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INVESTING IN THE HYDROGEN DELIVERY INFRASTRUCTURE: METHODOLOGY FOR A PUBLIC POLICY

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ABSTRACT

Hydrogen and fuel cells are a radical innovation with great potential, but they are currently surrounded by numerous uncertainties. It is argued that demand and technological uncertainties are particularly important. An economic analysis is performed for a hydrogen refuelling station to understand the way uncertainties work. Even though the investment has a negative NPV today, it can be justified by the option value given to the owner for the future. In addition, the profitability of the station depends heavily on the demand; the evolution of which is still unpredictable unless public authorities decide to create a stable early demand.

Keywords: infrastructure; uncertainty; hydrogen

RÉSUMÉ

L'hydrogène et les piles à combustible sont une innovation radicale avec un grand potentiel à long terme, mais ils sont actuellement entourés par de nombreuses incertitudes. Les incertitudes technologique et de la demande sont particulièrement importantes. Une analyse financière standard de la mise en place d'une station-service à hydrogène est menée afin d'évaluer la rentabilité du projet ainsi que de comprendre l'effet des incertitudes pour l'investissement. Bien que l'investissement dans une station d'hydrogène ne soit pas rentable aux conditions actuelles, il peut être justifié par la valeur d'option acquise pour l'avenir. De plus, la rentabilité de la station dépend fortement de la demande dont l'évolution reste imprévisible, à moins que les autorités publiques décident de créer une demande initiale stable.

Mots-clés : infrastructure ; incertitude ; hydrogène

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INTRODUCTION

Current trends in transportation are clearly unsustainable. Global transport demand is expected to rise by a factor of three by the end of 2050 (mainly driven by the growth in China and India) (WBCSD, 2004). Energy consumption in the transport sector is projected to double during the same period, increasing oil needs dramatically (about 60%) and thus the vulnerability to the "peak oil" (Criqui and Mima, 2008). The increase of carbon emissions in transportation will reinforce global warming, leading to concentration levels beyond the 500 ppmv carbon dioxide (CO2) equivalent and therefore to a temperature increase superior to 2°C by 2100, provoking in this way a major weather disruption (IPCC, 2007).

In the short to near term, existing technologies can be deployed in order to curb oil consumption and carbon emissions, such as more efficient engines and hybrid electric vehicles (Demirdoven and Deutch, 2004). Nevertheless, radical technology breakthroughs may be required to deeply cut emissions like hydrogen-based technologies. That needs immediate public support for research, development and demonstration (R&DD).

Hydrogen produced from carbon-free sources like wind or solar, and used in fuel cells, has the potential to revolutionize the energy sector in a sustainable way (Clark and Rifkin, 2006). Hydrogen has many applications for stationary and portable utilizations, but it's in transportation where there are the highest hopes to reduce the "oil addiction".

Even though hydrogen and fuel cells have a great potential in the long run, there are many hurdles to overcome before the commercialization stage. The most important challenges are technology preparedness (cost, performance, durability), and the absence of infrastructure[1] (IEA, 2005, 2007; NRC, 2004, 2008). The availability of hydrogen refuelling stations is of paramount importance for consumers and carmakers in order to introduce hydrogen cars in the market (Farrell et al., 2003; Sperling and Ogden, 2006). Some demonstration projects are already on the road all over the world.[2] According to the European Hydrogen Energy Roadmap, large demonstration projects should start after 2010 enabling an initial fleet of 1,000 vehicles by 2015 (HyWays, 2008).[3] More recently, the European Commission (EU, 2008) considered the possible requirement for filling stations to enable the necessary infrastructure to permit the diffusion of alternative fuels such as biofuels or hydrogen.

Nevertheless, it is difficult to coordinate efforts on a large scale demonstration because the players may not have the same incentive to start investing (Sperling and Ogden, 2006). Carmakers and fuel cell developers may see "first-mover' advantages in moving earlier to the next technology (e.g. image brand, competition).

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[1] The concept of hydrogen infrastructure is defined as the system needed to produce, store and deliver hydrogen to users (see also Ogden, 1999). In our definition, the infrastructure is composed by the following activities: production; storage; transportation; and distribution at the refuelling stations.

[2] Worldwide demonstration projects atlas http://www.iphe.net/newatlas/atlas.htm (300 projects surveyed). It is reported about 140 refuelling stations (further 90 are under construction) fuelling 400 fuel cell vehicles and 100 buses worldwide. See also http://www.h2mobility.org .

[3] The Roadmap advocates the construction of 400 small stations in the early user centers by 2015, plus 500 stations located in the motorways linking these centers during the same period.

Conversely, infrastructure promoters like oil companies have invested in the conventional energy network, and they may want to amortize them as much as possible. Finally, as technology is expected to progress very fast in early years, so consumers may prefer to wait for better and cheaper hydrogen cars.

This study focuses on financing the early hydrogen infrastructure for road transport. The objective is to improve the understanding about the context of the investment, as well as the role of government to reduce the risks and promote investments. Uncertainties are first identified and a methodology for the profitability assessment of a hydrogen station is then presented. The project is rejected under conventional financial tools, although the conclusion changes when the specificities of this new industry are taken into account. Particularly, we suggest that under large technological and market uncertainties early investments in hydrogen infrastructure have an information value that compensates first financial losses. Demand is critical for the economics of the station, which may have important implications in terms of public policy.

1. UNCERTAINTIES IN THE HYDROGEN INFRASTRUCTURE INVESTMENT

Hydrogen is mixed with air in the fuel cells, resulting in power and water with zero emission. It can serve to power mobile, stationary and portable appliances. Hence, hydrogen-based technologies are a radical innovation with the potential to revolutionize the energy sector (Freeman, 1986).[4]

The development of an innovation follows different phases that can be summarized in four stages (Rotmans et al., 2001): pre-development; take-off; acceleration; and stabilization. In the pre-development phase, the resistance to changes from the conventional technology can hamper the efforts to develop a new technology, particularly in energy technologies where it has been argued that there is a "lock" into carbon fuels by an historical path-dependent process which inhibits the diffusion of cleaner technologies (Unruh, 2002). In the take-off phase, it is important that firms do not take an opposite direction than every other firm in the industry due to technology interconnections, network economies and learning curves (Arthur, 1989).

Different types of uncertainty will dominate according to the phase of the diffusion and to the role of the players in the innovation. Uncertainties may have many sources. In this paper, we follow the typology proposed in Meijer et al. (2005). Hence, the main sources of uncertainties reviewed are technological uncertainty, resource uncertainty, supply uncertainty, consumer uncertainty, and political uncertainty (Fig.1).

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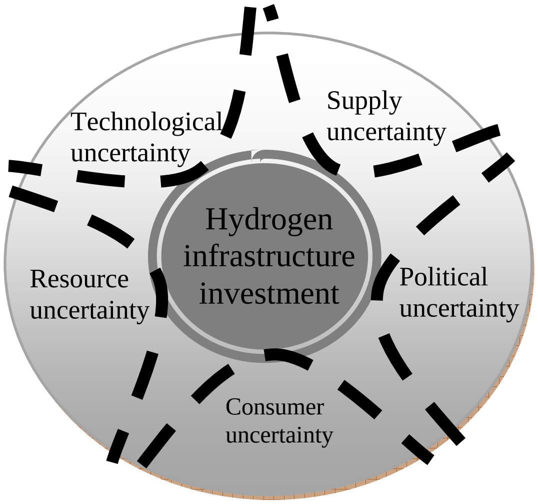
[4] Hydrogen and fuel cell technologies have the potential to accomplish the five conditions for an "authentic revolution" according to Freeman (1986): cost reduction; efficiency gains; social and political acceptability; environmental compatible; implications to the overall economical system.

Figure 1: Tackle uncertainties in the investment in hydrogen infrastructure



1.1 Technological uncertainty

One of the main sources of uncertainty in the hydrogen investment is technological uncertainty. According to its nature, technological uncertainty can be subdivided into uncertainty about the technology itself, uncertainty about the infrastructure, and uncertainty about alternative technological solutions.

1.1.1 Uncertainty about hydrogen technologies

Despite recent advances in stationary markets, such as in the emergency backup power and material handling applications (i.e. forklifts) where fuel cells are becoming competitive with conventional power technologies, in mobile applications they are still in the pre-market stage. Some progress has been recorded recently, although it is not certain if they can become competitive soon.

Current technological uncertainties can be analyzed at three levels: production; delivery and storage; and end-use, particular with fuel cells.

Hydrogen production technologies are well known in the industry. The annual production of hydrogen in the world is estimated at 65 million tons (less than 2% of world total primary energy supply), from which 95% is produced from fossil fuels and almost the half of it is from the reforming of natural gas (IEA, 2007). However, hydrogen is still three to four times more expensive to produce than gasoline (NRC, 2004, 2008). In addition, producing hydrogen from fossil fuels (e.g. natural gas, coal) doesn't solve the problem of carbon emissions without a carbon capture and sequestration system. Despite a couple of demonstration plants running in the world, the technology is still in the pre-demonstration phase and concerns about security are not fully resolved (NRC, 2008). Hydrogen can otherwise be produced from renewable sources (e.g. wind, solar, geothermal) or nuclear energy by the method of water electrolysis with zero emissions of carbon dioxide. However, these pathways are still more expensive than producing hydrogen from fossil fuels. In a world more concerned with climate change and with penalties for carbon emissions, zero-emissions pathways can more quickly become competitive provided that costs of the technologies keep going down (IEA, 2005, 2007).

The logistics of hydrogen is penalized by its low energy density. Storage is one of the major problems, especially onboard hydrogen storage. The goal is to store sufficient hydrogen on board to drive 500 km without refuelling. Original equipment manufacturers (OEM) can currently store sufficient hydrogen onboard for a 400 km (or more) range drive, cryogenically or under high compression rates at 350 bar and 700 bar, at the expense of excessive volume, weight or cost (NRC, 2008). Technological breakthroughs in storage (compressed, cryogenic or solid) are required in order to reach a satisfactory drive range, with reasonable dimensions, density and weight, and at an affordable cost (IEA, 2005).

As for fuel cells, technological improvements have been announced recently, though performance must be substantially ameliorated in terms of durability, efficiency and cost (NRC, 2008). Minimal cost requirements for market introduction are fixed in comparison with current technology in each market, which explains different cost targets for stationary and mobile appliances. The official cost target for the proton exchange membrane (PEM) fuel cell—the main fuel cell type considered for transports—is $US 30/KW by 2015 in the United States (DOE, 2007), and €100/KW in Europe (HFP, 2007). Recent projections indicate a cost of $US 100/KW (NRC, 2008) or 50 €/KW—stack only (Roads2HyCom, 2009)—but at the condition of mass-production (500,000 units produced). Otherwise, current costs for prototype or low volume systems are greater than 500 €/KW (Roads2HyCom, 2009). A synthesis of cost targets and current status for hydrogen, fuel cells for mobile and stationary appliances, and onboard storage, are presented in the table 1.

Table 1:
Overview of the gap between today costs/performances and targets for hydrogen technologies

	DOE's 2015 target	HFP Snapshot 2020 (HyWays Snapshot 2030)	Current status
Hydrogen cost at the pump (untaxed)	$2-3/kg	2.5 €/kg [a]	$4-5/kg
On-board vehicle storage	$2/kWh	10 €/kWh (5 €/kWh)	$15-18/KWh [b, c] >$60/kWh
Transportation fuel cell system cost	$30/kW	<100€/kW (<50€/kW)	$100/kW [c] >500€/kW
Fuel economy	60%	-	37-41%
Durability (transport FC)	5,000 hrs.	5,000 hrs.	2,000 hrs.
Stationary fuel cell system cost	$750/kW [d]	2,000 €/kW (Micro) 1,000-1,500 €/kW (industrial CHP)	$2,500/kW
Durability (stationary FC)	40,000 hrs. [d]		20,000 hrs.

(a) The goal is ranging the cost of production through a longer-term sustainable hydrogen supply between 2 and 5€/kg (HFP, 2007).

(b) 350-700 bar compressed hydrogen.

(c) Based on 500,000 units production per year. (or 50 €/KW stack only)

(d) DOE's (2007) target to 2011.

CHP states for Combined Heat and Power.

Source: IEA, 2006b; DOE, 2007; HFP Implementation Plan, 2007; HyWays Roadmap, 2008; NRC, 2008; Roads2HyCom, 2009; http://www.StorHy.net.

Cost reductions are required at all different levels before hydrogen becomes competitive. They are expected to come along with scale economies from the increased production, as well as with learning economies from a higher cumulative production (Arrow, 1962). Market introduction may accelerate technical improvements and cost reduction (Kemp et al., 1998). Hydrogen and fuel cells might enter into the market in a sequential way, starting with stationary appliances that are closer to competition (Bourgeois et al., 2000). The deployment in the stationary market may improve performances and reduce costs, which will benefit the introduction of the hydrogen fuel cell car into the transportation market.

1.1.2 Uncertainties about the infrastructure

Large socio-technical systems need a supportive infrastructure in order to operate. Building the hydrogen infrastructure requires high initial investments with a long recovery period, under an uncertain response of demand. So investors might be sensitive to the risk of stranded investments (Plotkin, 2007). McNutt and Rodgers (2004) analyzed past experience with alternative fuels in the USA to conclude that private players do not support high initial costs in infrastructure before being sure of the demand.

The hydrogen infrastructure can assume multiple configurations. Hydrogen can either be centrally produced and shipped to the consumption place or produced on site. It can be produced using different technologies (e.g. reformation of fossil fuels, electrolysis), and delivered under compressed or cryogenic form by truck, pipeline or train. The choice of the pathway depends mainly on the forecasted demand, regional resources and geographical factors (Sperling and Ogden, 2006). The absence of a shared view about the suitable infrastructure for the hydrogen economy gives rise to additional uncertainties (McDowall and Eames, 2006).

Nevertheless, there are some patterns repeated in different studies. In the early years, hydrogen may be produced in small quantities on site to serve a low but growing demand. Later on, large scale production facilities with lower unit production costs should replace on site production once demand becomes sufficiently large (Agnolucci, 2007; NRC, 2004, 2008).

The choice of the infrastructure must take into account the future onboard storage system (liquid, solid or gaseous compressed) (IEA, 2005). That is the reason why some argue that it is premature to start building the infrastructure today given that key technologies are under development (IEA, 2007).

Another possibility is the utilization of the natural gas network to transport hydrogen (McDowall and Eames, 2005). This strategy could reduce costs with the transition by the utilization of the existing infrastructure. However, pipeline materials can react with the hydrogen resulting in serious damages.[5] More studies must be performed in order to confirm or reject this transition strategy.

1.1.3 Uncertainties about alternative technological solution

The unpredictable evolution of alternative solutions contributes to amplify uncertainties, thus hampering market penetration of hydrogen. Technological characteristics of different technologies evolves during the initial time to learning

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[5] It has been argued that hydrogen can be safely mixed with natural gas up to 25 % of the final stream. See http://www.naturalhy.net/ (accessed in May 2, 2008).

(Arrow, 1962), the speed of improvements and the arrival in the main market (Kemp et al., 1998), and the possibility of new technologies to replace older ones (Arthur, 1989; Katz and Shapiro, 1986).

Hydrogen and fuel cells do not have a new market and must compete with older and new technologies for each market. As for transportation, hydrogen and fuel cells compete with other alternative fuels, such as biofuels and electric cars, in order to displace oil use (Demirdoven and Deutch, 2004). Comparing to other alternatives, hydrogen vehicles have a great potential in terms of environment improvement and performances, although they face many problems in terms of costs and infrastructure. A synthetic comparison of the state of the art of alternative options to road transportation is presented in table 2.

Table 2:
Competing alternative systems for road transportation

	Biofuels fuelled vehicles	Battery electric vehicles (BEV's)	Hydrogen vehicles
Cost	Almost competitive today	Remains expensive	Remains very expensive
Infrastructure & R&DD needed	Little adaptation of infrastructure; R&DD needed to develop 2nd generation of biomass fuels	Further R&DD needed and infrastructure adaptations	Much more infrastructure and R&D needed
Performance	Equivalent performance to conventional vehicles	Many problems with range and recharging times	Potentially better performance than conventional vehicles
Energy source	Resource is limited. Lack of consensus on the socio-economic and environmental impacts	Can use any primary source. Zero pollution at the end of the pipe	Can use any primary source, though with lower efficiency than BEV's

Source: Roads2HyCom, 2007.

Alternative fuels like hydrogen are not likely to penetrate the market just on the basis of environmental and energy advantages. Oil price is a key factor for their economics (HyWays, 2008; Leiby and Rubin, 2004; Sperling and Ogden, 2006). If high price levels (more than $USD 60-70/barrel) are not perceived as sustainable, players may reduce their interest in alternative fuels.

1.2 Consumer uncertainty

The consumer is at the centre of the project because it is unlikely that one firm would be interested in investing without demand. In addition, innovation is often guided by the perception about market opportunities for the technology, which is very uncertain (Christensen, 1997).

The diffusion of a technology is complex and constrained by historical circumstances. Technological change is generally path-dependent (David, 1985). That is explained by the existence of increasing returns to adoption that accelerates or blocks the diffusion, therefore increasing uncertainty about the outcome. The major sources of increasing returns are (Arthur, 1989) scale economies, learning economies, adaptive expectations and network economies. An increase in production reduces costs and improves performances by means of scale economies and learning (Arrow, 1962). The uncertainty of the quality of the technology is reduced with use (Arthur, 1989). In the presence of network externalities, the benefit that a consumer derives from using a good technology depends on the number of consumers using compatible items (Katz and Shapiro, 1986).

It is therefore understandable that new low-carbon technologies face more difficulties to penetrate the market because of the technological "lock-in" into widely used conventional carbon technologies, even if the former perform relatively better than the latter technologies (Unruh, 2002).

The uncertainty about demand behaviour over time is more important in the case of radical innovations. According to Rogers (1995), the adoption rate depends specifically on the relative advantage of the innovation, compatibility with conventional technologies, complexity, trialability and observability.

In the case of hydrogen and fuel cells, technological advantage is already debatable; there is a low compatibility with the existing infrastructure; there are a few demonstrations on the road although they are still focused in niche markets (buses, small fleets, etc.), which doesn't allow for large trialability nor broad observability. In addition, demand will be dependent on climate change concerns, local air pollution, preference for efficiency and local energy (HyWays, 2008; McNutt and Rodgers, 2004). In sum, it is difficult to predict the diffusion of hydrogen and fuel cells and its stabilization in the market.

1.3 Resource uncertainty

A usual problem with radical innovations is the availability of financial, human, and raw materials resources (Meijer et al., 2005). The scarcity might be more important during the development period, when it is difficult to forecast all the resources needed for the project.

Human skills may be scarce during the development of the innovation. The scarcity may be more stringent in the case of radical innovations because of the competence-destroying character of the innovation (Freeman, 1986). Therefore, education and training programs are needed in order to ensure the availability of human resources to carry out the innovation (HyWays, 2008).

Financial resources are an important issue in the pre-market stage of the innovation, when there is a need for investments in R&DD, along with the infrastructure. This restriction is particularly felt by fuel cell developers. The industry is mainly composed by small or medium size companies who have generally negative profits and are highly dependent on public subsidies.[6] In this

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[6] Meanwhile, stories of chronicle losses (e.g. Ballard) or even bankruptcies (e.g. 'Millennium fuel cells') become normal in the fuel cell business. See http://www.fuelcelltoday.com/online/financials for more details about the financial situation of fuel cell companies.

highly risked and fragmented context, it is difficult for firms to get external funds. The hope is that as technology improves and enters in the markets, firms decrease losses, relying more on market revenues. Until that point, financial needs and R&DD programs are dependent on public grants and particular deployment projects.

The utilization of premium raw materials, such as platinum in the production of the PEM fuel cell, makes the innovation more expensive and raises concerns about the availability of the metal in the future. Recently, research has been oriented to reduce the use of platinum in the production process, as well as discover novel methods to recycle the metal (NRC, 2008).

1.4 Supplier uncertainty

The development of innovations is often dependent on the external supply of capital, goods and knowledge (Meijer et al., 2005). An important source of uncertainty for an investor in hydrogen infrastructure is the behaviour of external suppliers in terms of timing, quality and cost of the delivery (Porter, 1980).

In the hydrogen-based technologies, the players are interconnected by mutual links. For instance, fuel cell developers supply carmakers and the economics of the fuel cell car produced by the latter depend critically on the cost of the fuel cell supplied by the former. Likewise, infrastructure promoters depend on the supply of equipment for delivery and production of hydrogen.

Uncertainty can be reduced by vertical integration (e.g. joint venture, merging) (Porter, 1980). Hence, fuel cell cars have been developed under partnerships between carmakers and fuel cell companies. For example, the Japanese carmaker Nissan has been working in cooperation with the US/Italian fuel cell developer Nuvera for the development of fuel cell cars. Recently, the former mobile department of the Canadian fuel cell developer, Ballard, was taken over by its car manufacture partners Ford, Chrysler and Daimler.[7]

1.5 Competitive uncertainty

In a competitive framework, firms are not sure of the results of their actions because they are dependent on the actions of their competitors. In the case of fast technology change, new entrants have an advantage over the firms already in the market because they do not bear the cost with the development of the technology (Porter, 1980). The threat of increasing competition directly affects the expected value of the investment by the potential impact on revenues (more competition is likely to reduce prices and quantities), as well as on production costs (more pressure on the input costs) (Bancel and Richard, 1995).

Competitive uncertainty has a particular importance for the timing of the innovation. In the context of a radical technological change, firms hesitate between making irreversible decisions—large sunk costs—in the new technology too soon or bearing the opportunity costs of losing momentum by a late move (Katz and Shapiro, 1986). The decision will depend upon the relative weight of "first-mover" advantages with regard to information about the potential of the market, early market share, and scale and learning economies.

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[7] See http://www.fuelcelltoday.com/online/news/articles/2008-04/Ballard (accessed in May 19, 2008).

A "first-mover" strategy is not absent of risks. There can be serious disadvantages of an early-move because of the existence of spillovers (Griliches, 1992). In this situation, the firm fails to appropriate all the social returns of the investment in R&DD, infrastructure or commercialization, resulting in lower levels of private innovation (Arrow, 1962). The spillovers can have the form of *knowledge* spillovers (where the technology developed by innovators is available to other firms), *regulatory* spillovers (where early-movers bear the cost of setting codes and standards to the new technology), *skills* spillovers (where the late-comer can use technical skills without supporting the cost with the training), or *support sector* spillovers (where followers may not need replicate the network of services that was created by pioneer firms).

The deregulation of electricity and gas European markets raises additional regulatory risks for potential infrastructure investors. Firms face increasing competition pressure as well as dynamic uncertainties about the evolution of the regulatory framework and its end-point (e.g. on market concentration issues, environmental regulation) (Jamasb and Pollitt, 2005). The new context is also expected to change the way that electricity and gas companies invest in the development of new technologies. They may prefer to invest in low risk innovations with short term profits over risky projects that may have high benefits in the long term for environment, fuel diversification or economy (van den Bergh and Kemp, 2006).

1.6 Political uncertainty

The uncertainty about the regulatory and the policy framework has a strong influence in the innovation outcome. There are several causes for political uncertainty, such as (Meijer et al., 2005) inconsistency or lack of regulation, government behaviour, and future changes.

There is a debate about the effects of regulation. Porter and van der Linde (1995) argue that environmental regulation contributes to strengthen the competitive advantage of companies because regulation will force companies to improve efficiency or ameliorate their products. According to the authors, the lack of regulation brings up additional uncertainties for investments in "greener" technologies. In particular, the interest in low emission technologies like hydrogen and fuel cells will depend heavily on the existence of a value to carbon (Neuhoff, 2008).

Another source of uncertainty deals with trust and credibility in government action. New regulations and unpredictable changes raise further uncertainties. A stable framework and a clear vision are necessary to reduce risks during the transition (McNutt and Rodgers, 2004). Moreover, the transition to hydrogen is not straightforward and public support will be necessary especially in basic R&D activities and in large scale demonstration projects. For example, if a tax credit for hydrogen infrastructure is being discussed without any decision, firms will prefer to wait because there is a high possibility that the cost of investment will fall (Dixit and Pindyck, 1994).

Nonetheless, there may be tension between the willing to promote a technological alternative to escape the oil 'lock-in' and the risk of "picking winners" (McDowall Eames, 2006). On the one hand, in the presence of high technical uncertainties, it is possible that government supports the wrong technology with high costs and little benefits (Leiby and Rubin, 2004). On the other hand, an incremental approach by a goal-oriented framework may be subject to 'lock-in' into current trajectories because the diffusion of the new technology is blocked by reinforcing mechanisms (e.g. the absence of infrastructure, rare compatible devices), which a "winner-picking" strategy can prevent. Investments approaches should therefore integrate the value of diversity, taking into account the irreversibility and technological lockouts that limit long term efficiency.

2. INVESTMENT BEHAVIOUR UNDER UNCERTAINTY: THE CASE OF HYDROGEN STATIONS

In the case of projects under great uncertainties about the future, it is impossible to analyze the financial feasibility with precision (Bancel and Richard, 1995). In this context, firms use simple methods such as the payback period or the net present value.

The availability of refuelling stations is necessary for hydrogen to enter into the transportation market. The infrastructure build up will require huge investments with a long recuperation margin. The complex environment surrounding hydrogen is likely to raise the risk premium for the capital, as well as require returns in a shorter period of time (Plotkin, 2007). This may lead the players to delay investments in the infrastructure or even to reject them definitively.

Nevertheless, conventional quantitative analyses do not take into account all the dimensions of the project. Using more realistic assumptions concerning the investment behaviour, a real options approach is a suitable framework to assess uncertain projects.

3. NET PRESENT VALUE (NPV) ANALYSIS OF THE HYDROGEN STATION

3.1.1 The model: basic assumptions and results

In this chapter, we analyze the economical feasibility of building a refuelling station to support the commercialization of hydrogen cars by the mean of standard analyses based on discounting expected cash flows. The net present value (NPV) is calculated as follows (Bancel and Richard, 1995):

$$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - I_0$$

Where:

r IS THE DISCOUNT RATE;

CF_t IS THE EXPECTED CASH FLOW OF THE PROJECT AT THE YEAR T,

T BEING THE LAST YEAR;

I_0 IS THE INITIAL INVESTMENT.

In the early years of the transition, onsite reforming of natural gas may be the cost-effective way to produce hydrogen (HyWays, 2008; NRC, 2008; Shayegan et al., 2006). This strategy is particularly suited in the context of a highly uncertain uptake. It makes use of the existing gas infrastructure, avoiding therefore the investment in underutilized central plants and delivery infrastructure (Ogden, 1999; Simbeck and Chang, 2002). However the economics of the production of hydrogen from natural gas has been challenged by the increasing price of the fuel.

Table 3:
Base case assumptions for a refuelling station supplying 120 tons of compressed hydrogen per year

€/08	Units	
Technical parameters		
Net capacity	t/yr	120
Capacity factor	%	85
Useful lifetime	Years	20
Efficiency	%	75
Cost parameters		
Investment	EUR/unit	657,645
Natural gas cost [a]	€/mmbtu	14.78
Real fuel escalation cost [b]	%/year	2.12
Maintenance coefficient	% of investment/yr	3.9
Total O&M	EUR/unit/year	22,857
Financing parameters		
Real discount rate	%	15
Revenues		
Hydrogen fuel price [c]	EUR/kg	4

(a) "Gaz de France" commercial rates for natural gas in 2008 for French small and medium companies, variable cost only: http://www.gazdefrance.com (accessed in April 29, 2008). Commercial rates for onsite production are significantly higher than industrial rates for central production of hydrogen.

(b) The escalation factor for the natural gas price until 2030 (2.12 % as the average of the real increase in the period) was taken from the Poles model.

(c) The price of the hydrogen is fixed for all the lifetime of the project and equal to 4 € (without taxes) so as to ensure that hydrogen will remain competitive against conventional fuels. This price coincides with the European objective by 2020 inscribed in the "Snapshot 2020" of the European Hydrogen and Fuel Cell Technology Platform (HFP).

In our analysis, we consider a medium-size fuelling station with a capacity for refilling about 65 cars per day, producing hydrogen on site by the mean of a steam methane reforming unit commercially available in Europe. Table 3 summarizes the "base case" assumptions for costs and revenues parameters. All costs are expressed in Euros of 2008. Cost and technical parameters are mainly derived from the HyWays database[8] complemented with information from the TechPoles database.[9]

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[8] Available online in http://www.hyways.de (accessed in April 4, 2008).

[9] From the technological database of the Poles model, Grenoble, April 2008.

The consistency of the information was tested by confronting the values with those from other studies (mostly for the United States) such as Agnolucci (2007), Simbeck and Chang (2002), Simmonet (2005), and Weinert and Lipman (2006).

It is assumed a utilization factor of 85% in the base case.[10] This assumption is probably too optimistic particularly during the early years, though low and variable loads deteriorate reformer efficiency.[11] High loads can be attained by serving fleets (e.g. buses, public agency fleets) (Farrell et al., 2003; Leiby and Rubin, 2004). Fleets are generally centrally refuelled and they have the critical size to justify a dedicated station. Although the number of cars needed may not be available at the beginning,[12] until there are a sufficient number of cars, the economics of the station can be improved by storing and supplying hydrogen and power to the community - a concept that is called 'hydrogen energy station' (Clark et al., 2005). In order to maximize environmental benefits, the hydrogen should be produced from renewable resources such as wind or solar. The price of the electricity may not be competitive with grid power (Simmonet, 2005); that may change if the externalities of health and environment, as well as security of supply, are taken into account by deploying decentralized generation and reducing oil dependence. Sensitivity analyses to demand changes and more realistic scenarios are performed further on.

For a discount rate of 15 %, the NPV of the hydrogen station is positive (117,141 €). The internal rate of return (IRR) of the project is 18.85 % (the maximum rate before that the NPV turns negative). The novelty of the project and all the uncertainties surrounding the technology may justify higher rates accounting for the riskiness of the project and more expensive debt. The effect of higher taxes on the profitability of the project is shown in table 4. The project is no more profitable (-28,748 €) for a discount rate of 20 %, which is a usual rate for innovation projects (Bancel and Richard, 1995).

Table 4: The effect of higher discount rates on the net present value (NPV)

NPV (€)		
10%	15%	20%
337,429	117,140	-28,748

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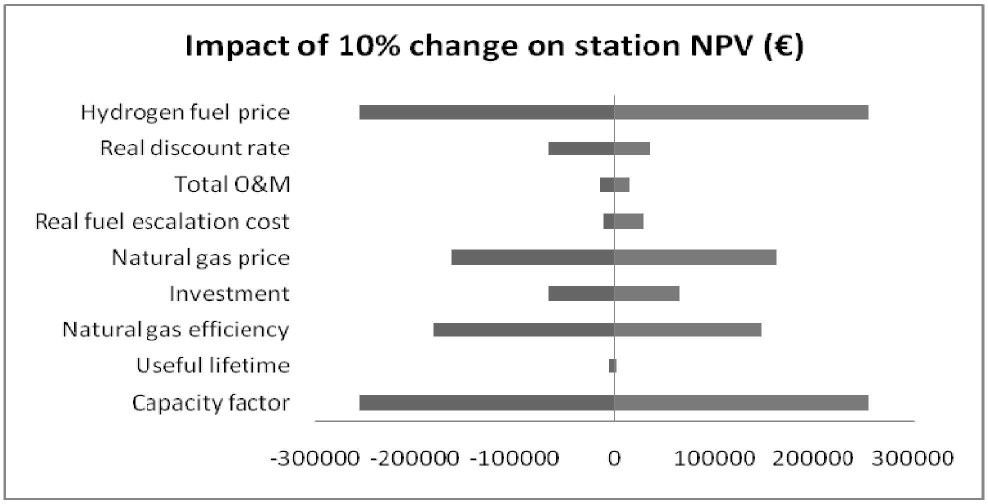
[10] Between 70 % assumed in Simbeck and Chang (2002) and 95 % assumed in Bartel et al (2004). In the case of production on site of the hydrogen, a full utilization (100%) means that the demand of the station corresponds exactly to the production capacity of the equipment. Feedback from the main demonstration projects in Europe, United States and Japan, can be consulted on the site www.roads2hy.com (deliverable 6.1-2 Review of technical, socio-economic and safety findings from fuel cell vehicle demonstration activities). The availability of the refuelling station surveyed was generally high. Some problems with the compressor, hydrogen contamination and the refuelling interface were also mentioned though.

[11] As for the implementation of hydrogen stations for buses in London, Shayegan et al (2006) found that loads below 30 % caused significant damage in the reformer unit.

[12] The station here considered has the capacity to supply 65 cars per day (5 kg of hydrogen per refilling what may allow for more than 400 km of autonomy). If we consider the car is refuelled once a week, the number of hydrogen cars needed for a full utilization of the station is 420 cars. This number compares with 400 fuel cell cars currently registered all over the world.

Although the discount rate captures the risk premium of the project, it doesn't give any information about the source of uncertainty. A sensitivity analysis measures the impact of each parameter changes on the profitability of the station. The next table shows the impact of a 10 % change (increase and decrease) of each parameter on the profitability of the station, with everything else constant.

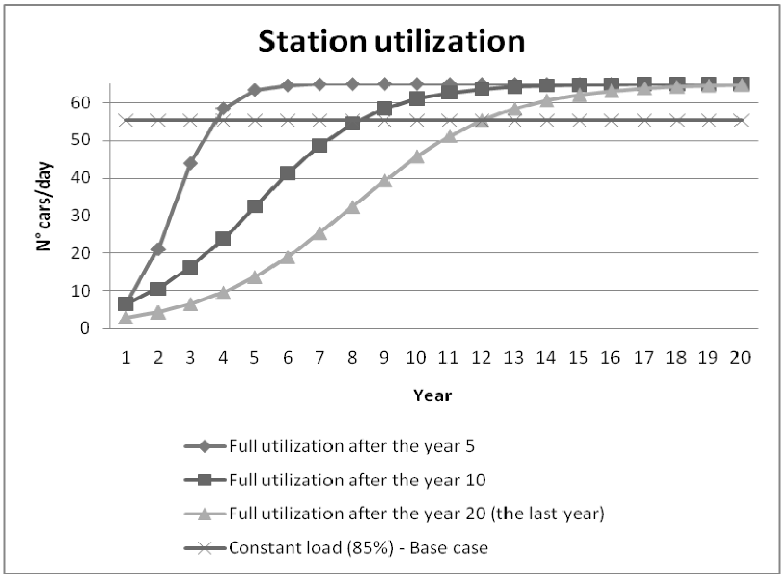
Graph 1: Sensitivity analysis



The economics of the station depend greatly on the efficiency of the reformer. Surprisingly, the overnight investment has a medium impact on the overall profitability. This can be explained by the fact that the analysis focuses on the construction of a unique station, and the capital problem arises more dramatically when not just one, but a network of stations, is analyzed. The sensitivity to the natural gas price is important because the fuel price is expected to increase in the future. The profitability depends heavily on both the price of hydrogen and the demand levels. The former is established by considering the price of conventional fuels, particularly taking into account the externalities. The sensitivity to the "capacity factor" is consistent with other studies where it is concluded that demand has the most significant impact on the economics of hydrogen stations (Agnolucci, 2007; Melaina, 2003; Weinert and Lipman, 2006).

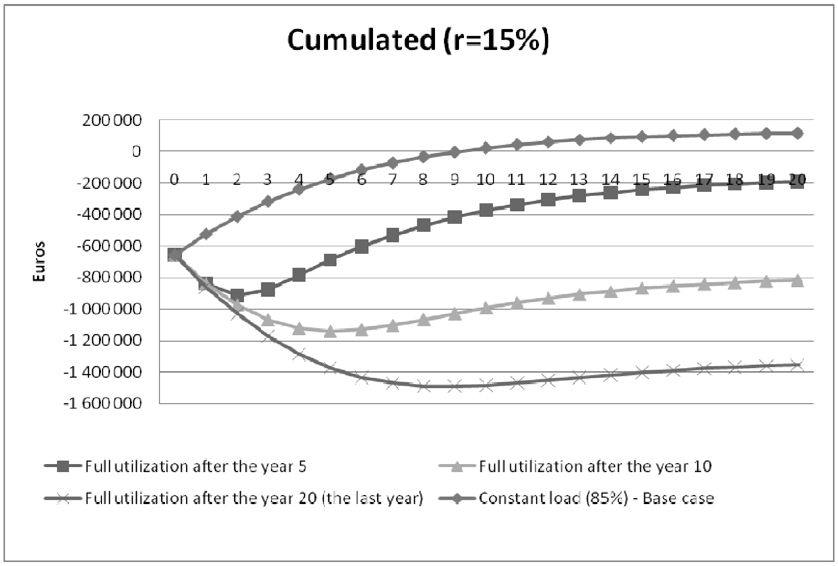
Concerning the demand, three more "realistic" scenarios are already considered. These scenarios assume that demand will progress over time following a logistic curve, starting with a low level and evolving continuously until reaching full utilization (for which demand the station was designed). Depending on the time needed to reach full utilization, we formulate a low (20 years or at the end of the station lifetime), medium (10 years) and high (5 years) scenarios, the latter meaning that demand grows at the expected rate (Simmonet, 2005). Graph 1 shows the three alternative scenarios plus the base case scenario.

Graph 2: Different scenarios for the utilization of the station



The impact of different demand profiles on the evolution of the cumulated cash flows is shown in the graph 2.

Graph 3: Cumulated cash flows under different demand scenarios



The "base case" sets an upper boundary to where more optimistic scenarios converge. In the reference case, the payback period is relatively short (10 years). Under more realistic assumptions, the station almost recovers the investment at the end of the period when demand grows at the expected pace. Otherwise it is not possible at all to recover the initial investment. So, under a more realistic assumption on the demand evolution, the financial risk more clearly appears to be what may discourage the investment.

3.1.2 Limitations of the NPV approach

In a context of great uncertainty, the application of discount flow methods can be constrained by the information available on the evolution of costs and revenues. On the other hand, the application of higher discounting rates—20% or more, reflecting the risk premium—can lead to reject projects with a great potential for the future.

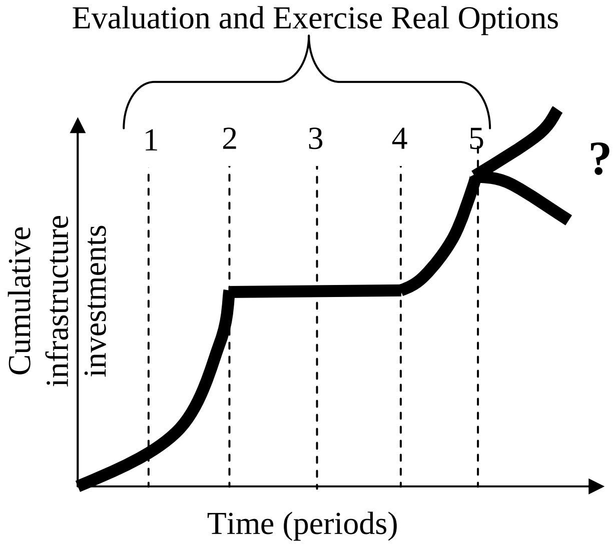
The NPV is an incomplete measure because it doesn't take into account the ability to delay or to recast the investment (Dixit and Pindyck, 1994). The project is accepted or rejected definitively, and decisions cannot be changed as new information arrives and uncertainties are dissipated. In addition, qualitative information about the benefits of the project for the firm (i.e. competitive advantages, learning) is also not accounted for in the NPV results. Thus, it is worthwhile to complement this analysis with other financial tools accounting for growing information.

3.2 Using real options approach to assess the investment in uncertain hydrogen infrastructure

In the real world, management can adapt its strategy to the evolving context. The decision maker may have the ability to defer, develop, expand, or abandon the project. This flexibility has an *option value* that affects the overall value of the project. This value can be converted into a *real option* upon making some additional investments (Dixit and Pindyck, 1994).

An Options theory is normally applied to assess the *value to postpone* an irreversible investment after the uncertainty is resolved or until more favourable conditions arise (see for instance van Benthem et al, 2005). However, there are some types of projects that can be recast and whose costs are under a great uncertainty. In these cases, information about costs is revealed only if the firm undertakes the first steps. Thus, early investments have an *information value* ("shadow value") that may reduce the expected cost of the investment (Dixit and Pindyck, 1994). This is particularly true in the presence of dynamic effects such as learning curves or scale economies, where the investment in cumulative production has the value of driving down costs.
Investment in early hydrogen stations can be seen as an "option to expand" (Damoradan, 2006). The project is initially not profitable but it can be decomposed into a series of stages, each one having an option to expand. The investor can stop/resume or abandon the investment at any time if it doesn't reach minimum performances, so large losses are avoided. The decision is particularly dependent upon the competition advantage for the firm, the benefit from the investment, and future prospects (Patil et al., 2006) (Fig.2). The principle is that the "information value" will accelerate early investments.

Figure 2: Sequential investment decision with real options approach



Adapted from Patil et al., 2006.

The first stage investment corresponds to a real option in which value is equivalent to hold a financial "call option", in the sense that it gives the right (not the obligation) to the decision maker to invest after receiving more information about the market and the technology (Damodaran, 2006; Dixit and Pindyck, 1994). Hence, the value of this "option to expand" can be measured by the optimal pricing model also known as the Black and Scholes (1973) formula:[13]

VALUE OF THE CALL OPTION $= S.N\ (d_1) - K.e^{-rt}.N\ (d_2)$

$$d1 = \frac{\ln\left(\frac{S}{K}\right) + \left(r + \frac{\sigma^2}{2}\right).T}{\sigma.\sqrt{(T)}}$$

$$d2 = d1 - \sigma.\sqrt{(T)}$$

Where:

S IS THE CURRENT VALUE OF THE UNDERLYING ASSET;

$N(.)$ IS THE CUMULATIVE NORMAL DISTRIBUTION FUNCTION;

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[13] The formula was named after the co-authors of the seminal paper Black and Scholes (1973). It is widely employed to estimate the value of financial European options which can only be exercised at the maturity date—in contrast to the American ones that can be exercised any time until the expiration date. Theoretically both types of options have similar values (Damodaran, 2006). The formula is based upon the idea of a replicating portfolio, between a risk free asset and the asset considered, which has the same cash flows as the project being valued.

K IS THE "STRIKE PRICE" OF THE OPTION;

r IS THE RISK-FREE INTEREST RATE;

t IS THE LIFE TO EXPIRATION OF THE OPTION;

σ^2 IS THE VARIANCE OF THE LOGARITHMIC VALUE OF THE UNDERLYING ASSET.

3.2.1 A methodology for valuing the option to expand the hydrogen refuelling station network

Let's consider the case of a firm willing to invest in a network of hydrogen refuelling stations that decides to fragment its investment in several steps in order to receive more information before the final decision. The firm invests in a fuelling station first, in order to yield an option to build a network later. The firm "buys" the "option to expand" the network of stations in the future if the project turns out to be profitable. For the first station we suppose that demand will evolve as in the medium "realistic" scenario, which assumes full utilization after the 10th year. The first station has an expected cost of 660,000 € and an estimated negative present value of the cash flows of 160,000 €, corresponding to a negative NPV of 820,000 €. Secondly, and if the conditions are favourable, the company constructs a network of stations. We consider a network of 10 similar stations, but this number can be generalized. The expected cost of the 10 new stations is 6,600,000 € - ten times the cost of the first station - a conservative assumption which doesn't take into account any learning or scale economies. The present value of the cash flows is estimated at 4,600,000 € supposing that stations are fully used after the 5th year — otherwise the firm would not invest.

The expected NPV of the second project is still negative 2,000,000 €. If it remains negative until the end of the option, the company will not invest. Nevertheless, in such an uncertain context, there is a possibility that the situation will change when, in more favourable conditions, the expansion project turns out to be profitable, thus compensating the losses in the first project.

The option can be measured by the mean of the financial option pricing model. The expected present cash flow of the expansion project is the current value of the underlying asset ($S=4{,}600{,}000$ €). The variance and the standard deviation ($\sigma^2=0.046$ and $\sigma=22$ % respectively) of the expected present cash flow is derived from the sensitivity analyses.[14] The expected cost of the expansion (the second project) is the "strike price" ($K=6{,}600{,}000$ €) of the option. The life of the option (T) is linked to the cost supported for keeping the option alive, thus it may be considerably shorter than the asset life - let's say, 5 years. The risk less rate is assumed to be 5%.

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[14] This is the variance of the logarithm of the value of the underlying asset according to the original specification of the model. We used the results of the sensitivity analysis performed in the previous chapter to calculate the variance. This method gives a rough image of the variance because it doesn't take into account the complete distribution of the outcomes, especially extreme values, and therefore variance may be underestimated. A more accurate method should use, for instance, the Monte-Carlo simulation, which was beyond the scope of the present study. However, those values should be considered as conservative estimations because a lower variance reduces the value of the option, as shown in Dixit and Pindyck (1994).

The value of the "option to expand" is computed as following:

Value of the option to expand = $4{,}600{,}000 \times 0.5319 - 6{,}600{,}000 \times e^{-0.05 \times 5} \times 0.3156 = 824{,}529.121$ €

The value of the option to expand is estimated at 824,529.121 €. This value is added to the NPV of the first project (-820,000 €) in order to find the overall value of the project:

NPV with Option to Expand = - 820,000 € + 824,529.121 € = 4,529.121 €

The value of the project becomes positive (4,529.121 €) if we account for the inherent option to expand the investment.[15] Therefore the firm should start building the station even if the current NPV is negative because this investment comprises an option value bigger than expected losses, and it allows for reducing uncertainties on the technology and market potential of hydrogen.

The use of the option pricing model in the assessment of innovations enables the decision maker to take into account both the information and the technological externalities of a gradual diffusion of new technologies. Hence this method is well suited to the financial analysis of projects like those in the hydrogen field. This result contrasts with the reticence of firms, such as oil companies, to invest in the hydrogen delivery infrastructure in practice.

4. Why should government intervene?

The development of hydrogen and fuel cells has many social benefits in terms of increasing energy efficiency, reducing pollution and greenhouse gas emissions, assisting the diffusion of renewable energy sources (notably by addressing the intermittence problem), and diversifying energy sources. It is particularly in transport that the benefits of hydrogen are more expected. In addition, fuel cell technology has a broad range of applications supplying high value services and products that may have positive impacts on the economy and the creation of jobs.

Most of these benefits are public goods which raise additional problems to firms for the valuation of the benefits of hydrogen and fuel cells investments, thus hindering the diffusion of them in the market. Private analyses do not take into account the positive externalities of improved local air quality, climate change and oil dependence. In particular, without valuing carbon by the mean of a tax or a right trading system, the competitiveness of low emission technologies against established technologies seems compromised. Levelling the playing field is a necessary but insufficient condition for the diffusion of climate technologies.

Once in the market, low carbon technologies face the competition of established technologies, which benefitted from many years of technical improvements allowing for actual high level performances (e.g. costs, durability). Like other technologies,

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[15] The interpretation of the results of the optimal pricing model should be done with caution. The model assumes that the value of the underlying asset (the cash flows of the project) is distributed lognormally. According to the model, the value of the option increases with volatility what may be explained by the probability of environment to change and not an improvement in the quality of the project. The Black-Scholes model is also constructed under the assumption of free trade of the assets with the absence of transaction costs, while real options may not be traded. Finally, results are dependent on the parameter specifications.

hydrogen and fuel cells need time to gradually reduce costs by means of learning and scale effects. This is a dynamic process that allows the technology to become efficient with adoption (Arthur, 1989). Incentives should be given to stimulate the progression of the technology.

It was previously shown that demand is a critical parameter for the economics of the station, the evolution of which is hardly predictable unless the government decides to create an early stable demand or stimulate its development.

The initial cost of the vehicle rather than the price of the fuel may be the most influential factor hindering the deployment of hydrogen. Incentive systems on the retail price of the vehicle such as subsidies or tax-breaks could be therefore an effective way to overcome initial barriers to adoption. Even if demand exists, it is not certain that carmakers will supply a sufficient number of hydrogen fuelled cars. In that case, authorities can help to aggregate demand for hydrogen cars in order to lower production costs. They can also stimulate agents by setting regulations, such as the Zero Emission Requirement for carmakers in California, or the Low-Carbon fuel standard with flexible mechanisms allowing refiners to earn credits by supporting alternative fuel projects.

Public and private organizations can collaborate together in order to finance projects that improve sustainability, elsewhere called « civic-markets » (Clark and Lund, 2001). An important number of initiatives in the hydrogen field have already been made possible in this framework.

CONCLUSIONS

Hydrogen and fuel cells have a high potential in the long run, but they are currently surrounded by many uncertainties (technological, resources, demand, competition, supplier, and political). Without public support to R&DD, it is unlikely that hydrogen can enter the market and benefit from the virtuous cycle where the experience drives costs down, opening new markets, which in turn dissipates uncertainties and boosts investments, yielding more experience.

In addition, a new infrastructure is required of which the availability and the timing for its deployment is not yet certain. The investment in hydrogen stations is not profitable according to the use of conventional financial instruments. In particular, its economics depends highly on the demand behaviour which is unpredictable. These methods do not capture qualitative attributes of the project such as learning effects, information about the market, and strategic market positioning. Real options complement the discount cash flows analysis by accounting for qualitative gains of the project. The methodology presented here showed that firms willing to become active in the future hydrogen market may find the interest to invest in the infrastructure. Even though the investment is not profitable in the short term, it has a much greater option value for the future. Finally, results depend heavily on the uncertainties regarding the evolution of demand. However these can be addressed by suitable public policies.

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