Investment in the infrastructure for hydrogen passenger cars – New hype or reality?

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Abstract

Hydrogen fuel cell vehicles have the potential to address both the environmental problem and oil dependency in transportation, but the construction of an infrastructure is a major issue that remains to be solved. The chapter reviews the challenges raised by the investment in infrastructure after the last "hype" around hydrogen. The paper analyzes the main obstacles posed by the establishment of a network of refueling stations, and examines the strategies that have been followed by pioneer countries to deal with these barriers. Particularly in California, Japan, and Germany, where experience shows how important is cooperation between the actors (automakers, fuel suppliers, technology providers), as well as the support from public authorities to the installation of the early infrastructures. This analysis unveils not only the characteristics of the "revival" of an innovation after the disappointment, but also the strategies that have been followed to gain again visibility and come back in the course for the car of the future.

Keywords: Innovation; infrastructure; hype; transport; hydrogen.

Abbreviations

AFCC: Automotive Fuel Cell Cooperation
BEV: Battery Electric Vehicle
CaFCP: California Fuel Cell Partnership
CARB: California Air Resources Board
CEP: Clean Energy Partnership
CHP: Combined Heat and Power
DOE: United States of America, Department of Energy
EU: European Union
FC: Fuel Cell
FCH JU: European Fuel Cells and Hydrogen Joint Undertaking
FCV: Fuel Cell Vehicle
H2 or H_2 : Hydrogen
HEV: Hybrid Electric Vehicles
HRS: Hydrogen Refueling Stations
HySUT: Japanese Research Association of Hydrogen Supply/Utilization Technology
LH2: Cryogenic (or Liquid) hydrogen
METI: Japanese Ministry of Economy, Trade and Industry
MoU: Memorandum of Understanding
NGO: Non-Governmental Organization
NIP: German National Innovation Programme for Hydrogen and Fuel Cell Technology
NOW: German National Association for the Advancement of Hydrogen and Fuel Cells
OEM: Original Equipment Manufacturer
PEM: Proton Exchange Membrane
PZEV: Partial Zero-Emission Vehicle
R&D: Research and Development
RD&D: Research, Development and Demonstration
SHHP: Scandinavia Hydrogen Highway Partnership
SMR: Steam Methane Reformer
US: United States
ZEV: Californian ‘Zero Emission Vehicle’ mandate

Introduction

Hydrogen can be produced from an unlimited flow of renewable energies and combined with oxygen in a fuel cell to power cars, with the only release of water vapor. Hence, hydrogen fuel cell vehicles have been promoted as a long term fuel option to reduce greenhouse gas emissions and oil dependence in transportation (NRC 2013, 2008; Hoffmann, 2012). Tens of thousands of those vehicles have been on the roads in demonstration in the last decade (Bakker et al., 2012; Bakker, 2010a), but commercialization still requires scaling up production to tens of thousands units per year. Even though some progresses have been made in fuel cells which could indicate that technology approaches readiness (Reuters, 2014; DOE, 2013), the absence of a network of hydrogen distribution impedes the start of the transition (Ogden et al., 2011). The construction of the early infrastructure is a major challenge because consumers will only begin using the first hydrogen cars in case there are enough stations to refuel them conveniently, whereas fuel suppliers will deploy a network of stations provided that there are enough vehicles to justify the high investments.

The implementation of hydrogen fuel cell vehicles implies radical changes both at the level of the car and at the level of the infrastructure. The key challenge for the transition to such a radical innovation is the fact that a number of different actors have to come together (at the same time) and coordinate their actions to provide the technology (e.g. fuel cells, hydrogen storage devices), market the car, establish a new business model for the distribution of the fuel, and set up the institutional conditions (e.g. codes and standards) (Konrad et al., 2012). This adds to the high uncertainties (e.g. technology costs, performances, choices, market uptake, regulatory conditions) that organizations already face in the early years, when no cars are commercialized and no infrastructure distributes hydrogen fuel to consumers (Bento, 2010a). Within this context, actors have to take their decisions based on prospects - or what the theories of "sociology of expectations" in science and technology call *collective expectations*, i.e. expectations that are shared by a broad range of stakeholders (van Lente, 1993; van Lente and Rip, 1998; Borup et al., 2006; Bakker et al, 2011, 2012) - rather than solid information. This increases the risk of technological hypes and disappointments.

Hydrogen and fuel cell actually went through several hypes and disappointments cycles in the past forty years. More recently, the expectations on the potential of the technology started to raise significantly at the end of the 1990s and peaked in early 2000s with a focus on mobile applications (Bakker 2010; Ruef and Markard, 2010; Bakker and Budde, 2012; Konrad et al, 2012; Romm, 2004). The hype was largely triggered by strong statements from Daimler – followed by other companies such as Honda, Toyota, and GM - about the commercialization of hydrogen cars in 2004.[1] But, soon after, automakers decided to postpone the market launch, under the argument of technical problems and high costs of fuel cells as well as the lack of hydrogen filling stations, leading to a generalized disappointment around hydrogen-powered cars. Indeed, the succession of overoptimistic and modest announcements in the same year could have served the purpose of automakers to cool off the intention of governments in California and Europe to adopt stricter emissions' regulations in the belief that the technology was "ready", as noted by Bakker (2010, p.6543).

A concept often employed to analyze hype-disappointment dynamics is the empirically observed "Gartner hype cycle", which is used by Gartner consultants to define the timing of strategic investment in emerging innovations (Fenn and Time, 2007). The basic regularity starts with a technology trigger that rapidly raises public attention what culminates in the "hype", i.e. a peak of inflated expectations. This is followed by a strong disappointment and decline of expectations that leads to the trough of disillusionment. Then, the technology gradually enters into a slope of enlightenment (i.e. a less visible period of slower, but surer, progresses), preparing it to reach the plateau of productivity that enables commercialization. The underlying rationale of the Gartner's cycle is that the damage of disillusionment should be relativized because most of emerging technologies follow their maturity curve to reach the market at the end (Fenn and Time, 2007; Ruef and Markard, 2010).

Hydrogen fuel cell vehicles came back on the energy agenda in the past two years. Several factors contributed to this "revival", such as the (announced) falling costs of fuel cell vehicles (FCVs) and the involvement of automakers in the installation of the infrastructure (Bullis, 2013). In addition, the slow penetration of battery electric vehicles in the market and their technical problems helped to increase enthusiasm around fuel cell vehicles. The latter surpassed the former in terms of perceived importance for the future of the automobile industry according to the KPMG global automotive survey 2013, and even enlarged its advantage in the 2014 survey (69% against 59%) (KPMG, 2014). This resurgence raises the question on whether the technology is finally arriving to the plateau of productivity or beginning another hype-disappointment cycle.

The chapter reviews the challenges posed by the investment in hydrogen infrastructure after the hype. This is a central question that has to be solved in order to enable the transition towards a hydrogen economy. The paper analyzes the major obstacles posed by the construction of an early infrastructure, and examines the strategies that have been recently followed by pioneer countries to address these barriers. The study unveils not only the characteristics of the "revival" of an innovation after the disappointment, but also the strategies and motivations that permitted fuel cells to gain again visibility and come back in the course for the car of the future.

[1] Bakker (2010) ironically notes that "Contrary to popular belief, hydrogen is not always ten years away" because at this point it would be "only two years into the future."

The remainder of the article is structured as follows. Section 1 presents the principal barriers to the investment in hydrogen fuel infrastructure. Section 2 provides evidence from the study of three cases (California, Japan, Germany), which have on-going initiatives to build up the network of refueling stations, by providing a brief contextualization of each of them and a review of the mechanisms used to meet the challenges. Section 4 discusses about current and future trends regarding hydrogen fuel cell vehicles, before concluding.

1. The uncertainties surrounding the investment in hydrogen infrastructure

Hydrogen and fuel cell vehicle is a complex technology system composed of many elements that are still under research, development and demonstration (RD&D) stage. The progress towards the long-awaited goal of widespread commercialization goes hand-in-hand with advancements in hydrogen production, storage, delivery and fuel cell technologies. The latter is particularly important as it directly provides the energy service to end-users. This section analysis the current obstacles that face the development of a hydrogen infrastructure, including transition issues regarding early commercialization.

1.1 The challenges of building a new infrastructure for hydrogen

The availability of a hydrogen infrastructure is a precondition for the introduction of FCVs in the market. An early network of refueling stations, with an acceptable coverage, is needed to allow the development of a demand for hydrogen-powered cars, but fuel providers will only provide a network if there are enough vehicles to use the stations (Ogden et al., 2011). Indeed, the large irreversible ('sunk') costs and the uncertainties on utilization (especially in early years) reduce the incentives of firms to invest in such infrastructures (Bento, 2010a).

Hydrogen is the most plentiful gas in the universe but it only exists in nature associated with other elements from which it has to be extracted. The annual production of hydrogen is approximately 80 tons per year, of which about 40% is manufactured and used in refineries to make gasoline and diesel with 96% of the gas (used in refining) produced by steam reforming of natural gas.[2] So, alike electricity, hydrogen is an energy carrier. It must be produced from a primary source (hydrocarbons, renewable electricity, nuclear) and transmitted to the consumption place in order to deliver an energy service (stationary, mobile, portable) using fuel cells technology for higher efficiency. An infrastructure for hydrogen production and delivery is

[22] https://www.eni.com/en_IT/innovation-technology/technological-focus/produzione-idrogeno/produzione-idrogeno.shtml (last access 30/5/2014)

therefore required. In the case of mobile applications, hydrogen refueling stations (HRS) have also to be built in a sufficient number and strategically located to reduce capital needs.[3]

The deployment of the infrastructure should be gradual and co-evolve with the development of demand over time (Ogden et al., 2011). Initially, on-site production of hydrogen is the most likely choice to supply the low levels of demand - which are insufficient to justify the investments in central production and delivery - by making use of the energy infrastructure already in place. So, small steam methane reformers (SMRs) are a strong option whenever the cost of hydrogen production is the criteria. Alternatively, on-site electrolysis of renewable electricity is a possibility in case the environmental benefits weight in the investment decision. As the number of FCVs grows, and so the demand for hydrogen, it may become economical at some point to invest in a large central plant to reap economies of scale in production that compensate for the additional costs with the delivery system (by trucks or pipelines). Geographical specificities in terms of primary energy endowments (and feedstock prices) and demand density will determine the choice of supply strategies. Thus, the technologies retained for production, delivery and distribution, i.e. the hydrogen "pathway", might look different from region to region. In the past decade, several studies estimated the capital costs of building the infrastructure for hydrogen fuel. Ogden et al. (2011) provides a review of the results for the United States and Bento (2010d, 2008) synthesizes the findings for Europe. The project HyWays (2008) estimated at €60 billion the total investment cost in the infrastructure (production, delivery and distribution) required to assist 16 million cars (8% of the fleet) in Europe by 2030. As for the United States, the build-up of the infrastructure is expected to cost around $70 billion ($2005) (Ogden and Yang, 2009). However, these projections should be updated with more recent data available, namely from first the demonstration projects, which could better inform about actual costs of technologies as well as likely opportunities for cost reductions through economies of scale and learning.

The key issue in the transition period is to reconcile the need for a reliable and convenient refueling network - especially in early years when the number of vehicles is small - with the costs of building (small and under-utilized) stations that are unprofitable in the short term. In other words, hydrogen supply and demand should co-evolve as much as possible in order to reduce investment risks and costs. The complexity of this "chicken-or-egg" problem stems from the fact that several stakeholders - in fuel distribution, hydrogen production and vehicle manufacturing - have to rely in each other's investments to start the system successfully (Bento, 2010b; Ogden et al, 2011). Strategies exist to help the establishment of the first hydrogen fuel infrastructures – early investments often receive the support of the government given their spillovers for the development of the network (Bento, 2008). A possible solution is the gradual construction of a network of refueling stations in major agglomerations and highways. This strategy is currently pursued by the German initiative "H2 Mobility" or the Japanese HySUT project. Another strategy is the creation of early dispersed mini-networks, or "lighthouse" cities, where the first

[3] The cost per station is estimated around $1 million in Europe (cf. German "H2Mobility" initiative), $1-$2 million in the United States (California) and $5-$6 million in Japan (cf. Hara, 2013).

fleets are demonstrated and cars deployed together with the refueling infrastructure (Ogden et al, 2011). A small number of stations would be enough to assist the initial demand in these "clusters", which could serve as starting points to scale up the network at national level. California is actually funding the development of five urban clusters to prepare the commercial launch of fuel cell vehicles which is expected to 2015 (CaFCP, 2012). This strategy replaced the precedent vision that wanted to start the transition around a "California Hydrogen Highway Network".

In addition to the infrastructure challenge, technology costs must be substantially reduced in the coming years in order to make hydrogen fuel cell vehicles a credible alternative to the incumbent technology.

1.2 The need of reliable and affordable technologies

Fuel cells can use hydrogen produced from multiple domestic renewable and low-carbon sources to power diverse applications: stationary, portable and transport. They started to be used in space programs by NASA in the 1960s. Nowadays, fuel cells are gradually being adopted by public and private sectors as the new generations of the technology are getting more affordable, reliable and durable (Sharaf and Oran, 2014). Even though they are still not mature and improvements are needed to make them competitive against conventional technologies, fuel cells approach commercialization in some niche markets where the benefits derived from their use are able to compensate for the disadvantages in terms of cost and durability (IPHE, 2013). This is the case of forklift trucks where the use of fuel cells provides silent operation and zero emissions which are an advantage over conventional technologies. Furthermore, they can be operated almost continuously with lower operational costs, and requires less equipment (less space) in comparison with battery electrical trolleys. Other early markets for fuel cells comprise stationary applications in residential combined heat and power, backup and remote power generation (IPHE, 2013; Carter and Wing, 2014).

Figure 1 (leftmost graph) shows the gradual take off of the number of fuel cells shipped per year since early 2000s. The annual number passed from a few hundred fuel cells in 2001 to more than 66,000 that were estimated in 2013 (Carter and Wing, 2014). The data also reveals a break in the upward trend during the years 2009 and 2010, resuming the previous tendency in 2011. Sales were pushed by the growth in stationary applications, both in terms of unit numbers (rightmost graph) and capacity (graph below). The market is mostly driven by the Japanese residential fuel cell micro-combined heat and power (micro-CHP), "Ene-Farm" program, which had subsidized the installation of more than 40,000 units that were in operation by May 2013 (IPHE, 2013).[4] However, in terms of capacity, the major part of the capacity installed were in the power generation segment which is fundamentally shared between three companies (FuelCell Energy, Bloom Energy and ClearEdge Power - ex-UTC Power Technology[5]) and concentrated in two countries, the United States and Korea (Carter and Wing, 2014). Other stationary applications, such as back-up and remote power generation (e.g. for communication towers), are experiencing a raising interest in the telecom sector, especially after the 2009 Recovery Act funding in the United States. Conversely, the prospects of growth in portable applications have not been confirmed and, as a consequence, the share of this market has been falling over the years. As for transport applications, the sales of fuel cell systems for material handling equipment have dominated the market - apart from the limited number of fuel cells installed in small fleets of cars and buses for demonstration purposes. This market has known interesting developments in the United States since the Recovery Act and funding, and more units are nowadays sold even without subsidies (IPHE, 2013).[6]

Within this context, the commercialization of FCVs is key to increase dramatically the number of systems shipped per year. The large-scale production of fuel cells would create spillovers in terms of cost reductions and technology improvement that could boost the development of the technology in the other applications, as well.

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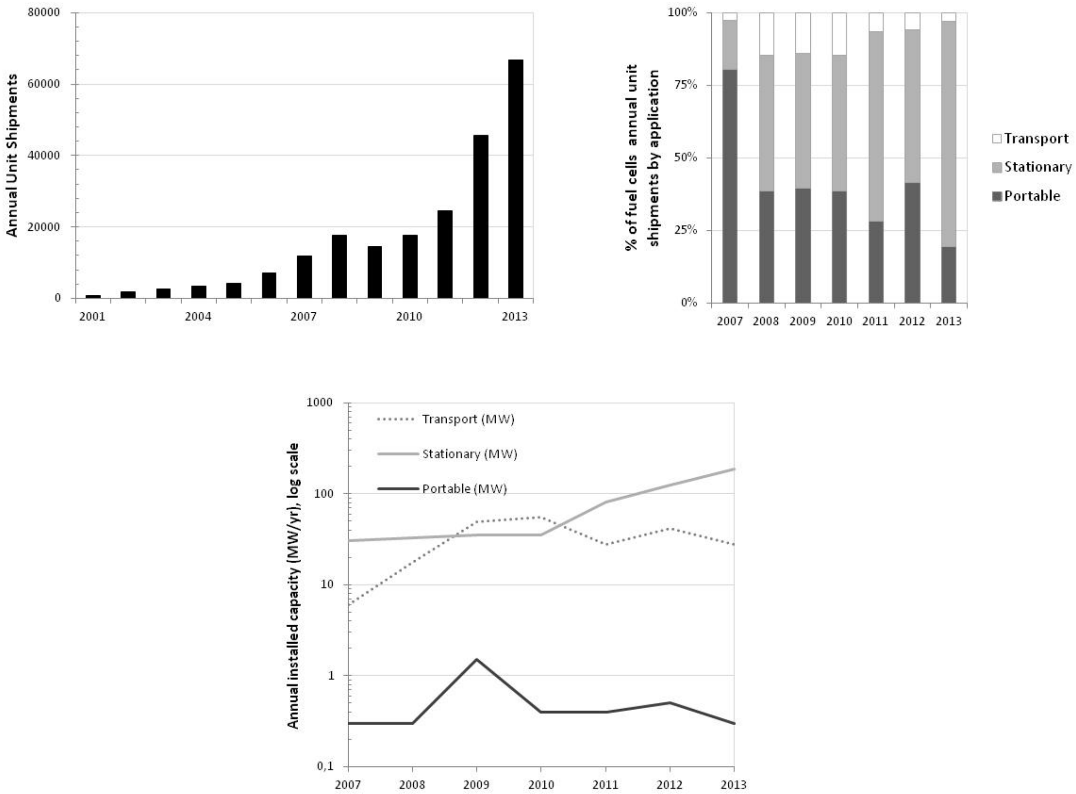
[4] This scheme has lately inspired the European project "Ene.field" which aims to install a thousand micro-CHP units across twelve Member States by 2017. In Germany, the Callux project has deployed 350 systems between 2008 and 2012 and there are plans for two hundreds more until 2015 (IPHE, 2013).

[5] In a very recent development, ClearEdge abruptly closed operations, laying off 268 employees and announcing the intention to file for bankruptcy. The company's manager pointed to the delay of a significant contract and problems in collecting money that was owed by the customers as the main reasons for that decision. This case again shows the financial fragility of fuel cells companies which face strong expenditures in the short term and extremely volatile and narrow markets. See news in: "ClearEdge confirms closure, bankruptcy intent," Hartford Business Journal, 4/29/2014, http://www.hartfordbusiness.com/apps/pbcs.dll/article?AID=/20140429/NEWS01/140429939

[6] The announcement of an important Wal-Mart order to Plug Power's fuel cell forklifts and the perspectives of profits for FuelCell Energy have recently spurred a surge in the stocks of these companies. Several financial analysts remembered the waves of hype around fuel cells in the past, and pointed to the automobile market and "whether automakers ultimately start rolling out fuel cell vehicles en masse" as a possible game changer. See: Wile R., "Wall Street Is Going Crazy For A Revolutionary Technology That Could Change The Energy Market As We Know It", March 11, 2014, http://www.businessinsider.com/fuel-cell-rally-2014-3

Figure 1. Annual shipments of fuel cells in unit numbers (left), the share of each market segment in the units shipped (right) and the growth of annual installed capacity by application (centre, below)



Source: Carter and Wing, 2014; Adamson and Crawley, 2006; Fuel Cell Today (various): http://fuelcelltoday.com/analysis/industry-review

Table 1 reports on the progress of hydrogen and fuel cell technologies towards the goals set for commercialization in mobile applications, comparing the current status with the situation five years ago (when disappointment dominated) as well as with official targets. The price of the hydrogen at the station on the one hand is still above the American and European goals, especially when hydrogen is produced from renewable energies. Fuel cells on the other hand have made undeniable progresses over the past five years in terms of performance, operating life of equipment and costs. Yet improvements are still needed in order to become competitive in transportation.

Table 1. The achievement of specific milestones regarding automotive hydrogen fuel cell technologies in the United States and Europe, in 2009 and 2014

Technology	U.S. DOE's Milestones 2015	European "Snapshot 2020 (2030)"	Situation in 2009	Current Status 2014
Hydrogen cost at the station - untaxed	$2-3/kg	<2.5 €/kg [a]	$3-9/kg [b]	$2.75-5.7/kg [c] ($7.7-12.9/kg)
Onboard hydrogen storage	$2/kWh	10 (5) €/kWh	$15-18/kWh [d,e] >$60/kWh [e]	$15-19/kWh [d,e,f]
Fuel Cell Cost (PEM-FC system)	$30/kW	<100 (<50) €/kW	$60/kW [d] >$500/kW	$51/kW [d,f] $230/kW [f]
FC Energy Efficiency	60%	-	53-58%	53 [f] - 59% [g]
Durability	5,000 hours	5,000 hrs	2,000 hrs	2,521 hrs [g] 2,200–3,600 hrs [h]

([a]) Between 2 and 5 €/kg for hydrogen produced from sustainable sources, such as solar and wind (HFP, 2007).

([b]) $ 3/kg for on-site production from the reforming of natural gas; $ 9/kg for large-scale production from renewable sources (transport costs included).

([c]) Lower-bound refers to on-site natural gas reformation and upper-bound to on-site electrolysis. Early market in brackets, assuming 1,500 kg/day.

([d]) For an annual production of 500,000 units.

([e]) 5kg compressed hydrogen at 350-700 bar (35-70 MPa).

([f]) National Research Council (2013, Appendix F: Vehicles).

([g]) U.S. DOE (2013).

([h]) Defined as the average projected time of the stack before losing 10% of its original voltage (Kurtz et al, 2013).

Source: NRC, 2013, 2008; DOE, 2013; Kurtz et al, 2013; HyWays, 2008; DOE, 2009; Roads2HyCom, 2009; HFP, 2007.

The most important news for the hydrogen transition is that the cost of fuel cells is still high but has significantly reduced in recent years. The cost of the Proton Exchange Membrane (PEM) fuel cell, the most promising one for mobile applications, passed from $ 273/kW in 2002 to $ 51/kW today (NRC, 2013; DOE, 2009), assuming large-scale production (500,000 units) – otherwise the cost would still amount to $ 230/kW. In addition, the actual durability of fuel cells doubled from 940 hours to almost 2,000 hours between 2006 and 2009 (DOE, 2009). Although in the following five years the durability had increased less rapidly to 2,521 hours (DOE, 2013), which is still half the minimum operating time that is required for commercialization (i.e., 5,000 hours). More advances are therefore needed to solve the cost and durability issues before fuel cells can be ready for commercialization. Several lines of research have been followed such as minimizing or even eliminating catalysts platinum loading of fuel cells and reduce the cost of balance of plant (Sharaf and Orhan, 2014; DOE, 2013). Toyota recently announced that has cut by half the size of its hydrogen car's fuel cell system, and reduced significantly the cost of the entire fuel cell system to $50,000 (Reuters, 2014; Fairley, 2012). The company is planning to launch its FCV model in 2015 and, by that time, it would be possible to confirm (or not) these claims.

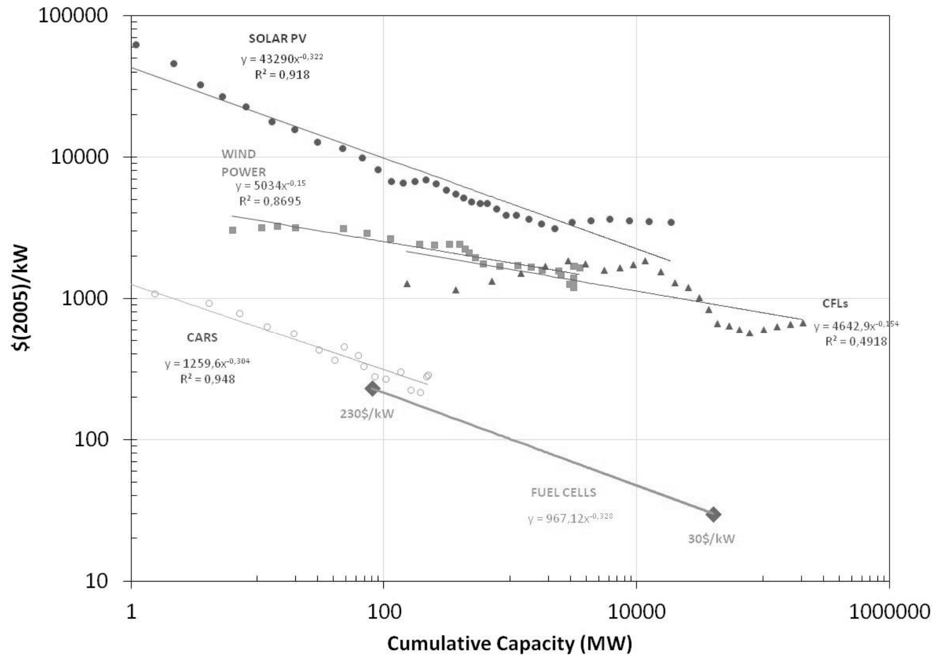
Figure 2 compares average cost reductions as technology manufacturers accumulate experience, i.e. learning rates, estimated for PEM fuel cells and reported for several energy technologies: onshore wind power in Denmark, 1981-2009; cars in the US (model T), 1907-1927; solar PV world average prices, 1975-2007; and CFLs world average prices, 1988-2006. Results shows that the targets and goals for fuel cell costs are feasible as they compare with the decrease in the cost of solar PV or cars in the past (learning rates of 20%).[7] However, two other historical examples are shown, i.e. wind power and CFLs, for which the speed of cost reduction was much slower (learning rates of 10%). Therefore, fuel cells could become competitive namely through major cuts in production costs like in the case of the automobile, or R&D advances that both cut costs and improve performances like in the case of solar PV.

The capacity to store enough hydrogen on the vehicle to drive 500 km without refueling is another key design issue because of the complexity and the bulkiness of the gas. Moreover, the method of hydrogen delivery depends on the technique used for storing it onboard, and must allow refueling in a few minutes with the same convenience as a gasoline car. Such hydrogen tanks already exist but are of a size, weight and cost deemed excessive (NRC, 2013). In fact, the cost of the tanks is still an order of magnitude higher than the American goal (up to $19/kWh versus $2/kWh of the objective for 2015), even when high-volume manufacturing is assumed. Major technological advances are taking place in several hydrogen storage technologies (e.g. compressed, liquid, solid materials) to resolve the challenge of onboard storage. Compression at very high pressure 700 bar (70 MPa) appears to be the most followed path by the industry in the medium term, in anticipation of the development of solid materials which would allow greater efficiency and storage capacity in the longer term (NRC, 2013; Bakker, 2010b).

In summary, further progresses are necessary in the PEM fuel cell cost and durability, hydrogen storage onboard, and hydrogen production (especially from renewable sources). Two factors can influence the ongoing dynamics. First, as is the case in any technological advance, we know that the penetration of hydrogen cars on the market will accelerate technical improvements and cost reductions due to economies of scale and learning. Second, fuel cells face the competition of other alternative fuel vehicles technologies (e.g. battery electric vehicles, plug-in hybrid vehicles, hybrid electric vehicles) to substitute the conventional internal combustion engine and petroleum fuels. Under these circumstances, the penetration of FCVs will also depend on the evolution of these technologies, and thus, a significant delay in commercial launch could undermine its market potential (Bento, 2010b). This raises additional uncertainties concerning the evolution and uptake of existing alternative technologies what affects the prospects of the investment in the infrastructure.

[7] The learning rate (LR) is the indicator of cost reductions whenever production doubles. This measure can be namely computed from the exponential (β) of the trend line (potential regression) as following: LR= (1-2^β)*100 . In the case of Fuel Cells, β takes the value -0.328 (see Fig.2) and thus LR= (1-2^(-.328))*100 = 20%: See more details and results for several energy technologies in McDonald and Schrattenholzer (2001).

Figure 2. Learning curves for selected energy technologies and PEM fuel cells (projected)



Source: NRC, 2013 [PEM-FC]; Grubler et al., 2012 [Wind]; Weiss et al., 2010 [CFLs]; Nemet, 2009 [Solar PV].

1.3 The importance of coordination among stakeholders to prepare commercialization

The previous sections show how commercialization of hydrogen-powered cars depends critically on the existence of an infrastructure, but the investment in high cost stations is risky as uncertainties persist on technology and demand behavior. In this context, demonstration projects have been organized in order to bridge the gap between the developments that fuel cell vehicles (FCVs) have known in the laboratory and the commercial launch expected to happen in the second half of the decade. These projects depend on a sufficient number of hydrogen refueling stations (HRS) and cars. Even though the gains for the companies with the experimentation of new FCVs and refueling equipment are likely to give them an advantage in relation to their competitors (e.g. learning, cost reductions, reputation), these first-mover benefits must be weighted against the costs of such projects – involving early FCVs that still cost more than a hundred thousand US dollars each and multi-million dollars HRS (Reuters, 2014). Hence, there is a high level of dependency between different actors' decisions, which is the main feature of this "chicken or egg" problem.

It is well-known in economics that whenever the transaction needs the establishment of a long term, very specific investment, a number of moral hazard issues arise as the group of intervening firms is reduced and a party may be dependent upon its contractual counterparty (Laffont and Tirole, 1993). For instance, the decision to deploy hydrogen vehicles becomes subject to the existence of a local infrastructure, and the viability of a certain hydrogen station will always depend on the number of cars that carmakers make available to that location. This dependency amplifies the risk of opportunistic behavior which increases the cost of transactions (Williamson, 1985). In this context, a cooperative engagement is often put in place in order to manage moral hazard and uncertainty problems (Ménard, 2004). In the case of hydrogen, hybrid organizations started with some time-limited agreements, such as research collaborations between manufacturers and public laboratories, and gradually moved towards the formalization of partnerships as the technology approached the commercialization stage and agents' strategies rely more on each others' decisions.[8]

The transition towards a hydrogen economy in transports is only possible if decisions are coordinated among actors in terms of research, development and demonstration (RD&D), market entry and infrastructure implementation (Konrad et al., 2012; Nygaard, 2008). This requires the collaboration between the main actors in activities that go beyond their core business in order to enable the formation of the first hydrogen "clusters" that would form the building blocks of the future infrastructure (Ogden et al., 2011). Many actors are currently involved in activities that aim to build infrastructure and bring hydrogen-powered cars into the market. Automakers' interest in hydrogen FCVs is explained by the raising regulatory pressures to reduce emissions and the fact that those vehicles do not oblige to a complete overhaul of the car (Bakker and Budde, 2012). Industrial gas suppliers and energy companies are also active motivated by the intention of preserving their prominent role in the mobility system, in the case of oil companies, or the prospects of new markets in areas related to their core business, in the case of industrial gas companies (Bento, 2010c). Fuel cell manufacturers are particularly animated by the market potential of fuel cells in mobile applications. And national governments, who often facilitate the administrative procedures and provide incentives and subsidies for the construction of the first stations, seek to both reduce carbon emissions and petroleum use in transportation at the same time that stimulate the economy and jobs creation.

The plans of carmakers have evolved in the past years and are a good indicator of the general expectations regarding the arrival of FCVs. Table 1 presents the number of FCVs involved in main demonstration projects as well as current plans for commercialization of the most active

[8] In the United States, the U.S. Department of Energy conducts programs of R&D and demonstration in collaboration with industry, universities and national laboratories (e.g. National Renewable Energy Laboratory or NREL) in order to overcome technical barriers to the commercialization of hydrogen FCVs. The Presidential Initiative for the promotion of hydrogen in transport has invested 1.5 billion dollars between 2004 and 2009. In 2009, the energy secretary at the time decided to cut funding for hydrogen FCV R&D under the argument that hydrogen need four miracles to happen (in production, distribution, on-board storage and to be used in more economical fuel cells), simultaneously, in order to have a future in transportation (Bullis, 2009). The budget for fiscal year 2010 was finally restored by the U.S. Congress, despite the initial proposition of the administration Obama, but this situation created more uncertainties about the emergence of hydrogen in transport and reinforced the perception of its decline after the "hype" earlier in the decade.

automakers. Tens of hundreds of vehicles are on the road today with Daimler, Honda and Toyota running more than a hundred FCVs each. Hyundai is rapidly catching up with this group lately. Indeed the Korean company recently reaffirmed its intention to produce a thousand vehicles between 2013 and 2015.[9] The largest part of the vehicles is equipped with a fuel cell and uses gaseous hydrogen (compressed at 35 or 70 MPa) – BMW had demonstrated a small fleet based on its 7-Series line that carried cryogenic hydrogen to burn in an dual-fuel internal combustion engine, but this famous exception was not followed by others (Bakker et al., 2012). The launch of hydrogen-powered cars is announced for 2015 in Japan, US and Europe. Honda, Hyundai and Toyota present the earliest plans for commercial launch. They also expect a growth in demand that make possible mass production of FCVs by the end of the decade. Toyota has released more details about its FCV that will be commercialized in 2015, which cost should reduce from the current $100,000 (under mass production conditions) to be priced between $50,000 and $100,000 (Reuters, 2014).

Table 2. Carmakers plans for demonstration and commercialization of hydrogen fuel cell vehicles

Companies	**Current plans**			**First announcement**	
	Demonstration	**Launching**	**Mass production**	**Year**	**Commercialization**
BMW (Germany)	2009 *100 7-Series ICE-LH2*				
Daimler (Germany)	*2013* *200 B-Class*	*2017*		1997	2004 *40,000 units*
Ford (United States)	2005-2010 *30 Focus*	*2020*		2002	2004 (launching) 2010 (comm.)
GM (United States)	Since 2007 *120 Chevy Equinox*	no plans announced	no plans announced	2001	2004
Honda (Japan)	2008-2012 *200 FCX Clarity*	2015 *5,000 units*	2018 *Target $65,000*	2001	2004
Hyundai (South Korea)	since 2011 48 *ix35* * 2013 *added 15 ix35*	2013-15 *1,000 units*	2015 *10,000 units* *Target $50,000*		
Nissan (Japan)		2015-16			
Toyota (Japan)	2013 100 units*	2015 *Current cost: $100,000* *Targets: Cost $50,000 Price $50,000-$100,000*	2020 *X0,000 units*	2001	2004

Source: Carter and Wing (2014), Fuel Cell Today (2013, 2009), Automotive News (2014); Reuters (2014), official carmakers websites.

* Demonstration vehicles on the road in the United States, cf. IPHE (2013).

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[9] Hyundai, « Hyundai's ix35 Fuel Cell Receives Technology Award At Annual U.K. Fleet World Honours 2013," Hyundai Motor News, 22 May, 2013, http://www.hyundaiglobalnews.com/prCenter/news/newsView.do?dID=1757

These announcements could give the impression that fuel cell cars are "just around the corner", but the recent experience is full of advances and setbacks which makes us more cautious before drawing any conclusion. Indeed, in early years 2000, when the "hype" around hydrogen was at its peak (FCT, 2013; Bakker and Budde, 2012; Romm, 2004), several auto companies were announcing the commercialization of thousands FCVs in a matter of years. In late 1990s, Daimler was already seeing the commercialization of 40,000 units in 2004. In the following years other companies made similar statements about the introduction of hydrogen cars into the market by the same date (Bakker, 2010a).

Notwithstanding, the highly competitive companies in the auto industry are nowadays forming multiple partnerships between each other to accelerate the development of fuel cell technology and reduce costs (Piper, 2014). In 2013, Honda and GM announced a partnership to collaborate on the next generation of a fuel cell systems and hydrogen storage technologies within the 2020 time frame. Renault-Nissan has also signed an agreement with Daimler and Ford to join the AFCC, what may result in the production a new fuel cell vehicle by 2017. Toyota and BMW have entered into a strategic partnership to share a number of technologies and jointly develop a new fuel cell vehicle platform by 2020. In addition to the development of FCVs, Toyota is also directly involved in the establishment of the early hydrogen network in California by investing $7.2 million in First Element Fuel, a company created to open and operate the first hydrogen stations in the state that also receives financial support from the California Energy Commission.[10]

At the same time, automakers started to collaborate with infrastructure providers and governments to prepare the introduction of hydrogen vehicles in the market. In September 2009, a group of six automotive original equipment manufacturers (OEM) – Daimler, Ford, General Motors, Honda, Hyundai-Kia and Toyota – signed a memorandum of understanding (MoU) addressed to oil and energy companies and governments. In this joint letter of intent the automakers restated their plans to commercialize FCVs by 2015 and called for the development of a network of HRS. Shortly after, a group of German industrials companies (Linde, Daimler, EnBW, OMV, Shell, Total, Vattenfall), Daimler, NGO (NOW GmbH National Organization Hydrogen and Fuel Cell Technology) and government representatives signed another MoU marking the beginning of the "H2 Mobility" initiative in Germany. This initiative aims to evaluate the setup of a hydrogen infrastructure in the country that eventually supports "the introduction of series produced hydrogen powered vehicles in Germany around 2015." In January 2011, the three largest Japanese carmakers – Honda, Nissan and Toyota – and ten Japanese oil and energy companies signed an agreement supported by the Japanese Ministry of Economy, Trade and Industry (METI) to cooperate in the introduction of FCVs into four major urban areas (Tokyo, Nagoya, Osaka, and Fukuoka), starting in 2015.[11] The carmakers agreed to reduce the

[10] "Toyota Joins California Hydrogen Push in Station Funding," Bloomberg, May 2, 2014, http://www.bloomberg.com/news/print/2014-05-01/california-awards-46-6-million-for-hydrogen-car-stations.html
[11] Toyota Motor Corporation, "13 Japanese Companies Eye Smooth Domestic Launch of FCVs," 13th January 2011, www2.toyota.co.jp/en/news/11/01/0113.html

costs of the future FCVs in order to increase sales in the second half of the decade, and the hydrogen fuel suppliers accepted to construct a network of 100 HFS in Japan by 2015. A year and a half later, in October 2012, a MoU was signed between automakers (Toyota, Nissan, Honda and Hyundai) and organizations of the Nordic countries to deploy FCVs and hydrogen refueling infrastructure there during the period 2014-2017. The signature of joint letters of intent becomes more frequent with the approximation of the date expected for the start of FCVs commercialization, around 2015. [12] [13]

Several countries are currently working with carmakers to establish the early hydrogen infrastructure in order to prepare the arrival of the first FCVs. Table 2 shows key data from some national hydrogen programs regarding both light duty vehicles and buses. The information is not exhaustive but should cover the most representative projects that are currently in progress around the world. The most active regions are still found in Japan, Europe and United States (especially, California). Other countries have also started important programs in recent years, such as Korea. The number of stations is planned to grow everywhere until 2015 to provide a minimum infrastructure for the commercialization of FCVs, which would raise the number of vehicles on the road from several hundreds to thousands of units by that time. There are already plans in Europe and Korea for a significant increase in the number of stations subject to the mass-commercialization of these vehicles around 2020. In the European Union, for instance, the European Commission announced in January 2013 a package of measures to enable the build-up of alternative fuel infrastructure across Europe.[14] The proposal, which has being discussed at the European Parliament and the European Council, includes "binding targets on Member States for a minimum level of infrastructure". The Commission intends "to form a network with common standards ensuring the mobility of Hydrogen vehicles" among the 14 Member States which currently have refueling stations. For that, the EU allocated almost €3.5 million from the TEN-T infrastructure programme to examine the feasibility of an interconnected hydrogen network.[15] In addition, the Commission has recently renewed the main European RD&D program on fuel cells and hydrogen, the Fuel Cells and Hydrogen Joint Undertaking (FCH JU2), with a budget of

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[12] These agreements reveal a positive attitude of the companies to collaborate towards the expansion of the use of hydrogen FCVs. However, it is worthwhile remembering that similar pledges were made in the past which were later postponed or even abandoned. Indeed, as early as September 2006, BMW, DaimlerChrysler, Ford, General Motors, MAN, Shell, Total and Volkswagen, issued a common position paper urging the authorities to deploy the infrastructure in Europe "more quickly in order to allow the beginning of commercialization of hydrogen vehicles around 2015 (or earlier)". A couple of years later several of these automakers dropped their expectations and became considerably more skeptical about the role that hydrogen could have in the future.

[13] "Next Steps for the Development of a Hydrogen Infrastructure for Road Transport in Europe - A common position paper of BMW Group, DaimlerChrysler AG, Ford Motor Company, General Motors Europe AG, MAN Nutzfahrzeuge AG, Shell Hydrogen B.V., Total France and Volkswagen AG", September 2006.

[14] "EU launches clean fuel strategy," European Commission, IP/13/40, 24/01/2013, http://europa.eu/rapid/press-release_IP-13-40_en.htm

[15] "Hydrogen on TEN-T road network closer to reality thanks to EU grant", European Commission, Innovation and Networks Executive Agency, 16 January 2013, http://inea.ec.europa.eu/en/news__events/newsroom/hydrogen_on_ten-t_road_network_closer_to_reality_thanks_to_eu_grant.htm

€665m - that must be complemented by an equivalent amount by industrial and research partners - from the Framework Program 'Horizon 2020'.[16]

All these initiatives contributed to rise the total number of hydrogen stations in service worldwide which was 185 (not all with public access) in May 2014, according to the website H2stations.org operated by the LBST and TÜV SÜD. Most of the stations in service are located in Europe (72), North America (67) and Asia (44, mostly in Japan and Korea). A third of the HRS installed in Europe is situated in Germany with 7 of them included in the demonstration project Clean Energy Partnership (CEP). This project tests hydrogen vehicles and filling station technologies in Hamburg, Berlin and Dusseldorf. In September 2013, Air Liquide, Daimler, Linde, OMV, Shell and Total, agreed on the action plan to expand the network of stations in Germany to 50 by 2015.[17] The so-called "H2 Mobility Initiative" is funded jointly by the Germany's federal government and the industrial sector that together will invest 40 million EUR in the establishment of a nationwide infrastructure. [18] The current state of progress of the initiative is globally in line with the plans, but early ambitions of deploying hundreds of stations to assist the diffusion of one million FCVs by 2015 had to be revised (Stiller and Wurster, 2010). Similarly, the initial plans had to be reformulated in other areas, such as in California where more than 4,000 FCVs were previously expected on the roads between 2012 and 2014 (CaFCP, 2009) and in Europe where the partnership between the industry and the European commission lowered its initial previsions of almost 2 million cars in 2020 (HFP, 2007) to a more realistic 500 thousand (FCH JU, 2014). These revisions were the result of the delays taken in the progress of the FCVs as well as the overoptimistic assumptions concerning the development of the technology in late 2000s.

Therefore, the first commercial fuel cells vehicles are likely to be launched in regions where plans for the development of a network of HRS are the most advanced. These regions historically comprise California, Germany and Japan. The next point provides an overview of the hydrogen programs in these areas, their current targets and instruments deployed to promote the penetration of hydrogen in mobile applications.

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[16] "Green light for FCH 2 JU," Horizon 2020 Projects, 7 May 2014, http://horizon2020projects.com/industrial-leadership/green-light-for-fuel-cells-and-hydrogen-joint-undertaking/

[17] "H2 Mobility initiative: Leading industrial companies agree on an action plan for the construction of a hydrogen refuelling network in Germany," Stuttgart, 30 September 2013, http://www.now-gmbh.de/en/presse-aktuelles/2013/h2-mobility-initiative.html

[18] "50 hydrogen filling stations for Germany," Press/News 20.06.2012, http://www.now-gmbh.de/en/presse-aktuelles/2012/50-hydrogen-filling-stations-for-germany.html

Table 3. The number of fuel cell cars and hydrogen stations involved and projected in several demonstration projects around the world

Project	Region	Period	Deployment plans	Target stations	Actors involved	Sources
California Fuel Cell Partnership (CaFCP)	California (USA)	Current 2015 2023	200 FCVs not specified "	9 (+ 47 planned) 68 stations 100 "	Air Liquide, Air Products, Ballard, Chrysler, Daimler, GM, Hyundai, Honda, Hydrogenics, Linde, Nissan, Toyota VW, …	Office of Governor(2013) FCT (2013) CaFCP (2009)
Fuel Cells and Hydrogen Joint Undertaking (FCH JU 2)	EU	2008-2012 2013 2015 2020	>150 FCV, >45 buses 31 buses 5K FCV, 500 buses 500K FCV, 1K buses	> 20 stations not specified <300 stations >2000 "	Air Liquide, Air Products, Ballard, BMW, Ceramic Fuel Cells, Daimler, Honda, Hyundai, Linde, Nissan, Opel, Shell, SOFCpower, Toyota, Vattenfall, Volkswagen, Volvo,…	FCH JU (2014) Carter and Wing (2014) FCH JU (2011)
HySUT	Japan	Current 2015	n.a. Commercialization	23 (+19planned) 100 stations	(19 companies:) JX Nippon Oil & Energy Corp., Iwatani, Toyota, Nissan, Honda, Mitsubishi Kawasaki, ,..	H2stations.org http://hysut.or.jp/ Hara (2013) Carter and Wing (2014)
Scandinavia (MoU'12)	Norway Sweden Denmark Iceland	Current 2014-17	19 FCVs deployment (500 FCVs *)	9(+2 planned) not specified (30+15 stations*)	Toyota, Nissan, Honda, Hyundai, infrastructure companies, HyNor, H2 Link, H2 Sweden, SHHP, Icelandic New Energy,...	scandinavianhydrogen.org news release from automakers *Vision of the SHHP by '15 (scandinavianhydrogen.org)
Korean program and roadmaps	Korea Republic	Current 2015 2030	100 FCVs (2013) 1,000 FCVs not specified	10 stations 43 " 500 "	Local infrastructure companies, Hyundai, government	H2stations.org Kim (2013)
H_2 Mobility Initiative	Germany	Current 2015 2018 2023 2025	n.a. 5,000 FCVs not specified " "	25 stations 50 " 100 " 400 " 1000 "	Air Liquide, Daimler, Linde, OMV, Shell, Total, BMW, Honda, Hyundai, Intelligent Energy, Nissan, Toyota, VW	H2stations.org Press releases available at now-gmbh.de FCT (2013)
Clean Energy Partnership (CEP)	Berlin, Hamburg (Germany)	Current (2011-2016)	>100 FCVs, 30 buses not specified	7 stations (+5 planned)	BMW, Daimler, Ford, GM/Opel, Honda, Hyundai, Toyota, VW, Air Liquide, Berlin BVG, EnBW, Hamburg Hochbahn, Linde, Shell, Siemens,SSB, Total, Vattenfall	H2stations.org cleanenergypartnership.de
UK H_2Mobility	United Kingdom	Current 2015 2020 2025 2030	n.a. not specified 10K FCV annual sales not specified 1.6 millions FCVs (300K annual sales)	13 (+12planned) 65 stations not specified 330 " 1,150 "	UK Government Departments, Greater London Assembly, FCH JU, Air Liquide, BOC, Daimler, Hyundai, Intelligent Energy, ITM Power, Johnson Matthey, Nissan, Toyota,..	H2stations.org ukh2mobility.co.uk Carter and Wing (2014)

n.a. – not available.

2. The implementation of the early infrastructure: case studies

2.1 Californian initiatives to promote fuel cell vehicles commercialization

California has a long story of promoting the commercialization of new zero-emission technology in transportation. In 1990, the state began setting more advanced vehicle emission standards, such as the Zero Emission Vehicle (ZEV) mandate, to solve severe air quality problems (Collantes and Sperling, 2008). The ZEV program obliges automakers to produce a certain percentage of zero emission vehicles for sale in California, such as hydrogen fuel cell and battery electric vehicles. The California Air Resources Board (CARB) is in charge of the ZEV program, and typically updates it every three years. However, this regulation has faced a strong resistance from automakers over time that delayed and greatly restricted its implementation in practice.[19]

The early version of the ZEV regulation required 2% of vehicles for sale in California in 1998 and 10% of vehicles in 2003 to be zero-emission vehicles. The reaction from carmakers as well as concerns about the readiness of technology lead the CARB in 1996 to remove the intermediate 1998 mandate, but left the 10% ZEV requirement for 2003. At the same time, the CARB allowed credits for partial zero-emission vehicle (PZEV) that were not 100% ZEVs, such as hybrid electric vehicles (HEV). The following years saw the introduction of battery electric vehicles (BEV), including the GM EV1 and Toyota EV RAV4, and the HEVs Honda Insight and Toyota Prius. In 2001, the CARB again changed the ZEV regulation in order to allow automakers to meet the 10% requirement through more environmentally efficient (conventional) gasoline cars (6%), and the remaining 4% distributed equally between pure ZEVs and advanced technology PZEVs. Even so, the automakers processed the program to stop its application, and in 2003, the CARB was forced to transform it into a complex system that allows the banking of credits. It also created an Alternative Path requiring significantly fewer FCVs. In 2012 the CARB completely reformulated the ZEV program, which is now part of the Advanced Clean Cars standards regulation focusing on California's long-term global warming goals.[20] This new emission-control program also includes the control of smog, soot and global warming gases. In the end, the ZEV mandate led to the growth of less radical innovations (e.g. HEV) but was unsuccessful to promote the commercialization of BEV and FCV. Still, it stimulated the development of several FCVs programs and the expansion of the number of hydrogen stations across California.

[19] For a good overview of the origins of the ZEV mandate, see: Collantes and Sperling (2008). The website of the CARB provides detailed information about the changes of the ZEV program over time: http://www.arb.ca.gov/msprog/zevprog/zevregs/zevregs.htm .

[20] In 2006, the California Global Warming Solutions Act (AB 32) established the goal of reducing greenhouse gases to 1990 levels by 2020. An Executive Order issued by Governor Schwarzenegger and reinforced by Governor Brown called for reducing GHGs a total of 80% by 2050. According to the CaFCP (2009), the CARB estimates that meeting the 2050 goal will require nearly 100% of passenger vehicles sold by 2040 to be ZEVs.

The 'California Fuel Cell Partnership' (CaFCP) was formed in the sequence of the ZEV program. The partnership was established in January 1999 between two public agencies (California Air Resources Board and California Energy Commission) along with six private companies (Ballard, DaimlerChrysler, Ford, BP, Shell Hydrogen, Chevron) to promote the commercialization of fuel cell vehicles in transportation. Since then, this initiative has supported the installation of refueling stations and the demonstration of hundreds of hydrogen-powered cars.

In 2012, the California Governor Edmund G. Brown's signed an executive order[21] that urged state government to assist the commercialization of zero-emission vehicles (ZEVs, including FCVs and BEVs) in California. This order and the "2013 Zero Emission Vehicles (ZEV) Action Plan" contain much of the current hydrogen policies of the state. The action plan includes a roadmap towards the goal of reaching 1.5 million ZEV on the Californian roads by 2050. It also mandates that by 2020 "the State's zero-emission vehicle infrastructure will be able to support up to one million vehicles", and incorporates the suggestion of the CaFCP's roadmap to build a network of 68 hydrogen stations in order to allow FCVs launch in 2015. In September 2013, Governor Brown received legislative authorization to spend $20 million a year for 10 years in the construction of 100 stations.

In May 2014, the California Energy Commission awarded $46.6 million for the installation of 28 new stations to add to 9 existing and the 17 stations currently planned.[22] If the construction of all the projects is confirmed, these 54 stations would represent a progress towards the goals of 68 stations by 2015 and the 100-station network to support the commercialization of FCVs in California in the time frame of a decade. In particular, more than $27 million went to the startup FirstElement Fuel - the startup that is also backed with $7.2 million from Toyota - for the construction of 19 new stations. In order to be eligible for this grant, a third of the hydrogen sold by the stations must come from renewable energies. Funding is derived from taxes in vehicle and boat registrations, as well as smog check and license plate fees.

The history of the Californian initiatives to promote fuel cell vehicle is at the same time pioneer in the world and illustrative of the succession of ups and downs that hydrogen energy went through in the past two decades. Besides the problems with the implementation of the ZEV program, the official expectations had to evolve to reflect the real progresses of the technology. A decade ago, in April 2004, Governor Schwarzenegger announced his vision for the "California Hydrogen Highway Network" initiative which comprised the installation of 50 to 100 stations along California's major highways by 2010. These stations would support "automakers [which] have indicated that "tens of thousands" of fuel cells vehicles will be commercially available, provided there is fueling infrastructure in place." Meanwhile, the CaFCP have released several

[21] Executive Order B-16-2012, Governor Edmund G. Brown, State of California, 2012.

[22] "California Investing Nearly $50 Million in Hydrogen Refueling Stations," The California Energy Commission, 1/5/2014, http://www.energy.ca.gov/releases/2014_releases/2014-05-01_hydrogen_refueling_stations_funding_awards_nr.html

surveys of automakers' estimates for fuel cell vehicle roll out in California. In the 2009 study, carmakers estimated that more than 700 hydrogen FCVs would be on the road by 2011, increasing to over 4,000 by 2014 and reaching about 50,000 vehicles by 2017 (CaFCP, 2009). In the 2012 Action Plan, the projections were more cautious suggesting a much slower ramp up of sales with around 1,300 vehicles in 2014 and 5,000 to 10,000 in 2015 (CaFCP, 2012).[23] These more modest plans may be sign of realism and a more pragmatic approach. Indeed, California has recently joined the H2 USA project, a public–private partnership led by the U.S. Department of Energy focused on studying the establishment of a nationwide infrastructure following the example of current projects in Germany and UK.

2.2 Japanese association for infrastructure development

The coordination of the infrastructure deployment in Japan is ensured by an industry grouping, HySUT[24], the Research Association of Hydrogen Supply/Utilization Technology, encompassing nineteen private companies and organizations. The association started to operate in 2009 with 13 private companies (mostly oil and gas utilities, as well as industrial gas suppliers) to prepare the construction of the hydrogen supply infrastructure for FCVs launch in 2015 - the target year was set by the Fuel Cell Commercialization Conference of Japan (FCCJ, 2008). In January 2011 thirteen companies - including automakers and energy firms - signed a memorandum of understanding (MoU) confirming 2015 as the year of introduction of FCVs and agreeing on the installation of 100 hydrogen refueling stations across four major metropolitan areas prior to commercialization. This goal became a national target with the “Japan Revitalization Strategy” in June 2013, at the same time that Toyota and Honda reasserted their commitment to launch FCVs in 2015 (Hara, 2013).

A $46 million government subsidy had been made available in 2013 and $82.5 million were requested in 2014 to support the construction of hydrogen refueling stations in Japan (Hara,

[23] In the early 2000s, the perspectives of market development for hydrogen-powered cars in California were often much more ambitious, translating the general context of “hype” that hydrogen and fuel cells were passing through. In a very cited article entitled “An Integrated Hydrogen Vision for California”, Lipman et al (2004, pag.36) suggested a “A California Hydrogen Strategy” that anticipated the begin of roll out “to be at least through 2008, with up to 1,000 hydrogen-powered vehicles in California and perhaps 50-60 refueling locations”. The commercialization was expected to start around “2008 through at least 2011 with from 1,000-20,000 hydrogen powered vehicles in the state and 100 or more refueling stations of various sizes”. Finally, the growth accelerated "Post-2012 with over 20,000 hydrogen-powered vehicles in California and hydrogen fuel becoming widely available.”

In Europe, there were echoes of these high expectations. For instance, the high level group formed by the European Commission to study the development of the hydrogen economy published in 2003 (HLG, 2003) its vision about the penetration of FCVs in transport: 5% of new cars in 2020 (2% of the fleet); 25% by 2030 (15% of the fleet); and 35% by 2040 (32% of the fleet).

All these overoptimistic projections added to the usual humor around hydrogen FCVs that it would always be “ten years away”, as noted by Dan Carter in the “The last Analyst View from Fuel Cell Today” (January, 2014, www.fuelcelltoday).

[24] http://hysut.or.jp

2013).[25] The subsidy covers up to 50% of the station's capital costs with a maximum of $2.5 million per project – HySUT estimates the current costs per station around $5 million (Hara, 2013). This enabled the construction of 19 new stations in 2013 that are going to enlarge the existing network of 23 stations in operation. If the budget requested in 2014 for HRS construction is confirmed, the subsidy could support 34 more stations, bringing the number of stations in Japan close to 76 stations. However, the subsidy is provided for early dissemination of HRS and it may reduce over time, giving the incentive to private companies to accelerate investments prior to 2015 what would put the 100 stations goal within reach. Indeed, JX Nippon Oil & Energy Corp. and Iwatani recently announced plans to construct 60 of the 77 stations needed to meet that target (Wing, 2013). Some of the new HRS may be built at existing gasoline stations, thus reducing capital needs. Government agencies are collaborating with automakers and infrastructure companies in Japan to streamline regulations on the stations and FCVs, reduce vehicle costs and create early demand for the cars (Hara, 2013).

In Japan there is a tradition of collaboration in the field of fuel cells – even if the companies then compete fiercely between each other to be on the edge of the technology.[26] In fact, the developments mentioned above appear in the sequence of the 'Japan Hydrogen and Fuel Cell Demonstration Project' (JHFC). This landmark project was launched in 2002 by the Ministry of Economy, Trade and Industry (METI) in partnership with major Japanese and foreign carmakers (Toyota, Honda, Nissan, Daimler and GM), and energy companies (e.g. Tokyo Gas and Shell). The program supported the opening of 12 hydrogen stations which had assisted the demonstration of nearly 60 hydrogen cars up to 2010 (Aki, 2009).

2.3 Clean Energy Partnership (CEP) and H2 Mobility initiative in Germany

As the technology progresses in the deployment phase, there is a growing need for more formal and specific commitments. It concerns, particularly, concealing different elements such as: demand growth and public incentives; number and location of refueling stations from fuel providers; number of vehicles from carmakers; and costs and performance from fuel cell manufacturers.

The German collaboration between public and private actors, "H2 Mobility," seeks to promote the commercialization of FCVs in 2015 through the deployment of the hydrogen infrastructure in Germany. Established in September 2009 between the National Association for the Advancement of Hydrogen and Fuel Cells ('NOW') and seven private companies (Daimler, Linde, EnBW, OMV, Shell, Total, Vattenfall), the "H2 Mobility" initiative aims to develop a nationwide network of stations starting as early as 2011. This program comes in the sequence of the

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[25] Considering an exchange rate: ¥100 = $1.00 .

[26] There are even reports of strong internal "embarrassment" and "shockwaves" produced in the rival company whenever Honda and Toyota present new FCVs models. See Reuters, 2014.

agreement signed in 2009 between the car manufacturers Daimler, GM, Honda, Toyota, Ford and Hyundai, for the commercial launch of FCVs by 2015. The initial plans included the construction of hundreds of hydrogen stations in Germany before 2015 (Daimler, 2009), but that number was significantly reduced to 50 – certainly influenced by a less favorable context around FCVs. In June 2012, the federal government signed a joint letter of intent agreeing to support the expansion of the German's network of HRS from 15 to 50, in both metropolitan areas and major interconnections between these regions. Similarly to the Japanese case, the government subsidizes half of the stations' capital cost - estimated at 40 million Euros - through the National Innovation Programme for Hydrogen and Fuel Cell Technology (NIP). The construction of the stations is coordinated by the 'NOW' and they will assist the 5,000 FCVs expected to be on the German roads by 2015.[27] In addition, the industry partners of the "H2 Mobility" initiative recently called the government to enlarge the network to 100 stations between 2015 and 2017, and to 400 by 2023.[28] As of May 2014, there are 25 hydrogen stations in operation and more three dozens are planned in Germany what is in line with the objectives for 2015.[29] [30] A large part of the stations are operated in the context of the Clean Energy Partnership (CEP).

The CEP is one of the largest demonstration projects in the world and a lighthouse initiative of the German's programme (NIP), under the coordination of the 'NOW'.[31] In fact, European regions have been organizing significant lighthouse projects, such as Berlin and Hamburg in the framework of the CEP project, London with the local Hydrogen Partnership, or Scandinavian cities under the Scandinavian Hydrogen Highway Partnership. The interest in hydrogen projects is often driven by the need to reduce pollution emissions, as well as the willingness to support local industry and employment (HyLights, 2009). The CEP was formed in 2002 as a joint political initiative lead by the German Ministry of Transport and industry. Partners are currently composed of technology, oil and energy companies, major carmakers, public transport systems, government agencies and German states. All these actors work together to test the deployment of hydrogen as a fuel in everyday use, contributing to raise its social acceptance. This comprises the use of hydrogen-powered vehicles as well as the operation of the hydrogen chain (production, storage and distribution). The project runs seven stations in Berlin and Hamburg that assist a fleet of more than hundred cars and thirty buses. By testing and optimizing vehicles and infrastructure,

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[27] "50 hydrogen filling stations for Germany," Press/News 20.06.2012, http://www.now-gmbh.de/en/presse-aktuelles/2012/50-hydrogen-filling-stations-for-germany.html

[28] "H2 Mobility initiative: Leading industrial companies agree on an action plan for the construction of a hydrogen refuelling network in Germany," Stuttgart, 30 September 2013, http://www.now-gmbh.de/en/presse-aktuelles/2013/h2-mobility-initiative.html

[29] cf. H2stations.org (accessed in 26/5/2014).

[30] Moreover, the industry initiatives, the National Organization Hydrogen Fuel Cell Technology (NOW), the Clean Energy Partnership (CEP), H2Mobility and Performing Energy (PE), reaffirmed their commitment to market hydrogen and FCVs in Germany by signing a declaration to invest €2 billion (US$2.7 billion) over the next 10 years. This commitment is subject to the continuation of the NIP funding of hydrogen and fuel cells R&D by the Federal government. See: "Industry initiatives reinforce market introduction of hydrogen and fuel cell technologies – locations for H2 refuelling stations are confirmed," NOW Press release, 08/04/2014, Retrieved at http://www.now-gmbh.de/en/presse-aktuelles/2014/visit-state-secretary-reiche.html (last access 24/5/2014).

[31] http://www.cleanenergypartnership.de

the CEP intends to become both a predecessor and a facilitator of the national infrastructure for hydrogen.

2.4 Synthesis of the cases

The three cases analyzed above have several characteristics in common when it comes to promote the use of hydrogen and fuel cells in transport. On the one hand private-companies are increasingly working with public authorities in order to build up the infrastructure and prepare the arrival of FCVs in the target date. On the other hand the promotion of economic competitiveness and jobs creation are important drivers for public action in all the three cases. Other factors more specific to each case were also important to spark the interest on these technologies, such as: the reduction of local pollution in California; the concerns about fuel import dependency in Japan; and the maintenance of a strong position in the auto industry in Germany. Yet there are differences in the approaches followed by each region in the preparation of the hydrogen energy transition.

California has the longest experience supporting these technologies starting already in the 1990s. The state took a more radical legislative approach by setting command and control type of policies like the ZEV mandate requiring the auto manufacturers to sell a certain percentage of specific technologies (BEVs or FCVs). As a consequence, the state had to face a strong resistance of the carmakers in the courts that blocked almost always the application of the law. Even though the legislation was unable to spur a massive adoption of ZEVs, it set a favorable environment for the penetration of more incremental innovations in the auto industry, such as hybrid vehicles and plug-in hybrid vehicles.

In Japan there is a strong commitment to develop FCVs and the hydrogen infrastructure at the national level. The interest in these technologies started early and was resilient against the waves of “hypes” and disappointments that surrounded hydrogen energy over the past decade. The government has played a central role in the R&D and demonstration stages, and his collaboration with the industry is still essential in this phase of infrastructure deployment.

In Germany the strategy seemed more concerned with not lagging too far behind the more advanced areas, especially California and Japan, than searching for a leadership in the field. This explains the fact that, for longtime, the main hydrogen project was the CEP which is more regional (around Berlin and Hamburg) and directed towards demonstration and testing of vehicles and infrastructure. The recent decision to scale up the partnership to a national level was made possible namely thanks to the support of the federal government and the mobilization of the organizations that were involved in the existing projects.

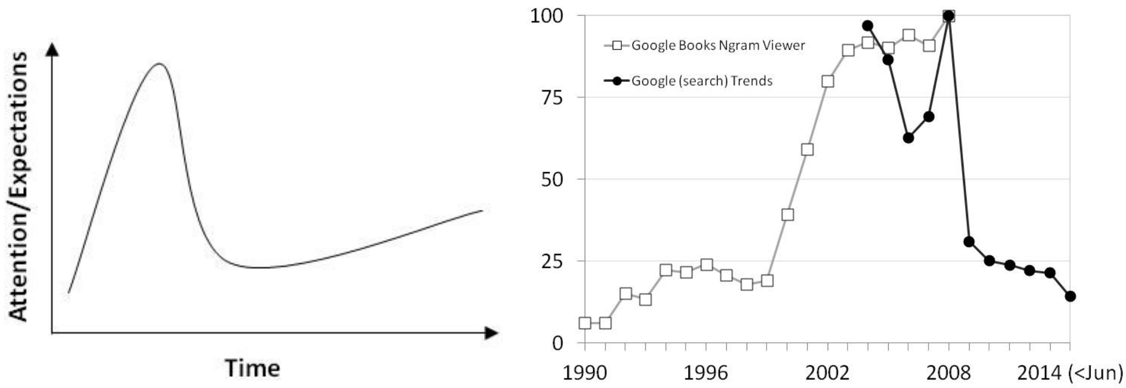
3. Future trends

The current dynamics of development of hydrogen refueling stations raise the question about the possible tendencies they may entail for the next decades. It is reasonable to assume that future trends will be influenced, more or less closely, by the tendencies that come from the past, especially in terms of the attention/visibility of the hydrogen cars and the readiness of fuel cell technologies.

Hydrogen and fuel cell vehicles give increasing signs of returning to the energy agenda lately. Commercial launch is again announced to start within one or two years like one decade ago when expectations were at their highest. Thus, very soon it will be possible to know whether these are serious statements or just a new episode of "overexpectations". A clear hype-disappointment cycle such as described by the Gartner curve was registered a few years ago. Figure 3 shows the number of times that the term "fuel cell vehicles" had appeared in the books between 1990 and 2008 (last year available in Google Books Ngram Viewer).[32] This is compared with the number of times the same phrase was searched for in Google during the past ten years.[33] In both cases, the raw data is indexed to the maximum value in the sample (which is shown with the number 100) to ensure comparability of the results. The figure shows on the one hand a marked raise in the number of times that the term "fuel cell vehicles" appeared in published books after 1999. The trend of the number of searches in Google reveals on the other hand multiple peaks in 2004 and 2008, followed by a major drop afterwards. Even though the count of the number of search results and appearances in the books have several problems, it confirms the findings of previous studies that documented a hype around hydrogen in the last decade (Bakker and Budde, 2012; Konrad et al., 2012; Bakker, 2010a). The question now is to understand to what extent the technology is really improving and reaching the plateau of productivity or entering into a new phase of "hype" that would turn in large disappointment (or even abandon).

[32] https://books.google.com/ngrams (analysis performed in 5/6/2014 for the number of times the phrase "fuel cell vehicles" (case-insensitive) occurred in the English corpus of books).
[33] http://www.google.com/trends (analysis performed in 5/6/2014 for the number of times the phrase "fuel cell vehicles" was searched in Google in the past decade).

Figure 3. The Gartner hype cycle (left-hand) and the number of times the term "fuel cell vehicles" appeared in the books and was searched for in Google (right-hand), between 1990 and 2014

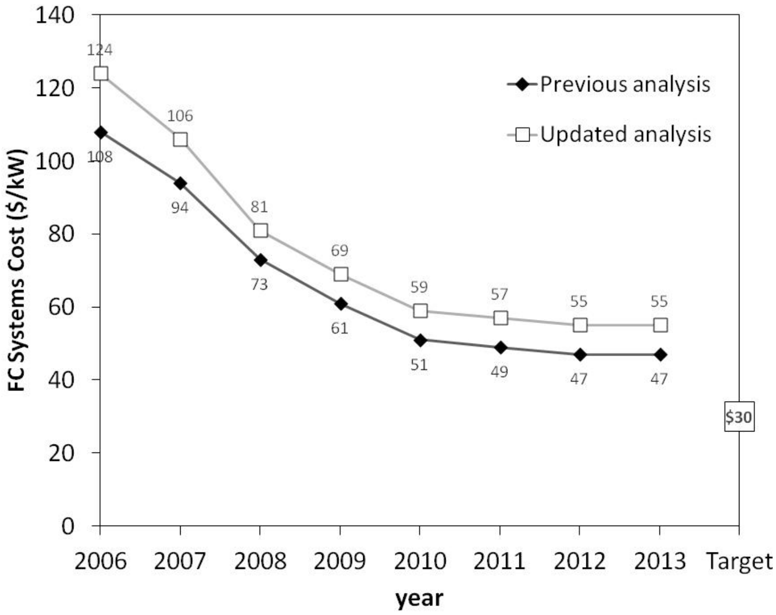


See more details in the text.

Fuel cell costs have declined significantly over the past decade, despite the increase in the cost of platinum. The American Department of Energy (DOE) recently upgraded its cost projections to high-volume manufacturing of 80-kW automotive PEM fuel cell system in order to take into account the new price of platinum (from $1,100 to $1,500 per troy ounce) and the new DOE requirements regarding heat management. This increased the projected costs from $47/kW to $55/kW in 2013, when assumed a production of 500,000 units per year (Spendelow and Marcinkoski, 2013). Figure 4 shows the decline in the costs according to the old and the updated methodology. However, in the first years of commercialization, the number of cars produced should stay around the thousand units, what would raise the cost of fuel cells to $285/kW (Spendelow and Marcinkoski, 2013).

The reduction in fuel cell costs appears to be confirmed in the last reports from the industry. Toyota announced that brought down the cost of its fuel cell propulsion system from $1 million a decade ago to $50,000 today – this translates into $500/kW or $625/kW depending on the system power considered, 100kW or 80kW, which was not specified by the company. Among other improvements, the new fuel cell would use around 30 grams of platinum, down from 100 grams previously (Reuters, 2014). Even though the ultimate targets for the cost of fuel cells seems to be within reach, the key challenge remains the financing of the first tens of thousands vehicles. The rollout of these more expensive units is essential to begin the transition commercialization, but the total cost to buy down FCVs to competitive levels - through economies of scale and learning – might amount to tens of billions of dollars. Automakers should take a part in these learning costs motivated by the possibility of increasing their share in the future market like in the case of Toyota with the Prius in the past. Nevertheless, further support could be necessary, especially in case the most optimistic predictions of cost reductions are not confirmed. The actual evolution of fuel cell costs will be primordial for the commercial success of FCVs, namely against the other new alternative technologies.

Figure 4. Cost projections from the DOE for an automotive 80-kW PEM fuel cell, assuming mass-production (500,000 units per year)



Source: Spendelow and Marcinkoski, 2013.

Hydrogen and fuel cells are in competition with other alternative fuel vehicles for the car of the future. However, they can also beneficiate from the increasing electrification of vehicles to penetrate more rapidly in the market. E.g., the new hydrogen-powered car announced by Toyota for 2015 uses spare parts of other gasoline-electric hybrids produced by the same company (Reuters, 2014). In addition, some lessons can be drawn from a couple of success cases in the commercialization of BEVs. In Norway, for instance, tax exemptions in acquisition and several other factors, such as driving in bus lanes or free parking, have contributed for the rapid take off of the market for electric cars – which already accounted for 15% of new immatriculations in the first semester of 2014.[34]

Finally, the number of fuel cell prototypes and demonstration fleets has considerably increased in the past decade (Bakker, 2010a). This growth was accompanied by the opening of more hydrogen refueling stations in the world (they were often associated to demonstration projects). The declining cost of hydrogen fuel cell vehicles may allow the demonstration of more cars and consequently incentivize the construction of more stations in the coming years.

[34] "Au pays du pétrole, la voiture électrique va bien," Le Monde, 17/07/2014.

4. Conclusions

The hydrogen economy in mobile applications will only become possible one day if there is a sufficient network of refueling stations capable to assist adopters of hydrogen-powered cars (which most likely will be equipped with fuel cells). Hydrogen and fuel cells are resurging from a period of generalized disappointment after the hype in the early 2000s. The investment in the early infrastructure for such an emergent innovation is then risky and surrounded by many uncertainties. The choice of the infrastructure's configuration on the one hand raises important questions as the least expensive "pathways" for production and distribution of the fuel (e.g. on-site small methane reforming) to supply the (weak) initial demand are unlikely to produce the cheapest hydrogen. Moreover, the choice of the infrastructure depends on the type of technique adopted to store hydrogen onboard, but this seems more of a consensus as automakers are increasingly adopting higher gas compression. The adoption of fuel cell vehicles will on the other hand depend on the price of the car which is still dominated by the fuel cell cost. This has significantly declined in the past few years and independent projections indicate that they can further reduce to competitive levels in the future, assuming high-volumes manufacturing. However, the production of half a million units per year is unlikely to happen in the early years of commercialization, and it is still unclear how the additional costs would be shared among the stakeholders (automakers, users, governments, etc.). What is more, the durability of fuel cells remains an issue that must be rapidly solved in order to enable the commercialization of FCVs.

Under these circumstances, the first network of stations started to be built in several points of the world to prepare the commercial launch of hydrogen-powered cars now expected to 2015. These projects often involve the collaboration of fuel suppliers, fuel cell providers, local authorities and automakers, which in one case (California) financially help the construction of the first stations. The local efforts to build the infrastructure and commercialize FCVs were analyzed more in detail for three leading cases: United States (California), Japan, and Germany. Some lessons can be derived from the study of these cases. The Californian zero emission vehicle mandate started in the 1990s; even though it was never applied in its original form, the mandate was decisive to put the hydrogen car in the agenda of the automobile industry. The stable support provided after the "hype" by the governments in Japan and Germany was essential to preserve the knowledge created during the previous phases and gradually progress the technology. Nevertheless, the success of hydrogen and fuel cell vehicles in the future seems to depend mostly on the reduction of fuel cell costs and the readiness of the technology. This would allow the commercialization of the car on time, what could ameliorate the general credibility of the technology and, by that mean, help in establishing gradually the infrastructure.

5. Sources of further information and advices

A non-exhaustive list of websites which provide updated and useful information in the field of hydrogen and fuel cells can be found here:

http://www.iphe.net - International Partnership for the Hydrogen Economy
http://iahe.org - International Association for Hydrogen Energy
http://www.ieahia.org - International Energy Agency (IEA) Hydrogen Implementing Agreement
http://www.fch-ju.eu - European "Fuel Cells and Hydrogen" Joint Undertaking
http://www.h2euro.org/ - European Hydrogen Association (EHA)
http://www1.eere.energy.gov/hydrogenandfuelcells - Fuel Cell Technologies Office of the U.S. Department of Energy (DOE).
http://www.hydrogen.energy.gov – Hydrogen and Fuel Cells Program of the DOE
http://www.fchea.org - Fuel Cell and Hydrogen Energy Association (US)
http://www.cafcp.org - California Fuel Cell Partnership (CaFCP)
http://hysut.or.jp – Japanese Research Association of Hydrogen Supply/Utilization Technology (HySUT)
http://www.now-gmbh.de – German National Organization for Hydrogen and Fuel Cell Technology (NOW)
http://www.hfcletter.com - The Hydrogen & Fuel Cell Letter
http://www.fuelcells.org/ - Fuel Cells 2000
http://www.fuelcelltoday.com - Fuel Cell Today
http://www.nrel.gov – U.S. National Renewable Energy Laboratory
http://steps.ucdavis.edu - Sustainable Transportation Energy Pathways research program from the University of California, Davis
http://www.h2mobility.org - LBST database on hydrogen vehicles and stations
http://www.cleanenergypartnership.de - Clean Energy Partnership (CEP)
http://www.scandinavianhydrogen.org - Scandinavian Hydrogen Highway Partnership

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