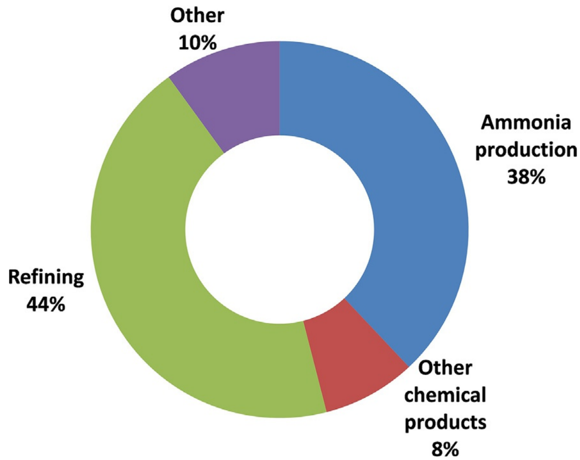

FIG. 7.6 Today world hydrogen demand. *(Data from Alphéa Hydrogène, 2014. Actualité Chimique n°347. In: AFHYPAC, 2016, Mémento de l'Hydrogène - FICHE 1.3 (in French).)*

60 million tons per year. As it is pointed out in next figure, this demand is driven by industrial needs (cf. Fig. 7.6).

7.1.2.2 Tomorrow

In the years to come, hydrogen applications are expected to grow:

- Oil refining will require additional hydrogen to meet the standards.
- Hydrogen mobility (through synthetic fuels, biofuels, full-hydrogen cars or range extenders) will develop.
- Interconnection between energy carriers (through power-to-gas) is also a promising route.

Overall, the global need for hydrogen will increase, as depicted in Fig. 7.7, which provides an outlook of a selection of hydrogen markets by 2050. Of course, such a development will be tightly linked to exogenous factors, among which the fossil prices and the carbon one. From the figure, it can be pointed out that the greatest volumes are expected from the mobility market.

With a similar perspective, the US Department of Energy also published a study called "Hydrogen at Scale," in which it is foreseen that hydrogen will represent more than 10% of the US energy flow by 2050, compared to 2% today (H2 at scale, 2016).

Hydrogen is expected to play a significant role in the energy system in the years to come, even if the dynamics of its development are still to be clarified. Two major drivers are, of course, political will (and policies implemented as a result) and the economic competitiveness of hydrogen solutions for different market segments, with the first influencing the latter. This is what is discussed in next section.

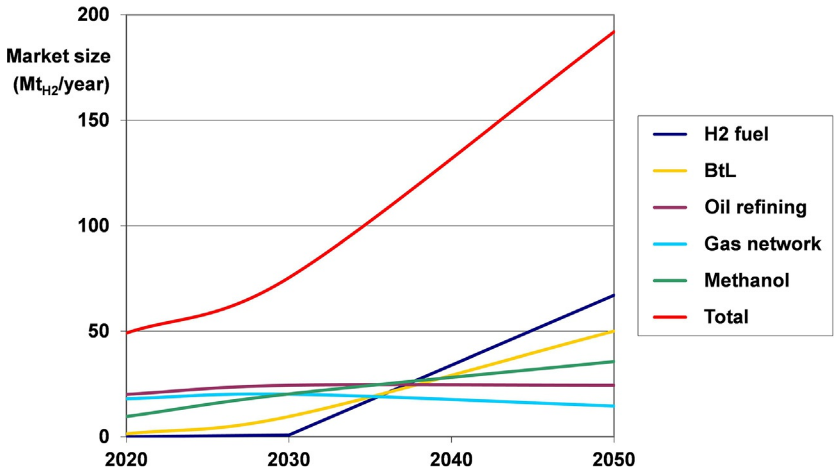

FIG. 7.7 Prospective assessment of world hydrogen demand, according to the market (Mansilla et al., 2012a).

7.2 THE HYDROGEN MARKETS: WHAT IS THE ECONOMIC EQUATION? WHAT IS THE POTENTIAL?

As previously mentioned, the economic competitiveness of hydrogen solutions will be key. As one key opens one lock, economic competitiveness depends on the competitors. As a result, the economic equation will not be unique, but will depend on the market segment. Depending upon the targeted market, the target price (and therefore, production cost) will be different, as will the drivers.

7.2.1 The Key Drivers

7.2.1.1 For Industry

In the industrial markets, hydrogen is needed as a chemical product. Therefore, hydrogen needs are related to the development of the industrial market.

Depending on the industry, hydrogen production can be either captive (which means that the hydrogen production process is installed on-site), or merchant (hydrogen is then produced by a gas company and sold to the client).

In both cases, sustainable hydrogen production will compete with the benchmark process, which is steam methane reforming.

The key drivers in this market will be the key variables of steam methane reforming: the natural gas and carbon dioxide prices, as depicted in Fig. 7.8.

If water electrolysis is considered the competitor (a sustainable one only if low-carbon power feeds the process), power price becomes a critical factor for economic competitiveness. This is shown by Fig. 7.9.

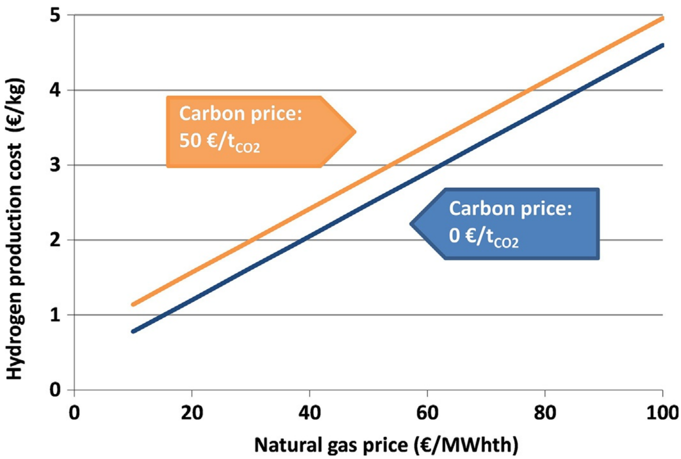

FIG. 7.8 Hydrogen production cost by steam methane reforming. *(Data from Afhypac, 2014. Production d'hydrogène à partir des combustibles fossiles. Mémento de l'Hydrogène - FICHE 3.1.1 (in French).)*

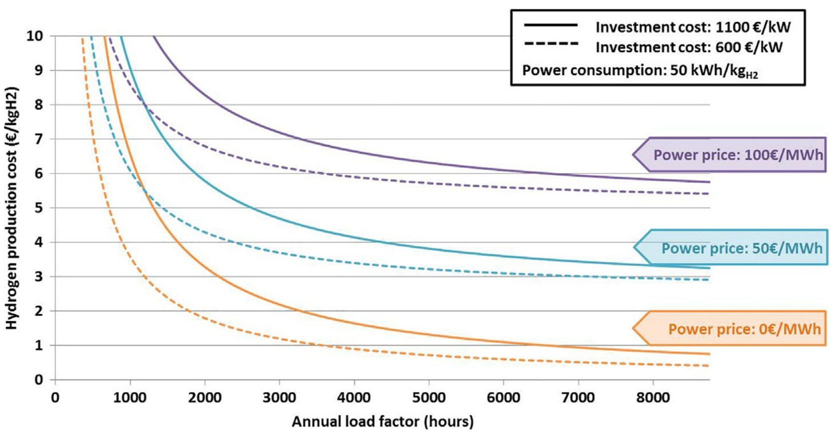

FIG. 7.9 Hydrogen production cost by water electrolysis (own calculation). *(Adapted from Caumon, P., Lopez-Botet Zulueta, M., Louyrette, J., Albou, S., Bourasseau, C., Mansilla, C., 2015. Flexible hydrogen production implementation in the French power system: expected impacts at the French and European levels. Energy 81, 556–562.)*

7.2.1.2 For "Green" Gas

In the "green" gas application, hydrogen is used as an energy carrier to be substituted (at least partially) for natural gas.

The straightforward competitor is then natural gas price on an energy basis. Indeed, the customer pays for an energy service, not a volume of gas. Comparing low heating values on a volume basis (cf. Table 7.2) shows that hydrogen's

TABLE 7.2 Hydrogen Physico-Chemical Properties and Comparison With Natural Gas

	Hydrogen	Natural Gas
Density	0.08988 kg/Nm^3	0.6512 kg/Nm^3
Low heating value	120 MJ/kg	50 MJ/kg
	10.8 MJ/Nm^3	32.6 MJ/Nm^3

performance is three times lower. So, depending on the amount of hydrogen blended with natural gas, the customer must buy more cubic meters for the same service (+7% for 10%$_{vol}$ hydrogen, +13% for 20%$_{vol}$ hydrogen).

As a result, competition is tough in this market segment because of the low price of natural gas.

To ease competition, the regulatory framework (carbon tax, or generally, the fiscal environmental framework), can propose measures to be leveraged.

7.2.1.3 For Mobility

Hydrogen as an energy carrier for mobility applications competes with classical fuels, such as diesel and gasoline. In the mid- to long term, if the hydrogen vehicle prices reach those of internal combustion engine vehicles (diesel or gasoline, as foreseen by McKinsey, 2010), the differing total costs of ownership will rise from fuel consumption.

On a purely economic basis, the customer will not want to spend more to drive 100 km with a hydrogen car, compared to a classical internal combustion engine vehicle (figures will be provided in Section 7.2.2.1 of this chapter). So, fuel consumption should not be more expensive, taking into account the improved performance expected for diesel or gasoline engine specifications over time. A 25% gain is foreseen by 2030 (Ademe, 2013), and a 30% gain by 2050 (McKinsey, 2010).

Other factors will matter, such as the charging time at the station, or the range of the car. These factors that may affect electric mobility are assets for hydrogen mobility.

So, from the customer's viewpoint, oil prices and tax policies will make the difference in deciding whether to switch to hydrogen mobility. Tax incentives could help make the decision. However, the applicable taxes represent substantial income for the government. In the United States, 15%–20% of gasoline's retail price is related to federal and state taxes. This percentage can exceed 50% in some countries such as France. However, macro-economically speaking, one could argue that this loss in income could be offset by the reduction of fossil fuel imports, thereby reducing the energy bill responsible for a large fraction of commercial deficits. Other benefits of developing hydrogen mobility could rise from the development of local employment, if the industry is developed in the country.

7.2.1.4 For Stationary Applications

When focusing on hydrogen use for stationary application, the local context is of paramount importance. First, the distinction should be made between on-grid and off-grid applications.

As a matter of fact, current power market prices rule out hydrogen from its competitors. With the massive penetration of variable renewables in the electric system (such as photovoltaic and wind power), power prices dropped. Indeed, variable renewables were first included in the electric system, but not in the market, being paid via feed-in tariffs, which contributed to the decrease of the prices on the day-ahead market. Variable renewables have low variable costs, which make them the first power plants to operate in merit order.

For off-grid applications, the picture looks quite different. As a matter of fact, energy prices are higher for remote areas. In such contexts, hydrogen systems can be a good alternative, especially if the environmental benefit is accounted for, and especially when considered complementarily with batteries (this will be discussed at the end of this chapter). Intermediate cases (such as micro-grids connected to the main power grid) should also be investigated, taking into account the externalities.

For stationary applications that involve heat generation (combined heat and power systems), in addition to the power price, the gas price is the other economic driver, but more importantly, this is the price spread between gas and power price, which generates the economic competitiveness of hydrogen solutions.

7.2.2 The Economic Target

After review of the drivers for economic competitiveness of hydrogen systems, we propose a few figures.

7.2.2.1 What Target Prices?

To achieve economic competitiveness on the markets we listed, we need to make assumptions on the economic drivers. Let us focus on the major ones: fossil fuel prices (oil and gas), and policy incentives. Here, we choose to focus on carbon prices. Of course, results strongly depend on the assumptions, so one should not concentrate on the precise numbers, but rather focus on the general trends.

Table 7.3 presents the assumptions, and Table 7.4 the resulting target prices necessary for hydrogen systems to be competitive on the selected market segments. The target price is the maximum price that hydrogen demand while still

TABLE 7.3 Assumptions: Fossil Fuel and Carbon Prices (Cany et al., 2017)

	2030	2050
Oil price ($\$_{2014}$/boe)	130	150
Gas price ($\$_{2014}$/MBtu)	13	14
CO_2 price (€$_{2014}$/tonne CO_2)	100	200

TABLE 7.4 Target Prices for Hydrogen Market Segments (€/kg$_{H2}$) (Cany et al., 2017)

	2030		2050	
€/kg$_{H2}$	*Without CO_2 Price*	*With CO_2 Price*	*Without CO_2 Price*	*With CO_2 Price*
H_2 as a fuel for mobility	2.8	4.6	3.0	6.4
H_2 to produce biodiesel	0.4	1.8	1.4	4.1
H_2 blending into gas network	1.1	1.9	1.2	2.8
H_2 for industries	1.7	2.6	1.9	3.6

remaining cost-competitive with its competitors on the selected market. Results are presented for two cases: one with the economic incentive of carbon price, and one without.

The higher the target price, the easier it is for hydrogen systems to enter the market. It appears that the best perspectives are for the mobility market. This is especially true because it is also from this market that the greatest volumes are expected. The target price assessed here focuses on car fuel consumption (in other words, by a timeframe when the hydrogen vehicle price will have converged with the diesel or gasoline ones; McKinsey, 2010). In accordance with the durability criteria defined by the European Union, hydrogen fuel should be competitive in the long term, without subsidies, with alternative fuels (European Parliament, 2009). Diesel/gasoline and hydrogen fuels were thus considered to be subject to the same amount of tax.

It must also be underlined that environmental incentives can really make a difference. With high carbon prices, hydrogen target prices can be increased anywhere from 50% to over 100%.

With regard to stationary applications, economic interest is highly dependent on the local context. To illustrate this, a comparison is made between three systems, in the context of the Gulf of Guinea (Guinot et al., 2015a). To replace the genset which is required as a back-up of a photovoltaic system (cf. Fig. 7.10), two alternatives are studied: a set of batteries (cf. Fig. 7.11) and a hybrid system made of batteries and a hydrogen solution (cf. Fig. 7.12).

As shown in Fig. 7.13, implementing a hydrogen solution (PV-Batt-H_2) makes it possible to reduce battery capacity by 45%, compared to the battery-only case (PV-Batt). The levelized cost of electricity is 15% less costly, making the electricity delivered by the hybrid system only 20% more expensive than by diesel. The hydrogen part of the system only represents 8% of the levelized cost of electricity produced by the hybrid system.

The competing options will be greatly preferred until environmental policies are implemented. Once again, the legal framework (regulatory and fiscal) is a key driver, especially for emerging markets. Demand-pull measures should be promoted (combined with accurate technology-push measures), to create the

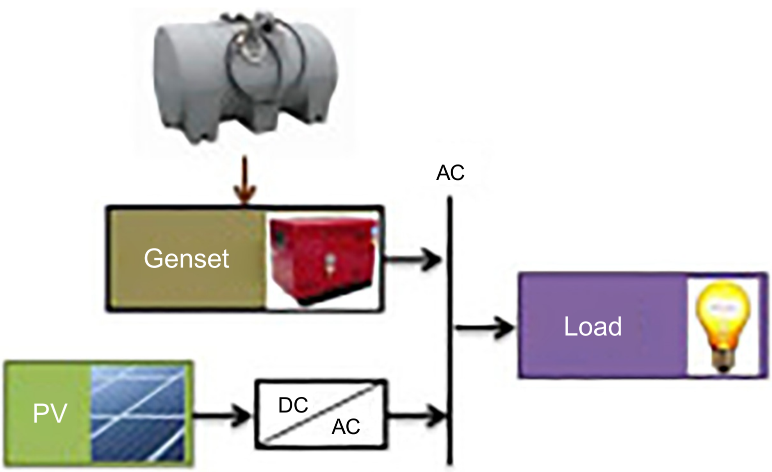

FIG. 7.10 System to be replaced (Guinot et al., 2015a).

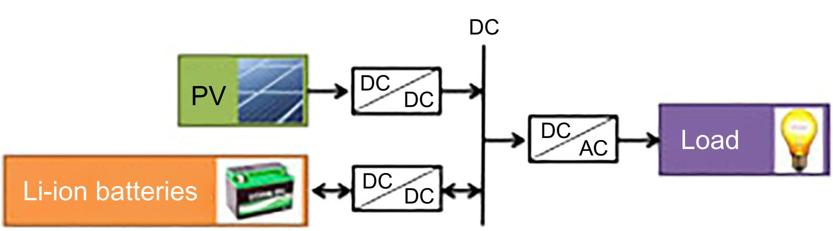

FIG. 7.11 Alternative 1: PV-Batt system (Guinot et al., 2015a).

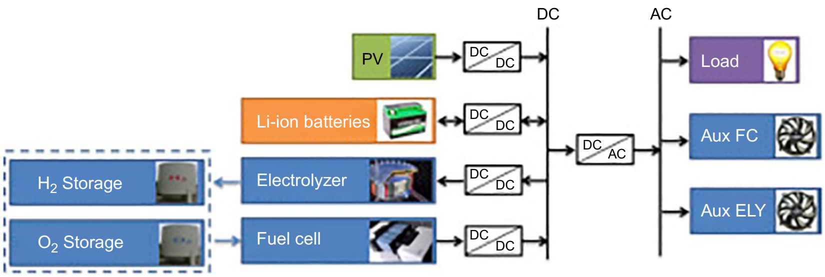

FIG. 7.12 Alternative 2: PV-Batt-H_2 system (Guinot et al., 2015a). FC, fuel cell; ELY, electrolyser.

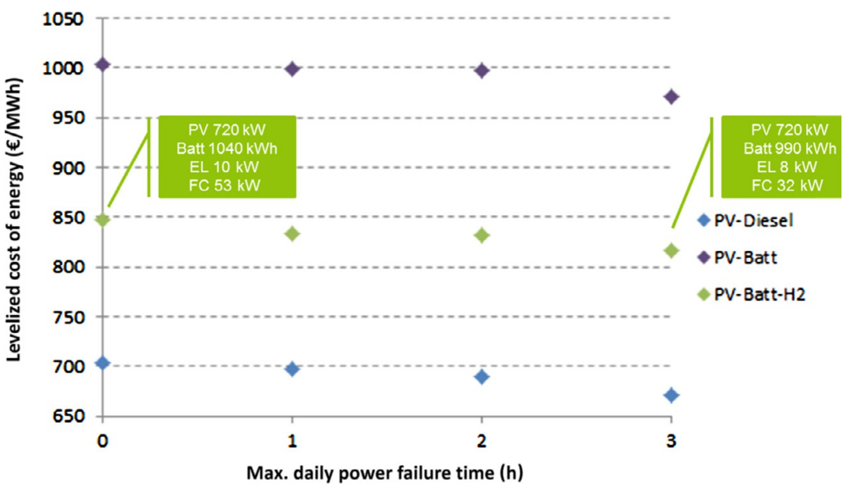

FIG. 7.13 Levelized cost of electricity according to the selected option, and the maximum power failure duration allowed each day (Guinot et al., 2015a). FC, fuel cell; EL, electrolyzer.

markets and the economic conditions for system deployment (Avril et al., 2012).

7.2.2.2 *What Target Costs?*

Target prices represent the upper boundary for target costs. The gap between the production cost and the target price will leave room for having more competitive systems, meaning systems that will be able to gain market shares. The gap is also required for profiting from hydrogen system sales.

From the comparison between current hydrogen production costs and the target prices, objectives in terms of investment costs (and load factor for non-steady state applications) and energy consumption can be established. Based on the current values, the economic equation can be tricky. Business models need to be examined on a case-by-case basis, and by considering

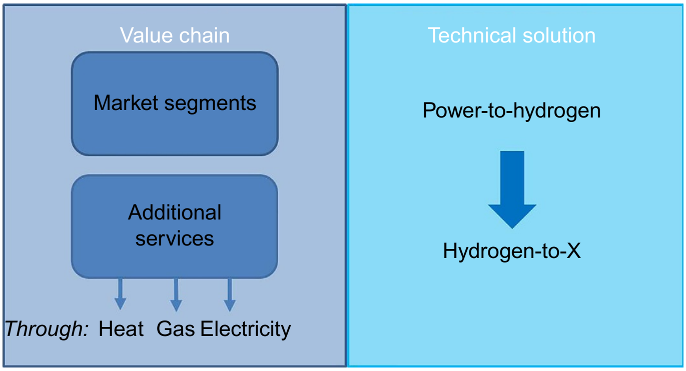

FIG. 7.14 Provision of services by hydrogen systems.

additional services. The idea is not only to valorize the hydrogen produced by the equipment (i.e., the electrolyzers), but also the equipment or the system itself, through additional services, as illustrated by Fig. 7.14 for power-to-hydrogen systems (i.e., hydrogen produced from power, via electrolysis).

In this way, the value chain can be expanded through the provision of services. The next section will address the topic of possible services provided to the electric system.

7.3 HYDROGEN SYSTEMS: NOT A SINGLE PRODUCT, BUT A PROVISION OF SERVICES

7.3.1 Services for the Electric System

The electric system is like a scale: balance must be achieved between the supply and demand, at all times, to maintain frequency (Fig. 7.15). On the supply side, we find all the "injections" into the electric grid, from power plants, imports, and storage systems, and also "negative" injection, thanks to demand-side management. On the demand-side, all the customers "withdraw" power from the

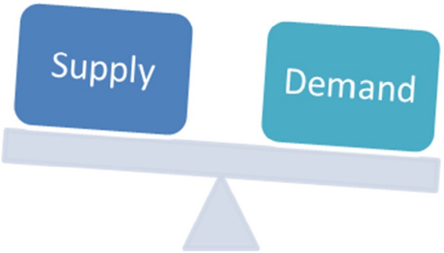

FIG. 7.15 Balance of the electric system.

electric grid, be they industrial customers or households, as well as exports and storage systems.

The supply and demand balance can be achieved:

- by adjusting supply though power modulation or curtailment;
- by adjusting demand through demand-side management or load shedding;
- by adjusting both supply and demand through storage or interconnections.

The characteristics of hydrogen production through electrolysis make it possible to quickly adjust power consumption, thus providing a new means to contribute to electric system management, either via local hydrogen production or central production.

7.3.1.1 Local Production

The first option is to connect the hydrogen production system directly to a renewable energy source, the whole system being connected to the grid (Guinot and Mansilla, 2016). As illustrated in Fig. 7.16, electrolysis consumption can be adjusted to smoothe the local production of a renewable energy source. The expected benefits will be to reduce the impact of intermittence, the forecasting needs, the needs for transmission capacity, and possibly enable the increase of renewable shares as a result.

The second option is to consider the hydrogen production system jointly to another power consumer, the whole system still being connected to the grid. Electrolysis consumption can then be adjusted to the intermittent consumption of the site it is connected to, as shown in Fig. 7.17.

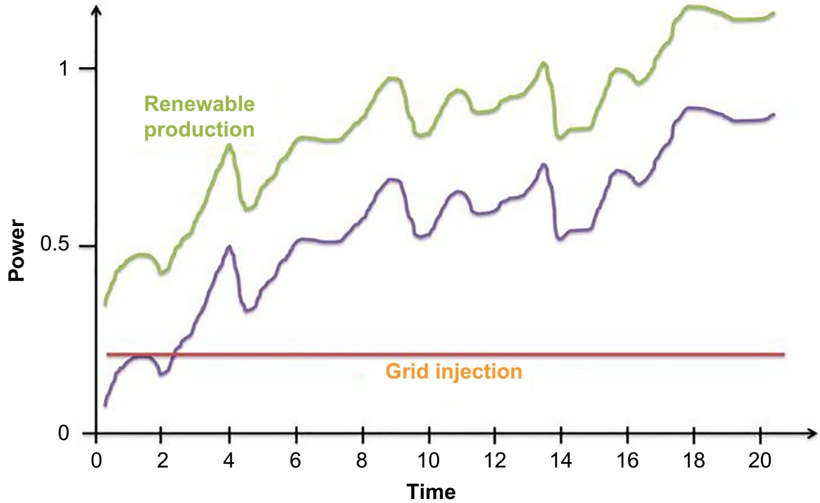

FIG. 7.16 Hydrogen local production to alleviate the renewable energy impact on the electric network (Guinot and Mansilla, 2016).

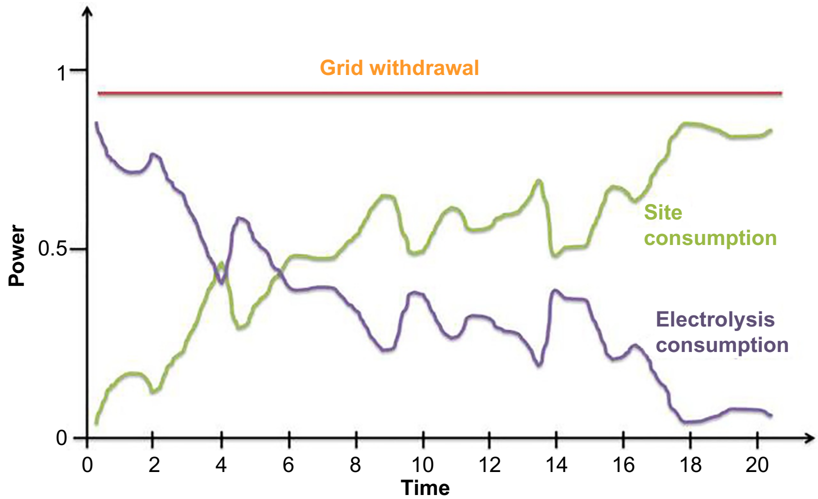

FIG. 7.17 Hydrogen local production to smooth the local demand (Guinot and Mansilla, 2016).

The benefits are similar to those in the previous case: reduction of the impact of variability (here of the demand-side), and forecasting needs.

7.3.1.2 Central Production

Hydrogen production can also be considered not as a power source or site consumption, but instead as a system (or a set of systems) simply connected to the grid (Guinot and Mansilla, 2016). From this perspective, electrolysis devices could participate in the balancing mechanisms or markets that are set up by the transmission system operators, in order to secure the balance between injections and withdrawals into the electric grid, to stabilize the grid frequency at any time. These mechanisms or markets are often named reserves, primary, secondary, and tertiary, according to their corresponding timescale (cf. Fig. 7.18).

The primary reserve (or frequency containment reserve) is used to restore the balance between supply and demand. Then, the secondary reserve (or automatic frequency restoration reserve) is harnessed to restore the frequency at its nominal level. Finally, the tertiary reserve (or manual reserve) is called upon to complete the frequency restoration if required, and reconstitute the reserves.

Several studies examined the economic relevance for hydrogen systems to participate in such mechanisms (Guinot et al., 2015b; Mansilla et al., 2012b). It was ascertained that, in the considered case, contributing to the electric system managements through these mechanisms is interesting from a purely economic viewpoint. The major uncertainty in this respect is the competition to provide

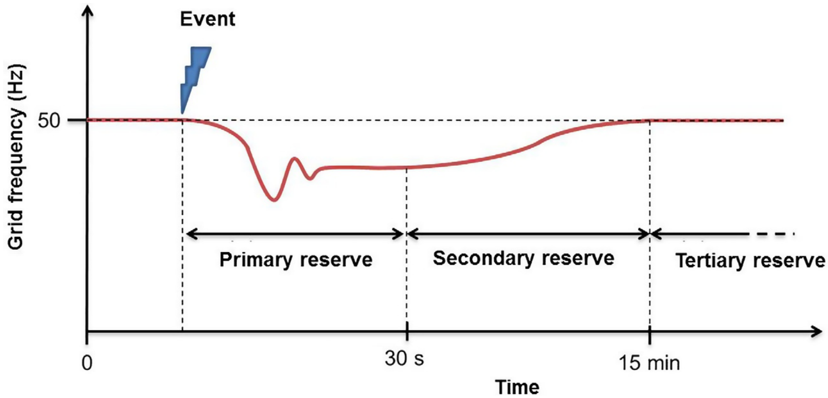

FIG. 7.18 Ancillary services to be provided to the electric grid (Guinot and Mansilla, 2016).

these services. As a matter of fact, a number of other technologies could supply similar services: storage systems, electric vehicles, or (more generally) any kind of flexible demand for power. The market for electric services will be fought for by these systems, according to the extent of their massive development and their relative price demand for providing these services.

7.3.2 Hydrogen to Foster Synergies

In conclusion, let us put things into perspective. Beyond enabling decarbonization of several sectors such as transport or industry, hydrogen could be a key ingredient to foster synergies:

– Between low-carbon energy sources, and
– Between energy networks.

In the current context of massive development of variable renewables, there exists an opportunity of developing deeply decarbonized power mixes by combining non-dispatchable renewable energy sources with low-carbon dispatchable sources, such as nuclear. In the French context, for instance, nuclear flexibility could be an asset to develop such mixes. Instead of reducing the nuclear load factor, the newly available energy could be taken advantage of by redirecting the "surplus" power (from the electric system viewpoint) toward other applications such as hydrogen production. This is what is illustrated by Fig. 7.19.

In this way, the nuclear fleet is fully used, and so are renewable energy sources. Indeed, hydrogen production as a flexible demand for power can also be useful in order to avoid curtailment when there appears to be a renewable energy surplus. This can be realized since interconnections make it possible to take advantage of the diversity of power mixes between neighboring countries (Caumon et al., 2015).

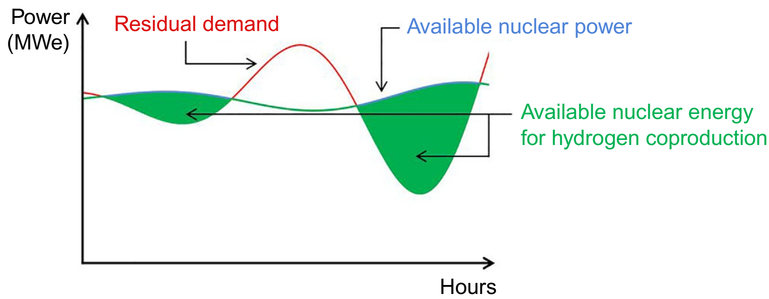

FIG. 7.19 Available nuclear energy assessment (Cany et al., 2017).

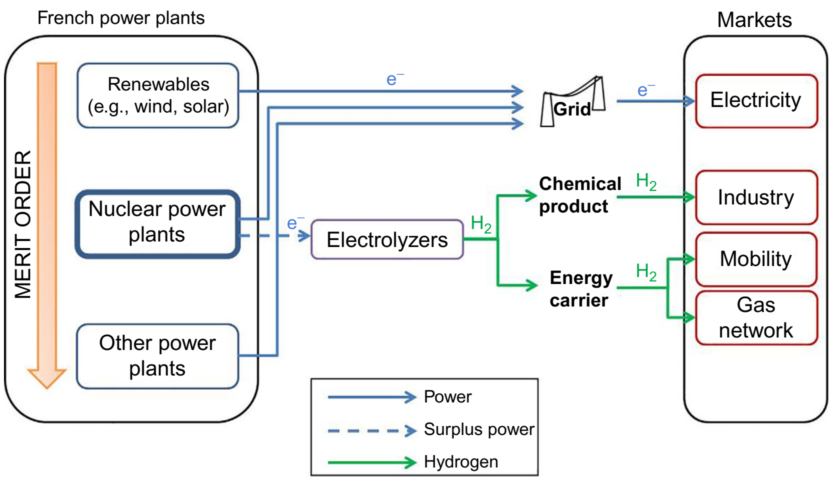

FIG. 7.20 Hydrogen fostering synergies between low-carbon sources and energy systems (Cany et al., 2017).

Another asset of the hydrogen system is its capacity to interconnect energy systems. The electric system was already mentioned; the gas network is a privileged channel for power-to-hydrogen systems (depending on the end-use for the hydrogen-natural gas mixture). Interconnections could also be done with heat networks. Thus, hydrogen can prove a privileged ingredient to foster synergies between low-carbon sources and energy systems, as depicted by Fig. 7.20.

Overall, system approaches are required to apprehend both hydrogen solutions in local contexts, and hydrogen systems' potential role in the energy system, as a provider of diverse energy services.

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