INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 42 (2017) 4276–4284

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/he

Policies and deployment for Fuel Cell Electric Vehicles an assessment of the Normandy project☆

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ARTICLE INFO

Article history:
Received 9 August 2016
Received in revised form
18 November 2016
Accepted 30 November 2016
Available online 24 December 2016

Keywords:
Fuel Cell Electric Vehicles
Cost benefit analysis
Public policies
Infrastructure

ABSTRACT

The paper provides a cost benefit analysis of one of the most prominent Fuel Cell Electric Vehicle deployment project in France, taking place in Normandy. The project builds on the substitution of a diesel Kangoo by an electric Kangoo ZE with a fuel cell range extender for public fleets. The sustainability of the scenario as it is envisioned today is questioned. A second scenario is explored. It builds on a more aggressive investment in infrastructure so as to generate a higher market share for FCEV, including long range vehicles and buses on top of light duty vehicles. It is shown that the resulting higher consumption of hydrogen would be a strong lever to reduce the cost of hydrogen refuelling stations as well as the transportation cost of hydrogen that would now be associated with on-site hydrogen production. This scenario may require a higher level in public funds at the early deployment phase but would deliver much better chances to achieve sustainability.

Introduction

Road transport contributes about one-fifth of the EU's total emissions of carbon dioxide (CO_2). They are approximately 20% higher than in 1990 and are still rising.[1] Moreover increasing concerns on air quality improvement in urban areas (such as the elimination of NO_x, sulphur dioxide, carbon monoxide and fine particle emissions) largely contribute to put pressure on policy makers to achieve a zero emission target. In this respect hydrogen has repeatedly appeared as a promising technology [3,1,7,10,16].

However, a number of prospective studies suggest that Fuel Cell Electric Vehicles (FCEV) will achieve parity with other powertrains around 2040–2050. Consequently the deployment of FCEV is expected to increase at a modest rate until 2030 [2,12–14,17,18,21,24,26].

Still quite a few pilot programs are taking place in various countries (see Ref. [4]; for an international comparison of current policies to trigger FCEV deployments). The Normandy project is the most prominent one in France. This paper intends to draw the first lessons from this on-going project. We have collected the action plan for this project as well as cost projections from the players involved. These costs will be compared with those collected by Cambridge Econometrics [6] which provides a recent analysis of the potential deployment of FCEV (along with other power trains) in France.

☆ The authors would like to thank the participants of the 21st World Hydrogen Energy Conference, Zaragoza, Spain, June 2016, for helpful comments.
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[1] https://ec.europa.eu/clima/policies/transport/vehicles/index_en.htm.
http://dx.doi.org/10.1016/j.ijhydene.2016.11.202

The current geographical deployments of BEV proceeded through clusters in large suburban areas, and then expanded through corridors that connect these clusters. These deployments point out the complementarity of direct and indirect consumer subsidies with infrastructure subsidies to avoid the so called chicken–egg dilemma.[2] Norway is considered as the ideal case study [25]. As pointed out by Meyer and Winebrake [15] this is bound to be even more so for the deployment of FCEV for three reasons: (i) the potential regional markets will be initially low because of the high price of the vehicle,[3] (ii) this means that many regional markets will be required to achieve a minimum efficient size for vehicle manufacturing, (iii) on each regional market the infrastructure will require large investments with low profitability in a hydrogen distribution network due to the initial low volumes of H_2 consumption. The Normandy project will be analysed in this perspective.

In Normandy a voluntary hydrogen plan has been designed and gained large political support. Details of this plan have been laid down for years 2016–2018. In terms of FCEV it builds on the substitution of a diesel Kangoo by an electric Kangoo ZE with a fuel cell range extender for public fleets. This hybrid solution delivers a vehicle with a range of 300 km (instead of 120 km for the battery electric Kangoo ZE) for a lower cost than a full hydrogen vehicle. The advantage of fuel cell range extender in terms of autonomy is particularly relevant for public fleets which cover long daily distances. The advantage over diesel Kangoo is in terms of CO_2 emissions and other indirect aspects such as the increasing awareness of health damages due to local emissions by diesel (notably fine particles), lower noise, less vibration and more comfort for driving. The whole value chain is reviewed in details: the hydrogen production cost by electrolysis or SMR, the distribution and the delivery costs of hydrogen, the manufacturing and running cost of the hydrogen Kangoo.

The total cost of ownership is compared with the cost of the corresponding diesel vehicle in 2025. In this scenario the current plan is directly extended. The comparison points out the large gap that should be filled to achieve cost parity. We derive the amplitude of the public subsidies needed to make the TCO's comparable. This provides an interesting assessment for the potential success of the Normandy project, i.e. what are the chances that it will turn into a self-sustainable project or that it will remain highly dependent on political support. It is shown that, in the scenario envisioned today, the second hypothesis is the more likely. A second scenario is explored which would be consistent with the first hypothesis. The scenario concern a more aggressive investment in infrastructure so as to generate a higher market share for FCEV, including long range vehicles and buses on top of light duty vehicles. It is shown that the resulting higher consumption of hydrogen would be a strong lever to reduce the cost of hydrogen refuelling station as well as the transportation cost of hydrogen that would now be associated with on-site hydrogen production.

The paper is organized as follows. Section "The Normandy project" gives the background for the Normandy project. The cost benefit analysis is carried out in Section "A cost benefit analysis of the Normandy project". Section "Discussion: the high level of subsidies to achieve sustainability for the Normandy project" draws the implications in terms of sustainability of the project and the amplitude of the public support to achieve this sustainability. Section "Concluding comments and suggestions for further research" concludes and suggests some further research.

The Normandy project

Normandy and the appealing factors for a hydrogen plan

The most ambitious project concerning hydrogen for mobility in France is the Normandy project (see Fig. 1). This project aims to install the utilization of hydrogen for a long term on the territory. The Manche county (one of the 5 counties in Normandy), which has some specificity, initiated it: the production of electricity is much larger than its consumption, and the difference is expected to grow further, moreover this electricity production is carbon free. There are currently two nuclear plants (REP) which produce 18 TWh per year and a wind farm (0.2 TWh). Two new nuclear plants are planned for 2017 and 2035 for an additional production of 13 TWh by 2050. This area also presents a high potential for renewable energy sources (RES) from wind power (offshore and onshore) and from sea power (wave and sea flows). More than 24 TWh could be potentially produced by 2050 by RES. The Manche consumption is currently estimated at 14 TWh per year. It will probably decrease with the energies efficiencies targets. Despite of the high electricity overproduction, Normandy imports 9 TWh of fossil resources for transport and heating.

In this context, the hydrogen solution has some appeal. Firstly, it decreases the import bill of fossil fuel and indirectly decreases the greenhouse gas emission. Secondly, instead of directly exporting the electricity overproduction, the production of hydrogen by electrolysis allows adding a value on the final product. Indeed, hydrogen may be used in several downstream markets including chemicals (such as methanol) and transport. It is also a possible way to store electricity produced by renewables. The development of the hydrogen energy vector is expected to increase local employment and attract highly qualified workers.

The project has gained much political support and been extended from the Manche county to the whole Normandy region.

The hydrogen Normandy FCEV project (EasHyMob)

The Normandy project is known as the EasHyMob project.[4] The project is coordinated by the Normandy Region, Serfim

[2] On the one hand, vehicles manufacturers need refilling stations to attract consumers and, on the other hand, infrastructure builders need vehicles. This chicken and egg situation would typically be solved through vertical integration. When the players are in different industries, such as it is the case for FCEV, vertical integration is unlikely to occur, inducing a delay in simultaneous investments.

[3] The price of the Toyota Mirai is around k€66 in Europe.

[4] http://www.ehd2020.com/wp-content/uploads/2015/09/Presentation-EAS-HyMob-16-July-2015.pdf.

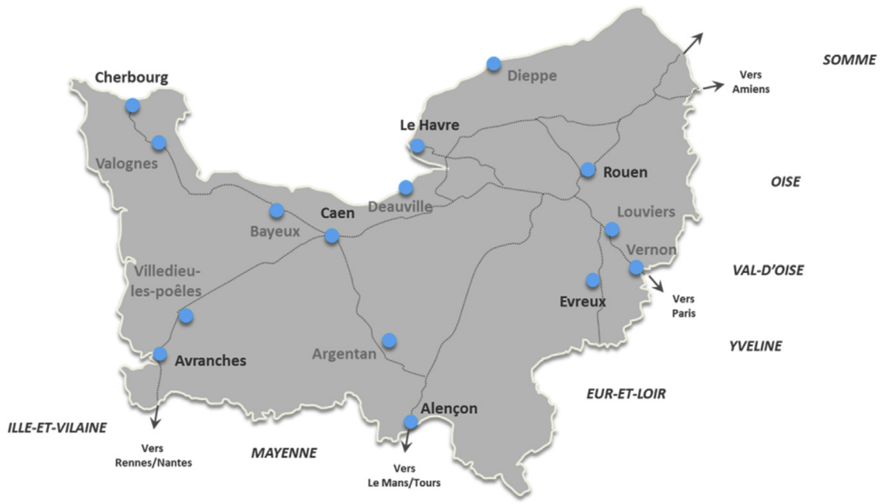

Fig. 1 – HRS targeted for 2018, Map of the Normandy FCEV project (source EasHyMob).

and SymbioFcell. It covers the 2016–2018 time horizon. SymbioFcell is a private company that designs and produces kits to extend autonomy of full electric vehicles. The project has been built with the support of EHD2020 which is an association founded under the hospices of the Council of the Manche county that gathers more than 40 members including industrial companies, local agencies and universities to promote the hydrogen plan in Normandy.[5] The project received the support of the European Innovation and Networks Executive Agency (INEA).[6] INEA funded 50% of the M€5 budget (for capital, civil and engineering costs) associated with an early deployment of 15 HRS of 350 bar with a capacity between 20 kg/day and 50 kg/day. A constraint imposed by INEA concerns the location of the stations. They need to be close to the highways and that at least 15 hydrogen vehicles be on roads at the opening of a station.

At the end of 2014 a first hydrogen refilling station (HRS) of 350 bar with 40 kg/day had been installed to initiate the deployment of hydrogen vehicles. In January 2016, there were 17 hydrogen vehicles on roads, of which 12 Hydrogen Kangoo and 5 Hyundai ix35 FCell. The HRS station can feed between 50 and 100 light duty vehicles (Hydrogen Kangoo), somewhat less full power vehicles as Hyundai ix35 FCell.

The Hydrogen Kangoo

The Hydrogen Kangoo is a BEV Kangoo ZE with a Fuel Cell range extender. The hydrogen device is composed of a fuel cell of 5 kW and a tank of 1.8 kg of H_2 under 350 bar. The lithium ion batteries give a range of 120 km and the hydrogen kit an extra 180 km, so that a total range of 300 km is available in urban cycle. The power of the fuel cell is low; it is used is to recharge the battery to increase the range.

SymbioFcell produces the fuel cell, Michelin (IMeca) assembles the hydrogen kit (fuel cell, tank, converter, etc.) and Renault (Renault Tech) installs the device on the Kangoo ZE. The deployment began at the end of 2014; in 2016, there were around 70 Hydrogen Kangoo on French roads.

The current price of the Hydrogen Kangoo is k€36.3 (VAT excl.): k€19.2 for the Kangoo ZE and k€17 for the hydrogen kit. In France, an ecological bonus of k€6.3 is allocated to such a green vehicle so that the purchasing net price is at k€30.

A version of Hydrogen Kangoo with a tank under 700 bar is now available and begins to be deployed in UK, Germany and North European Countries (Denmark, Norway, Sweden).

A cost benefit analysis of the Normandy project

Main hypotheses and data sources

Our cost benefit analysis of the Normandy project builds on the following main hypotheses:

- The cornerstone of the project is the substitution of a Diesel Kangoo (noted as D-K) by a Hydrogen Kangoo (to be denoted as H_2-K) for a number of public fleets;
- The whole value chain of this substitution is reviewed in details: the hydrogen production, the distribution and the delivery of hydrogen, the manufacturing of the H_2-K;
- The time horizon goes up to 2025, close enough to be meaningful for policy analysis and far away enough to assess the potential success of the project;
- Two scenarios are investigated: scenario 1 reflecting a moderate success under which the project would still rely on public subsidies and scenario 2 reflecting a full success under which the project becomes self-sustainable; the initial position in 2016 is also modelled as a reference to identify cost decreases;
- The occurrence of each scenario depends on the internal deployment of the H_2-K in Normandy but also on how successful the whole deployment of FCEV in France and possibly elsewhere in Europe takes place; we identify the main critical interfaces of this dependence;

[5] http://www.ehd2020.com/les-membres/.
[6] INEA is the successor of the Trans-European Transport Network Executive Agency (TEN-T EA). One of the missions of INEA is to ensure the cohesion, interconnection and interoperability of the trans-European transport network.

Table 1 – The scenarios, the associated value chain and the cost benefit analysis.

	Unit	2016 end of year	2025	
			Scenario 1	Scenario 2
Vehicles				
Hydrogen fleet	#	50	5000	10 000
Of which H_2-K	#	40	2000	4000
Production				
Production technology	""	SMR	Electrolysis	Electrolysis
H_2 production process	""	Centralised	Centralised on 2 sites	on-site
Distribution				
HRS capacity	kg/day	20	100	400
Nb of HRS	#	5	50	25
HRS utilization rate	%	50%	80%	100%
Storage	""	gas bottle	Tube Trailer	NC

- For each scenario our objective is to identify the total cost of ownership of both vehicles and the corresponding carbon abatement cost in 2025; then to use these results to assess the potential amplitude of public policies at that horizon and their optimal combination.

The data is coming mostly from interviews of the different actors of the Normandy project:

- For the characteristics of the Hydrogen Kangoo and the projections of its deployment in Normandy: SymbioFcell, EHD2020.
- For the characteristics of the electrolysis technologies and of the hydrogen retail stations: Air Liquide, GNVert, Keolis, Siemens, Areva H2gen, SERFIM, Tenerrdis, EHD2020, FCH-JU.
- For estimates of the electricity prices: RTE and EDF publications.
- For the scenarios: scenario 1 is based on the Actis bee study extended to the whole region, scenario 2 should be considered as our own construction to achieve sustainability in 2025.

The scenarios

The scenarios are described Table 1. For each scenario estimates of the total park (sedan, utility, trucks, coaches ...), the penetration rate of H_2 within the total park, and the number of H_2-K are given. From these estimates the H_2 consumption can be derived as well as the corresponding elements of the value chain: H_2 production, retail stations (HRS), logistics. Table 1 gives the optimal design along the value chain for each scenario: how and where the hydrogen is produced (centralized or 1 or several sites, eventually on site at the hydrogen retail station), how it is delivered to the retail stations in case of centralized production.[7] It is assumed that electrolysis production of H_2 is fully implemented in 2025 while in 2016 H_2 is still obtained through the steam reforming process (SMR).

The year 2016 corresponds to the deployment scheduled in the EasHyMob project for the end of year. The hydrogen is produced by SMR in refinery. This system is centralized with a distance refinery-station of average 200 km. The hydrogen is stored in gas bottle under 220 bar and delivered by trucks to the 5 HRS. The utilization rate of a retail station is of 50%.

Scenario 1 should be considered as the most probable continuation of the EasHyMob project. It assumes that the project is fully realized in 2018 and continues on the same trend until 2025. The hydrogen is produced in two high powered electrolysers and the average distance electrolyser-station is 100 km. There are 50 HRS with a capacity of 100 kg/day. The hydrogen is stored on the station in 400 kg tube trailers under 220 bar. The utilization rate of a retail station is of 80%.

Scenario 2 is our construction and should be considered as a sustainable target. The scenario assumes that EasHyMob project is fully realized in 2018 and accelerates in the following years. The hydrogen is produced on-site by electrolysis, i.e. at each of the 25 HRS with a capacity of 400 kg/day. The utilization rate of a retail station is of 100%. By construction the carbon abatement cost of this scenario has to be in line with a reasonable carbon price.

Observe that the two scenarios differ in the volume of hydrogen consumption which leads to different modes of hydrogen production and distribution. This will have important consequences on cost.

For each scenario we shall establish a total cost of ownership in €/km adding the various cost components along the value chain. All costs are in € 2016 and no inflation is introduced. Capital expenditures for an equipment of a given life time will translated into yearly equivalent expenses using an annual discount rate taken at 6%. Introducing the total cost of ownership for the D-K and its CO_2 emissions per km allows for deriving the implicit carbon abatement cost. This remains a static analysis and a more detailed dynamic analysis would certainly been worthwhile. Still the figures we obtain give an idea of the cost benefit of the substitution of the H_2-K versus the D-K.

As mentioned in the introduction it will be of particular interest to compare our cost analysis with the one for the low carbon scenario in Cambridge Econometrics (2015) [6]. In their scenario it is assumed that there is a strong penetration of advanced powertrains leading to a market share of approximately a combined 20% market share for BEV and FCEV in 2030, in spite of efficiency gains in ICE vehicles. While we focus specifically on the light duty vehicle segment and on the

[7] The detailed calculation that leads to the optimal design can be obtained from the authors upon request.

Table 2 – The production cost of hydrogen in both scenarios.

H_2 production cost analysis	Unit	Scenario 1	Scenario 2
HRS capacity	kg/day	100	400
Nb HRS	#	50	25
Utilization rate	%	80	100
Annual consumption	kg/yr	*730 000*	*3 650 000*
Capex of electrolyser			
Daily working period	h/day	12	12
Process efficiency	%	76	76
Whole installation efficiency	%	72	72
Equivalent hydrogen energy	kWh	39	39
Installation power needed	kW	*11 280*	*45 140*
Unit cost	€/kW	500	500
Capex	k€	*5640*	*22 570*
Installation and grid connection	% Capex	10	10
Storage infrastructure Capex	€/kg of capacity	500	500
Opex of electrolyser	% Capex	3.5	3.5
Life time of electrolyser	yr	15	15
Total fixed cost	€/kg H_2	*1.26*	*.94*
Electricity cost			
Electricity needed by kg of hydrogen	kWh/kg H_2	54	54
Electricity price	€/MWh	50	65
Variable cost	€/kg H_2	*2.7*	*3.5*
Hydrogen production cost	€/kg H_2	*3.97*	*4.46*

Normandy project, comparisons for the cost of hydrogen production through electrolysis and for the cost of HRS will remain relevant.

The H_2 electrolysis production cost in 2025

The main differences between the two scenarios may come from three factors:

- A higher power needed for centralized than for decentralized on site production;
- A lower utilization rate for scenario 1 than for scenario 2;
- A lower electricity price with centralized than for decentralized production.

Table 2 gives the detailed calculation to arrive at the hydrogen production cost by kg.[8] The first factor does not make much difference since in both cases the size of the electrolyser is high enough to allow for substantial economies of scale. A capex of 500 €/kW is assumed in both cases, based on the PEM (Proton Exchange Membrane) technology. This technology allows for some up and down production phases during the day to benefit from lower electricity prices. We assume that the electrolyser operates 12 h/day. The second factor makes the unit cost higher for scenario 1 than for scenario 2 but this is overbalanced by the third factor that is the lower price of electricity in scenario 1. The rationale for this lower price (on top of the average lower prices due to optimization of production during the day) comes under our assumption that the network fees are not supported in scenario 1 since the electrolysis sites would be close to the sites for production of carbon free electricity, which is more difficult to be achieved when hydrogen production is located in retail stations. It is assumed that both electricity prices exclude the CSPE (Contribution au service public de l'électricité). This consumer tax compensates the electricity producers for the constraints imposed by the regulator such as buying back electricity produced through renewables at feed-in tariffs or providing electricity to low income households. Some consumers such as production of hydrogen through electrolysis have been granted exclusion for the tax.[9]

Altogether it turns out that there is no significant difference in the unit cost of production. However we shall see shortly that the mode of production has a major impact on the delivery cost.

Our estimates for the production cost of hydrogen, approximately 4.0 €/kg H_2 in scenario 1 and 4.5 €/kg H_2 in scenario 2, differ from those obtained in Cambridge Econometrics, 8.1 €/kg H_2 in 2020 and 7.8 €/kg H_2 in 2030 (Fig. 4.3). The main difference comes from our assumptions used for the electricity prices, 50 and 65 €/MWh for scenario 1 and 2 respectively, while they assume approximately 125 €/MWh in 2025 (they estimate that the electricity price will increase from 107 to 148 €/MWh between 2015 and 2050). However they assume a standard electricity price, i.e. no optimization during the day.

Distribution network and logistics

The number and capacities of the HRS depend on the scenario, which also determines the number of production sites hence the distribution network. Table 3 provides both the cost of a HRS for each scenario (capex, opex and installation cost) and the associated transportation cost to deliver H_2 to the HRS network. The overall network average cost per unit of hydrogen consumed appears extremely high in 2016, because of low volumes. For scenario 1 the average cost is still significant so that the amplitude of public financing of the network remains an important question to study. For the scenario 2, the use of on-site production eliminates the transportation cost and thanks to the high consumption volume, the cost of the refilling station is low.

It may be noted that our estimates for the HRS cost in 2025, 2.2 €/kg H_2 for a 100 kg/day capacity at 350 bar and .9 €/kg H_2 for a 400 kg/day capacity at 350 bar, are very similar to those of Cambridge Econometrics: 1.9 €/kg H_2 for a 200 kg/day capacity at 700 bar in 2020 and .9 €/kg H_2 for a 500 kg/day capacity at 700 bar in 2030 (Figs. 4.5 and 4.6). In our study we have also identified the transportation cost specific to each scenario.

[8] In all Tables numbers in italic are obtained from the raw data reported in regular characters.

[9] https://www.edf.fr/entreprises/le-mag/actualites-du-marche-de-l-energie/evolution-de-la-contribution-au-service-public-de-l-electricite-cspe-au-1er-janvier-2016.

Table 3 – The logistic cost of hydrogen in both scenarios.

HRS cost analysis	Unit	2016	Scenario 1	Scenario 2
Retail station				
Capacity	kg/day	20	100	400
Capex	k€	200	500	1000
Opex	% Capex	6	4	4
Installation	% Capex	10	10	10
Life time	yr	15	20	20
Utilization rate	%	50	80	100
H_2 delivered	kg/yr	3650	29 200	146 000
HRS cost	€/kg	9.1	2.2	.9
Transportation				
Hydrogen storage		Gas bottles	Tube trailer	On site
Rental rate for storage	€/month	70	1700	
Subcontracting cost for transport	€/km	1.2	2	
Delivery distance	km	200	100	
HRS capacity	kg/day	20	100	
Utilization rate	%	50	80	
Quantity delivered/truck	kg	50	400	
Transportation cost	€/kg	10.7	4.4	0

The total cost of ownership and the implicit carbon abatement cost

To complete the cost benefit analysis one needs to introduce the manufacturing cost of the H_2-K, the lifetime of a vehicle, the number of kilometres it runs per year and the fraction of which it operates on the fuel cell extender, and the fuel efficiency of each mode. In this respect we use the specific numbers provided by Cambridge Econometrics (2015, see Fig. 3.2) for the H_2-K. All numbers are reported in Table 4. In this table, similar assumptions are also introduced concerning the D-K (manufacturing cost, fuel efficiency and diesel price).

These values allow for the derivation of the total cost of ownership (TCO) and the calculation of the implicit carbon abatement cost. For scenario 1 the abatement cost is estimated to be 500 €/tCO_2 which is much higher than the normative social cost of carbon suggested by economic studies (see for instance [19]). This should not lead to a negative appraisal of the Normandy project as long as one considers that a full deployment could be achieved some years later. For instance one could interpret scenario 2 as the projection of scenario 1 in 2030. Since scenario 2 delivers a sustainable assessment of the project with 47 €/tCO_2 in 2030 (lower than the 100 €/tCO_2 proposed in Ref. [19]), the static abatement cost obtained for 2025 of the deployment trajectory corresponding to scenario 1 should be taken as an intermediary result that does not reflect the full benefit of the scenario.[10]

[10] The interested reader is referred to [8] for a methodology to derive a relevant proxy of the abatement cost in the case of a progressive deployment of a green technology.

Our analysis of the value chain allows for a quantification of its different components. Consider first the purchase price and maintenance cost of the vehicle. The purchase price is expected to drop from its 2016 value by 14% with scenario 1 and by 39% by scenario 2. Learning by doing and spill overs should explain such decreases in the vehicle cost.[11] This will depend on the Normandy project but also, and probably more, on what happens to the deployment of the Hydrogen Kangoo and more generally on fuel cell and tank production costs at the European level. Consider now the fuel cost component. As expected the two scenarios generate very different delivered costs for hydrogen given the two different production and transportation modes. The cost drops from 8.7 to 5.4 €/kg. The decrease comes from the much higher volume of hydrogen consumption in scenario 2 and the corresponding joint optimization between production and networking. This suggests that a close coordination is required to optimize along the value chain to translate the progressive increase in consumption into cost benefits through on site production. In terms of amplitude, as long as the coordination is efficient, the decrease in the fuel cost from 2016 is approximately 75%.

Altogether the 33% decrease in TCO from scenario 1 to scenario 2 comes from the two components: purchase price and maintenance for 60% and hydrogen production and delivery for 40%. Complementarities in public policies to achieve these simultaneous cost reductions are clearly needed.

Discussion: the high level of subsidies to achieve sustainability for the Normandy project

This cost benefit analysis provides interesting insights for the design of policies to promote the deployment of H_2-K in Normandy. It allows for a quantification of the global amplitude of the public support that the project would still require in 2025.

We construct a target policy for scenario 1 in 2025 such that the TCO for the H_2-K would be equal to the TCO for scenario 2. We compare this target policy with the current policy in 2016 in Table 5. The current vehicle rebate is 6300 €/vehicle. It would have to be increased to 12 000 €/vehicle. An unreasonable rebate if it had to be extended in all French regions. As for infrastructure, the current subsidy in 2016 of 5 M€ for 15 HRS, that is 333 k€ for a HRS within 20–50 kg/day, would have to be increased to 412 k€ in 2025 for a HRS with 100 kg/day. Recall that the capital expenditures for a HRS were estimated at 200 k€ versus 500 k€ (Table 3). The level of subsidies for infrastructure would have to remain substantial.

Altogether the total subsidy would jump from 5.3 M€ to 81 M€. In comparing these two amounts we may subtract national subsidies at 6300 € per vehicle to the 12 000 € so that the regional subsidies for vehicles would be at $60\text{–}5 \times 6.3 = 28.5$ M€. We consider that the gap between $28.5 + 21 = 49.5$ M€ and 5 M€ is extremely large.

[11] See for instance Schwoon [23] and Schoots, Kramer and van der Zwaan [22] for an analysis of LBD in FCEV. Our estimates are consistent with those of Cambridge Econometrics [6] which discusses in detail the expected decrease in fuel cell and tank (see Fig. 2.2).

Table 4 – The cost benefit analysis of the H_2-K relative to the D-K.

Simplified cost benefit analysis	Unit	2016	Scenario 1	Scenario 2
Annual driving distance	km/yr	35 000	35 000	35 000
Life time	yr	7	7	7
Vehicle cost				
Purchase price				
H_2-K	k€	36.3	31.3	22.0
	€/km	.18	.15	.11
D-K	k€	10	10	10
	€/km	.05	.05	.05
Yearly maintenance cost				
H_2-K	k€/yr	.7	.7	.7
	€/km	.02	.02	.02
Rental fee for the battery	€/month	90	50	30
	€/km	.03	.02	.01
D-K	k€/yr	1.0	1.0	1.0
	€/km	.03	.03	.03
Fuel cost				
H_2-K				
Hydrogen production cost	€/kg	1.5	4.0	4.5
HRS cost	€/kg	9.1	2.2	.9
Transportation cost	€/kg	10.7	4.4	.0
Hydrogen delivery cost	€/kg	21.3	10.6	5.4
H_2-K consumption	kg H_2/100 km	1	.75	.70
Range done with hydrogen	km	180	180	180
Electricity consumption	kWh/100 km	18.3	6.3	5.7
Electricity cost	€/MWh	100	125	125
Range done with electricity	km	120	120	120
H_2-K fuel cost	€/100 k	13.54	5.07	2.54
	€/km	.14	.05	.03
D-K				
Diesel cost	€/l	1.0	1.2	1.2
Diesel consumption	l/100 km	7.0	6.3	6.3
D-K fuel cost	€/100 km	7.0	7.56	7.56
	€/km	.07	.08	.08
Total cost of ownership				
H_2-K	€/km	.36	.24	.16
D-K	€/km	.15	.15	.15
CO_2 emissions				
H_2-K	kg CO_2/100 km	5.9	0	0
D-K	kg CO_2/100 km	18.9	17.01	17.01
CO_2 abatement cost	€/t CO_2	1636	500	47

Table 5 – The subsidies in the target and current public policies.

Subsidies	Scenario 1	Target		2016	Subsidies in 2016	
Unit	# units in 2025	Total subsidy in M€	€/vehicle or €/HRS	# units in 2016	Total subsidy in M€	€/vehicle or €/HRS
Vehicles	5000	60	12 000	50	.3	6300
HRS	50	21	411 885	15	5	333 333
		81			5.3	

Concluding comments and suggestions for further research

Our analysis of the deployment of the Normandy project delivers several important results. We modelled the situation in 2016 and made projections for 2025 based on current assessments. Our analysis suggests that the Normandy project as it is envisioned today will remain highly dependent on the regional and national political support for the coming years. That it will take incentives or subsidies over a long time to support a fleet conversion involving a nascent and revolutionary technology such as FCEV is consistent with most prospective studies, in particular Zachmann, Holtermann, Radeke, Tam, Huberty, Naumenko and Faye [26], and Liu, Green and Bunch [13].

We constructed a second scenario in which sustainability is achieved (sustainability being defined as delivering an implicit carbon abatement cost in line with estimates of the social cost of carbon). This scenario could possibly be obtained in Normandy in 2030 or earlier, if circumstances are highly favourable. According to our cost benefit analysis the TCO of the Hydrogen Kangoo would need to be reduced by a half along this path. Through a detailed examination of the value chain we showed that there are two requirements to achieve this goal.

The first requirement assumes a significant level of learning by doing and spill overs in the manufacturing of the Hydrogen Kangoo (more specifically in the fuel cell and the tank parts) to allow for a 40% decline of the purchase price of the Hydrogen Kangoo vehicle. This can only be consistent with a success of FCEV deployment in two dimensions: (i) geographic that is not only in Normandy but all through Europe, (ii) across an extended line of H_2 vehicles that is not only for Kangoo but also through sedan, buses and trucks so that altogether a large increase of the hydrogen volume of consumption is generated in Normandy. To achieve this objective, high power vehicles (buses, trucks …) have an important role to play. Note that as early as 2003, Farrell, Keith and Corbett [11] suggested focussing on the deployment on heavy duty freight modes. The initial network should be viewed with this perspective in mind.

That this perspective is no longer wishful thinking can be documented. Indeed, bus projects are currently deployed in California, China or UK.[12] In Europe, the FCH-JU supports many bus projects (for a recent survey see Ref. [9]) and a new call will be published in 2017. Today, manufacturers as Evobus, Van Hool, Toyota, SymbioFCell/PVI and others have buses on sale with important prices rebates. Recent FCH-JU studies [20] compared the TCO of fuel cell and diesel buses and obtained a delta TCO decreasing from around 50% in 2015 to 20% in 2030. Concerning trucks, the latest report of the California Fuel Cell Partnership [5] planned a phase of early commercialization by 2030 and full commercialization by 2050. Today truck manufacturers as Nikola[13] (2020) or SymbioFCell/PVI (2017) already announced the commercialization of serial medium duty and high duty fuel cell trucks. There are several experimentations as in California[13] or in France.[14] Finally, hydrogen may be used in trains: Alstom announced a Coralia iLint in September 2016 with a first deployment in Germany where the Lower Saxony's local authority has ordered 14 units.[15]

The second requirement concerns a close coordination between hydrogen production and its delivery through refilling stations to take advantage of the expected increased volume of hydrogen consumption and manage the progressive substitution of SMR by electrolysis. More specifically we evaluated the two optimal designs (associated with centralized production versus on site production) that should constitute the successive stages of the optimal path for infrastructure. A successful coordination strategy would allow for a 75% decrease of the hydrogen fuel cost.

We then compared our sustainable target with the most probable scenario for 2025 and calculated the amplitude of public support that would be needed to make affordable the deployment of Hydrogen Kangoo for consumers. The required level of regional subsidies would have to be multiplied by 10 as compared with the level obtained for years 2016–2018. This suggests that a very strong political support for the Normandy project is needed for a long period which may endanger the success of the current project.

Our analysis points out further that while the level of subsidies for infrastructure is less important than the level of direct subsidies for consumers the path followed in the infrastructure deployment can be critical to achieve sustainability. This calls for some questions as regards the options followed by the Normandy project: the current project focuses on the Hydrogen Kangoo which implies some technical choices in terms of tanks and HRS (350 bar) and indirectly for small HRS (because of low hydrogen volumes since the Hydrogen Kangoo is a hybrid). These options, relevant given the envisioned scenario, may actually make difficult our transition to sustainability (based on 700 bar and large HRS associated with high consumption volumes). The possible dead ends arising from these options are important draw backs. This highlights the short term gains of scenario 1 and its potential long term risks. Alternatively a large deployment as expected in scenario 2, such as seems to be the case in Germany, would make the profitability of the early HRS deployment more risky while generating higher gains in the future. This would be worth exploring further a systematic year-by-year dynamic analysis.

It would certainly also be worthwhile to explore this question more formally. Our analysis suggests that the two cost components (vehicle and fuel costs) involved in the deployment of FCEV could be formalized as follows. The vehicle cost component would involve learning by doing generating a decreasing unit cost over time. The fuel cost component would involve convexities generating an increasing marginal cost at any point of time. The dynamic interaction between these two components would be such that a lower vehicle cost generates a lower fuel cost and vice versa, the first effect being much stronger that the second one. It would be interesting to formalize further such a joint cost function and discuss its implication in terms of policies and deployment.

Acknowledgements

The authors gratefully acknowledge the financial support from the Energy and Prosperity Chair. The research was conducted while Julien Brunet was research assistant at Ecole Polytechnique. Julien Brunet is now with SymbioFcell.

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