Why local initiatives for the energy transition should coordinate
The case of cities for fuel cell buses in Europe[1]

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Executive summary

This paper investigates the potential benefit of coordinating local initiatives in Europe in the transport sector and provides an evaluation of the JIVE programs with respect to FCEB. Our main argument is that the deployment of green technologies in transport faces a double challenge: a need to decrease its cost and a chicken and egg issue due to the network externality between vehicles and infrastructure. The first component of the challenge requires high volumes suggesting at least a European perspective while the second part suggests a regional/local perspective as exemplified by the multiplication of geographic clusters. Cities play a significant role in the latter due to their commitments towards zero emission urban transport.

Our analysis clearly demonstrates that at the current level of cost it would not be economically justified to deploy FCEB. The abatement cost for reducing CO2 emissions would be higher than 1000 €/tCO2. Considering the local pollutants (NOx and PM 2.5) and their social costs as impacting the health of population in high density areas would decrease the abatement cost to 300 €/tCO2, a level still much higher than the current level for the social cost of carbon. It follows that a substantial cost decrease is a necessary condition for justifying the deployment of FCEB. This condition is exemplified as a possible decrease in the purchasing price of FCEB from 700 k€ in 2018 to 450 k€ in 2025 for a standard 12m bus. Such a decrease would be consistent with a learning rate of 10 % associated with an annual market growth of 50 %.

We evaluate the potential of EU programs to achieving such volumes. As a matter of fact, EU has been engaged in support programs for the deployment of FCEB since 2001. However, while earlier programs remained essentially demonstration programs with a total of 114 FCEB deployed, the JIVE programs initiated in 2017 provide a change in scale triggering the deployment of more than 1000 buses. JIVE programs allocate a subsidy of 200 k€ per FCEB to cities that secure national/local financial support and engage into a long-term plan for the deployment of FCEB. 18 European cities are participating to JIVE. The benefits from JIVE is accruing through better information along three stages: Financing, Planning the HRS, Planning the Bus Operations. However, the vital importance of Government Policy Frameworks that incentivize or mandate Zero Emission public transport is a constant refrain when it comes to cities' willingness to find the funds to subsidize the new technology to encourage transport operators.

Altogether it seems that the JIVE program remains short relative to the objective of triggering a high enough demand, much lower than the required 50% annual growth rate combined with a 10% learning rate, even if we expect that future EU programs will consolidate the powering up phase initiated by JIVE for the FCEB deployment.

A detailed analysis of the value chain for FCEB, from the energy source to produce green hydrogen to the assembly of buses, suggests that the analysis should take a broader perspective. Firstly, there may be mutualization of components across various product lines for the production, storage and delivery of green hydrogen to HRS, and for the critical parts such as the fuel cell, the electric drive system and the hydrogen high pressure tanks. Secondly, one should go from a European to a world perspective and consider global strategies to analyse competition between incumbents and many entrants attracted by the potentially highly profitable emerging market associated with green hydrogen.

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1. Introduction

Green technologies are characterized by high initial unit costs and high learning rates, so that their deployment is often encouraged by public subsidies to circumvent the myopic behaviours of the players, consumers and firms alike. After some years, the costs decline and market competition with mature fossil technologies can take place. The early deployment of renewable energy through PV illustrates this sequence: it was initially facilitated by various forms of subsidies such as feed-in tariffs, the learning rate being estimated to be around 30% (i.e. the unit cost decreases by 30% every doubling of cumulative production); nowadays these subsidies have substantially decreased in most countries (Elshurafa, 2018).

Fuel cell and battery electric vehicles (ZEV)[3] just entered this route: at present they remain expensive compared to fossil fuel vehicles, but they are expected to be competitive in the future. However, these technologies face a further challenge known as the “chicken and egg issue”: their deployment needs the parallel deployment of a dedicated infrastructure. Without this infrastructure a ZEV is useless and vice versa. A further challenge comes from the fact that, given the high capital cost, the infrastructure should be developed in high density areas to maximize its utilization rate. But many such areas are much too small to generate a high enough volume of ZEV to decrease their production costs. This suggests that some coordination process across local deployments may be worthwhile.

Public policies to promote clean transportation typically do not consider these two issues jointly. Top down approaches for price rebates, fuel efficiency standards, mandates… are elaborated at the national level or EU levels (Anderson et al., 2016, Littlejohn and Probst, 2019). Bottom up approaches focus on specific geographic clusters in which the local actors elaborate ad hoc schemes to promote production, distribution and usages (mostly in transportation) of green energies (Meunier and Ponssard, 2018).

The potential benefit for coordinating these two approaches has been indirectly addressed in two recent papers. Zhou and Li (2018) empirically analyse BEV deployments in 353 US cities from 2011 to 2013. Using a calibrated model, they compare the actual national public policy with a contingent one. The national policy selects an identical rebate for all cities while the contingent one adapts it to each city depending on relevant local market characteristics such as the level of population, the average household income and education level, the price of gasoline... The public support is assumed to be budget constrained so that it will disappear after some time leaving the situation to market forces. Zhou and Li show that the 353 cities are spread across three configurations. More precisely in a first group of cities the local market is too limited so that the level of deployment will reverse to no BEV once the public support is gone. In the second group of cities a sustainable market will perdure, the public support had been enough to pass what is called a tipping point. In the third group of cities, a sustainable market would have emerged anyway, public support has been wasteful. The uniform policy is more expensive than the contingent one.

[3] The list of acronyms is at the end of the paper.

Meunier and Ponssard (2019) formalize the chicken and egg issue, namely the fact that infrastructure and cars are complementary goods. One objective of the model is to derive the optimal joint public subsidies for car rebates and retail stations depending on market characteristics. A context involving two markets is considered: the optimal set of subsidies is obtained under two configurations either autarky between areas or a global approach addressing the two markets with contingent policies. Using a numerical simulation, it is shown that the global approach significantly reduces the overall cost of public subsidies, allowing each market to benefit from the overall learning-by-doing effect.

Conceptually, the discussion about top down versus bottom up approaches can be related to the dichotomy between "comprehensive" versus "voluntary" approaches for international climate agreements (Morgenstern, 1991). The comprehensive approach favours agreements involving all parties and constraining policies. In a voluntary approach only a coalition of parties voluntarily coordinate their policies. These two approaches have been extensively discussed in the economic literature (for an early reference see Barrett, 1994). The efficiency of comprehensive approaches is limited by the lack of enforceability as demonstrated by the Kyoto protocol and more recently the Paris agreement. Voluntary approaches are self-enforceable, but the size of a stable coalition is typically very low. Still the Montreal protocol for the preservation of the ozone hole has demonstrated that under some circumstances combining both approaches, the initial size of the coalition may considerably be enlarged so that the whole process is quite efficient.[4] The ongoing collaboration of the C40 may be considered as a promising voluntary initiative for cities around the world to coordinate their efforts for addressing the climate change challenge.[5]

The objective of this paper is to empirically explore the potential benefit of combining the top down and bottom up approaches through a detailed case study. We have selected urban hydrogen fuel cell electric buses (FCEB) for the following reasons:

- Many city councils have been responding to the climate challenge by setting stringent objectives to decarbonize their transport system;
- Public transport (buses, rail, taxis …) is a significant share of total transport and this share is expected to increase;
- Urban buses are operated by public or private companies in which city councils are influential;
- The price of FCEB is currently much higher than diesel or battery only buses, which is a strong barrier to their diffusion.

Consequently, there are both positive and negative aspects to the promotion of FCEB. It turns out that the EU has been promoting this technology since the beginning of the 2000s. The originality of the recent policy, compared to the usual subsidy policies, is to combine a uniform rebate for the acquisition of FCEB with local conditions for being eligible for these rebates. Schematically these conditions relate to securing local support for the infrastructure, as well as commitment to a long term FCEB plan. Only a limited, but growing, number of European cities have joined the EU program, through a form of self-selection process.

[4] https://www.actu-environnement.com/media/pdf/news-32324-rapport.pdf
[5] https://www.c40.org/

The paper will provide an evaluation of the EU policy towards FCEB. How much cost decrease would be necessary to obtain an economically meaningful abatement cost for FCEB so as to justify the deployment of this technology. Will the JIVE programs achieve the goal of providing visibility to the OEM's to engage in a substantial cost reduction process? Will it provide the appropriate incentive for the cities to coordinate the local players: municipalities, operators of public transport, energy providers, to get access to appropriate financial support? What is the overall assessment of the EU scheme? How is the industry responding to this challenge?

Our analysis of the FCEB potential deployment in Europe and the associated EU policy relies on grey literature. It also builds on interviews with policy makers at various levels of authority (city council, regional, national and EU entities) and representatives from the hydrogen industry. Element Energy, a UK consulting firm in charge of monitoring the EU programs, provided detailed evaluation of these programs.

We also rely on the specialized academic literature on FCEB. Hua et al. (2014), summarizes the deployment and performance of FCEB in North America and Europe up to 2014. Stempien and Chan (2017) discusses the benefit of FCEB in Singapore through a detailed comparison of all pollutants for hydrogen, electric and diesel buses. Liu et al. (2018) cites the expected deployment of FCEB in Foshan and Yunfu (China) which expects to put 1000 buses and 20 HRS in operations in 2020 through the Synergy program.

The paper is organized as follows. Section 1 recalls the trend in urban transport towards zero emission in European cities and the role of FCEB. The cost analysis is continued in section 3. Section 4 provides an evaluation of the JIVE programs. A discussion of how the industry is responding to the challenge is given in section 5. Appendix 1 lists the main players in the FCEB market. Appendix 2 reviews some pending issues for the production, storage and delivery of hydrogen.

2. The FCEB market in Europe

2.1. The global demand, the role of cities and the trend towards zero emission buses (ZEB)

According to the *Europe Urban Bus Market Outlook Report 2017-2030*, the 2017 market size of the urban bus segment in terms of volume is estimated at 100,000 buses operating in 75 key cities in Europe. Of these, approximately 2% are hybrid/electric buses. In terms of value, the market value of buses in Europe ranges from \$ 28 billion to \$ 37 billion.[6] London, Paris, Madrid, Athens and Rome are the top five cities in terms of fleet size. These cities also have high population density and population levels.

The pressure to decarbonize urban buses comes from several sources. Urban buses are a component of heavy-duty vehicles which are the focus of recent EU regulation. From 2025 on, manufacturers will have to meet the targets set for the fleet-wide average CO2 emissions of their new lorries registered in a given calendar year. The targets are expressed as a percentage reduction of emissions compared

[6] https://www.researchandmarkets.com/reports/4432376/europe-urban-bus-market-outlook-report-2017-2030

to the EU average in the reference period (1 July 2019-30 June 2020): 15% reduction from 2025 onwards, 30% reduction from 2030 onwards.[7]

At the local level cities are adopting future targets to decarbonize public transportation. Table 1 gives the fleet size and the commitments made for the top five European cities in 2018.

City	Fleet size	Commitments
London	9 142	From 2020 all single decks in central London are zero-emissions and from 2025 ZE purchase policy extended to double deck buses.
Paris	6 700	From 2025 all diesel vehicles will be removed
Madrid	2 600	From 2025 all diesel vehicles will be removed
Athens	2 526	From 2025 all diesel vehicles will be removed
Rome	2 522	N/A

Table 1: Fleet size and commitments made of major European cities

The case of London

Former London Mayor, Boris Johnson, had set a target to reduce the city's carbon dioxide emissions by 60% of their 1990 level by 2025. His successor, Sadiq Khan, in his Mayor's Transport Strategy 2018, delivered his vision to improve air quality, which envisages among others that London's entire transport system will be zero emission by 2050. This includes delivering central London and town centre zero emission zones from 2025, creating a zero-emission zone in inner London by 2040 and a London-wide zone by 2050. Transport for London (TfL), the city's transit agency, is working towards the objective of the introduction of the Ultra-Low Emission Zone and the Toxicity Charge (T-Charge), using new alternatives to diesel buses, etc.

On the London City Hall's website[8], it was announced that "from next year, all new double-deck buses will be hybrid, electric or hydrogen to focus on only buying the greenest, cleanest buses." By 2037 at the latest, the Londoner zero-emission bus market will represent 9,200 buses across London.

Through the Healthy Streets Approach, the Mayor has provided support to his strategy to re-shape the bus network and meets the 2037 goal. This strategy includes 12 Low Emission Bus Zones and one Ultra Low Emission Zone (ULEZ). The introduction of Low Emission Bus Zones means deploying the greenest buses on the capital's most polluted routes to cut harmful nitrogen emissions. To further support the ULEZ, TfL will ensure all double-decker buses operating in the ULEZ will be hybrid and all single-decker buses will be fully electric or hydrogen.

The new greener buses, which will be a combination of hybrid and clean buses that meet Euro VI standards, are part of an improvement programme to 3,000 buses outside central London. Moreover, TfL will introduce more than 250 zero emission single-deck buses into central London by 2020.

In 2019 the fleet of buses and the commitments can be summarized as follows:

- Hybrid: over 3,000 diesel-electric hybrid buses, making up 30% of TfL's bus fleet.
- Over 150, 100% electric buses are part of the growing fleet of greener buses and from 2020 all new single deck buses entering the fleet will be zero emission at tailpipe. They will be a mix of hydrogen buses and electric buses.

[7] https://ec.europa.eu/clima/policies/transport/vehicles/heavy_en
[8] https://www.london.gov.uk/what-we-do/transport/green-transport

- In the future London wants to be a world leader in hydrogen and fuel cell activity. Currently, 10 hydrogen buses are operating in London, the city ordered 20 double decker fuel cell buses from Wrightbus in May 2019 – they will be delivered in 2020. This produced one of the lowest prices since development began on the technology (£500,000 each bus).
- Inner and outer London by 2030: 90% of single decks electric or hydrogen and 60% of double decks hybrid; 40% electric or hydrogen.

2.2. The prospective demand for FCEB

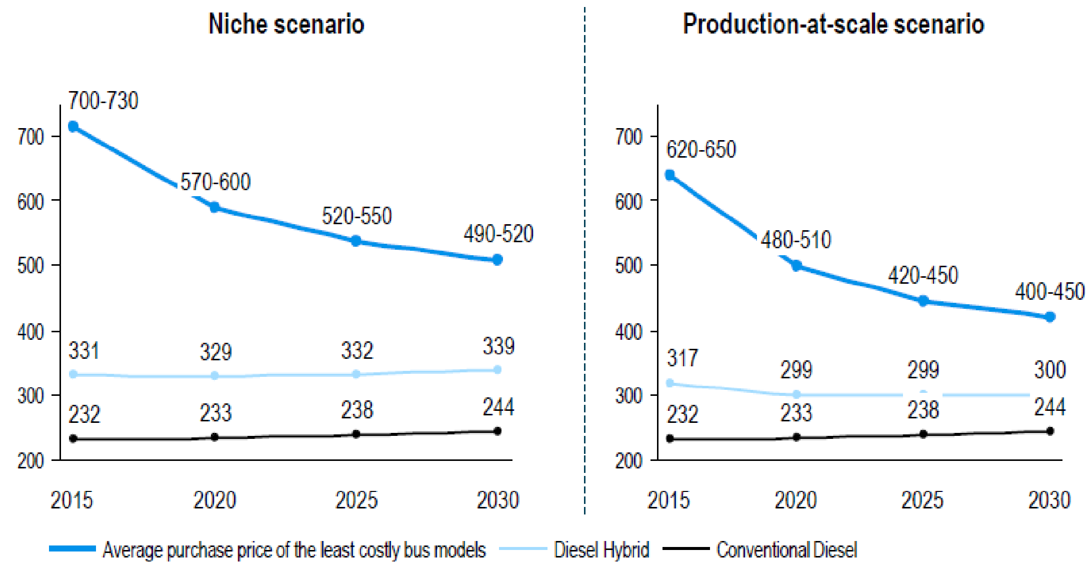
The two technologies which will be deployed in response to the general trend towards zero-emission buses in cities are battery electric buses (BEB) and Fuel cell electric buses (FCEB). These two technologies differ in several characteristics. We shall come back to cost issues shortly. The other main issues are summarized as follows:

- With a bus range of 450 km, FCEBs are well suited for cities with a mileage greater than 200 km.
- Demonstrations have taken place on challenging topographies, with or without heating / cooling systems on. FCEBs have been deployed in many different places with extreme weather conditions and unlike BEBs, the performance of FCEBs is not affected by weather conditions. They operate from -30°C to +50°C ambient temperature[9], without altering the autonomy, whereas such conditions can cause deep discharge cycles in BEBs.
- With fast refuelling and route flexibility, FCEBs don't affect bus operators' service or current operation processes, as no roadside infrastructure or change to operational processes is required. From a technology point of view, they are the easiest ZE transport to deploy, as they do not limit productivity and quality of service. On the contrary, opportunity-charging battery electric buses charge on-route and are tied to the specific route where chargers are located. Frequent compulsory charging can also cause schedule or operational issues.
- Refurbishing and recycling processes are easier for FCEBs. Rechargeable electric batteries (Li-ion, Ni-Zn, Ni-Cd) can also be recycled. Because of their electrical residual power that can cause fire or explosion, recycling those batteries is not an easy, energy-friendly process. Fuel cell stacks are easier to recycle. One of the biggest manufactuers, Ballard, certifies "the customer can return the fuel cell stack so that the membranes can be replaced while the existing hardware and plates are reused. "[..] More than 95% of the precious metals are reclaimed during this process. We refurbish and recycle 1000's of fuel cell stacks every year."[9] Ballard fuel cell stacks use no cobalt, lithium or rare earth materials.
- However, we must also take into consideration another key element that can negatively influence the market share of FCEBs: the social acceptance of the hydrogen

[9] Ballard, *Fuel Cell Electric Buses – Proven Performance and the Way Forward*, April 2019.

technology, which mostly depends on the public trust in hydrogen safety. Some passengers don't feel reassured with hydrogen storage in tanks on the roof of the bus.[10]

Altogether the FCEB market is expected to remain much lower than the BEB market. Two scenarios (volume and price) for the deployment of FCEB in Europe over the period 2015-2030 have been elaborated (Roland Berger, 2015).[11] A niche scenario and a production-at-scale scenario by 2025. The niche scenario is characterized by a cumulative number of 1,200-1,800 FCEB deployed on Europe's roads in total while the production-at-scale scenario is characterized by a cumulative volume of 8,000-10,000. According to Roland Berger, "the latter represents about 7-9% of the expected total cumulative urban bus purchases in Europe in the period 2015-2025". Figure 1 gives the corresponding projections for the purchase prices of FCEB over 2015-2030. It is expected to decrease to approximately €490k - €520k in the niche scenario and to €400k- €450k in the production-at-scale scenario. [12]



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- Figure 1: Purchase price of standard FCEB according to different scenarios [€ x10[3]].

3. Cost analysis, CO2 and local pollutants emissions

Based on these scenarios and other more recent data we can estimate the total cost of ownership (TCO) of FCEB versus BEB and diesel bus in 2018. The TCO is a convenient way to analyse the costs incurred by a durable good, using a discount rate for aggregating capital and operating costs. The TCO components can be divided into four categories:

- Acquisition cost (purchasing price)
- Maintenance & operating cost

[10] This has been subject of a significant amount of research. It would appear not to be as big a problem as once was thought; indeed, some might suggest not a problem at all. People generally just expect that the authorities will only provide safe vehicles for them to travel in.

[11] Roland Berger GmbH, *Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe, A Study for the Fuel Cells and Hydrogen Joint Undertaking*, September 2015

[12] Recently G. Topham, a specialised journalist for *the Guardian,* reported an order by London (TfL) of 20 hydrogen-powered double-decker buses with a unit price around €550,000.[12] This is consistent with the target price announced by Roland Berger for 2020 in the niche scenario

- Running cost (fuel cost)
- Disassembly cost (end-of-life cost)[13]

We use various sources to estimate the TCO of FCEB, BEB and diesel bus.[14] The results are summarized in Table 2 and reference the standard 12 m bus. The gap between the TCO of the clean technologies and the fossil one appears quite large.

TCO 2018 (€/km)	**FCB**	**Battery**	**Diesel**
Purchasing price	700 000	470 000	210 000
capex (10% discount rate)	***1,33***	***0,90***	***0,40***
maintenance	***0,40***	***0,80***	***0,30***
labor cost (10% discount rate)	***1,48***	***1,48***	***1,40***
energy price per unit	10,00	0,24	1,60
efficiency (unit/100km)	8,00	1,30	30,00
fuel (70 000 km/yr)	***0,80***	***0,31***	***0,48***
Total	**4,02**	**3,50**	**2,58**

Table 2: Estimates of the TCO for FCEB, BEB and diesel bus

Here are some details for the calculations:

- The purchasing price is annualized assuming a 12-year duration and a discount rate of 10%;
- Maintenance depends for the most part on variables such as the technology as well as vehicle age, duty cycle, topography or fleet maintenance practices; the corresponding numbers are global estimates;
- Labor cost are based on annual salaries over a 12-year duration and a discount rate of 10%
- Fuel costs are based on the unit price of the energy, the efficiency of the technology and the average yearly mileage for a bus.

The respective TCO can be used to derive the marginal abatement cost defined as the cost increase for reducing one-ton of CO2 emissions when a cleaner, presumably more costly, technology is substituted for a dirtier one.[15]

To apply this calculation to the substitution of diesel bus by BEB or FCEB one needs to compare the TCO and the CO2 emissions for each technology. [16] [17] Table 3 gives the result with different

[13] The disassembly cost will be assumed not to vary significantly between technologies and will be ignored. It actually might be cheaper for Electric Buses when compared with diesel buses.

[14]Roland Berger GmbH "Fuel Cell Electric Buses - Potential For Sustainable Public Transport In Europe", 2015. Ballard "Fuel Cell Electric Buses-Proven Performance and the Way Forward", 2019. Aber, "Electric bus analysis for the New York City Transit", 2016. Eudy, L., Post, M. 2019, *Fuel Cell Buses in U.S Transit Fleets: current status 2018,* National Renewable Energy Laboratory.

[15] This indicator has been extended to industrial items involving complex clean production processes such as offshore wind power or carbon, capture and sequestration. One may then order the different technologies by increasing abatement costs and infer the optimal launching date as the social cost of carbon increases (see for instance https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/sustainability/cost%20curve%20pdfs/pathways_lowcarbon_economy_version2.ashx).

[16] Source for FCEB and BEB emissions: Nylund, N-O, Koponen K. Fuel and Technology Alternatives for Buses – Overall Energy Efficiency and Emission Performance. VTT TECHNOLOGY 462012.

productions processes for H2 or the electricity used in batteries. The abatement costs for both technologies strongly suggest that neither of the two is worth implementing to reduce CO2 emissions.

Abatement cost €/tCO2	**FCB-SMR/diesel**	**FCB-RES/diesel**	**BEB-EUmix/diesel**	**BEB-RES/diesel**	*emissions gCO2/km*
gCO2/km	**320**	**0**	**720**	**0**	
€/tCO2	**1 594**	**1 177**	**1 824**	**749**	*1 222*

Table 3: Abatement costs for FCEB and BEB versus diesel bus

Note however that TCO and abatement costs are time dependent. They depend on the technologies available and on the "experience" accumulated at that time. It is noteworthy that "learning-by-doing" is a major factor that explains the decline in unit cost over time of new products so that the concept of TCO needs be used with care.[18]

To illustrate this point let us carry on some simple calculations. Firstly, we revisit the TCO and abatement cost for FCEB assuming a purchasing price of 450 k€ and a fuel cost of .56 €/km (corresponding to a H2 price of 7 €/kg), both assumptions in line with the production at scale scenario from Roland Berger (2015). The results are displayed Table 4. Even with these optimistic assumptions it remains unjustified to deploy FCEB to reduce CO2 emissions.

TCO FCB (€/km)	**2025**	**2018**
Purchasing price	450 000	700 000
capex (10% discount rate)	***0,86***	***1,33***
maintenance	***0,40***	***0,40***
labor cost (10% discount rate)	***1,48***	***1,48***
energy price per unit	7,0	10,0
efficiency (unit/100km)	8,0	8,0
fuel (70 000 km/yr)	***0,56***	***0,80***
Total	**3,30**	**4,02**
Abatement cost €/tCO2 in 2025	**FCB-SMR/diesel**	**FCB-RES/diesel**
gCO2/km	**320**	**0**
€/tCO2	**800**	**590**

Table 4: Target cost analysis for FCEB in 2025

Secondly, we introduce the impact of local pollutants that is, NOx and PM 2.5 emissions, and the respective social costs.[19] This increases the fuel cost of a diesel bus from .8 €/km to 1.02 €/km. We

[17] Source for diesel bus emissions: Mahmoud, M., Garnett, R., Ferguson, M., Kanaroglou, P., 2016. Electric buses: A review of alternative powertrains. Renewable & Sustainable Energy Review 62, 673-684, DOI: 10.1016/j.rser.2016.05.019

[18] See Creti et al. 2018 for a detailed analysis of this issue.

[19] The social costs of local pollutants are estimated through their impact on health. These costs could vary considerably depending on the area under consideration (from very high to very low density level of inhabitants, and the congestion levels of the traffic in the area). We have considered high density areas and used data reported in Stiempen and Chan 2017. The values fall within the bracket reported Quinet, 2013, page 45.

also increase the emission rate of a diesel bus from 1 222 to 2 880 gCO2/km. Then we revisit the CO2 abatement cost. The results are displayed Table 5. The abatement cost comes within a reasonable range as compared with the current social cost of carbon.

TCO 2025 (€/km)	**FCEB**		**Diesel**
Purchasing price	450 000		210 000
capex (10% discount rate)	***0,86***		***0,40***
maintenance	***0,40***		***0,30***
labor cost (10% discount rate)	***1,48***		***1,40***
energy price per unit	7,00		1,60
efficiency (unit/100km)	8,00		30,00
fuel (70 000 km/yr)	***0,56***		***1,02***
Total	**3,30**		**3,12**
Abatement cost €/tCO2	**FCB-SMR/diesel**	**FCB-RES/diesel**	*emissions gCO2/km*
gCO2/km	**320**	**0**	*2 880*
all other pollutants high	**69**	**62**	

Table 5: Target cost analysis for FCEB in 2025 with local pollutants

Thirdly, to get some feeling about the credibility of the 450 k€ target price we calculate the implied learning rate. Table 6 displays the accumulated production to be approximately in line with the expected production at scale scenario, gives the corresponding annual growth rate for the demand and the implied learning rate, namely 50% and 10 % respectively. An implied learning rate of 10 % may be achievable but the annual growth rate of 50 % for demand seems unrealistic. We apply the implied learning rate to the niche scenario (consistent with a 6% annual growth rate) which gets an estimate of approximately 520 k€ for the purchasing price in 2030, still a long way from a target price of 450 k€.

scenario		**prod at scale**	**niche**
year	**2018**	**2025**	**2030**
annual growth rate		50%	6%
production	165	2 819	332
cumulated	500	8 463	3 451
unit cost	700000	455 363	521 891
implied learning rate		**10%**	**10%**

Table 6: Implied learning rate for the target cost analysis for FCEB in 2025

This analysis points out clearly that a decrease in the cost of FCEBs is a prerequisite for its deployment to make economic sense.

4. The coordination schemes among European cities for FCEB

Over the years, the European Union has introduced new pieces of legislation to tackle transport challenges and meet its climate and energy targets. In addition, the EU has been a driver of hydrogen deployment programs, funded by European entities such as the Fuel Cell and Hydrogen Joint

Undertaking (FCH JU) or the EU Connecting Europe Facility (CEF). These programmes have been accompanied by a series of initiatives to bring together all stakeholders around the establishment of a low-carbon European bus system. This section will review these positive incentives the EU developed to deploy the hydrogen technology.

The programs will be classified according to a typology that relates which public policies are best suited to match the structural characteristics of each phase of deployment towards clean transportation. This ideal deployment would typically go through three successive phases: take-off, powering-up and cruising (Meunier and Ponssard, 2018). The take-off phase takes place in clusters through demonstration projects supported by local public-private partnerships and joint ventures between manufacturers and energy providers. Then the coordination among clusters is critical to move to the powering up phase to cash-in the benefit of learning-by-doing. Competition should be encouraged, and exclusive deals be eliminated while joint subsidies for infrastructure and vehicles remain necessary. Eventually subsidies are eliminated and market forces will allocate the available technologies to the relevant segments, this is what we call the cruising phase.

The FCEB deployment went through the take-off phase and we shall investigate whether it has now entered the powering-up phase.

4.1. The initial coordination schemes for demonstration projects

We have identified 6 major coordination schemes that have supported demonstration projects across European cities (CUTE, HyFLEET:CUTE, Clean Hydrogen for European Cities (CHIC), HIGHVLOCITY, HyTransit, 3Emotion). The first one emerged in 2001 and the latest one, which is still ongoing, in 2017. Table 7 gives the time span covered by each scheme, the cities that benefited, the total number of FCEBs involved, and the associated budget with the FCH JU part.

Coordination scheme	horizon	#FCEB	Cities	Funding Total/FCH-JU
CUTE	2001-2006	27	Reykjavik, London, Amsterdam, Porto, Madrid, Barcelona, Luxembourg, Stuttgart, Hamburg, Stockholm	
HyFLEET:CUTE	2006-2009	47	Amsterdam, Barcelona London, Luxemburg, Madrid, Hamburg, Berlin	43.16 M€
CHIC	2010-2016	26	London, Aargau, Bolzano, Milan, Oslo, Hamburg, Köln,	81,8M€ / 25,8M€
HIGHVLOCITY	2012-2019	14	Antwerp, Aberdeen, San Remo, Groningen	30M€ / 13M€
HyTransit	2013-2019	6	Scotland (Aberdeen)	£19M / £8,3M
3Emotion	2017-2022	21	Rotterdam, Aalborg, London, Roma, Versailles, Pau	39,2M€ / 14,9M€
Total		114		217M€

Table 7: The initial coordination schemes for take-off

We can see that these demonstration schemes took place in more than a dozen cities scattered all over Europe. Typically, such a project involved only a limited number of FCEBs and its goal was to demonstrate the feasibility of the deployment, to identify the possible challenges and avenues to solve them. The coordination between the deployment of the buses and the availability of the H2 production and delivery was also at stake.

A detailed evaluation of these programs has been made.[20] The following conclusions emerged:

- Successful tests on range, energy efficiency, CO2 emissions, bus availability and HRS access;
- Need to reduce prices to achieve commercialization;
- Need to increase social acceptability among regional stakeholders through adequate safety regulation and production of green hydrogen.

Table 8 gives in more detail, the technical and economic objectives of each scheme and provides an evaluation of its main achievements and pending issues.

Project	Objectives	Success/ Achievements	Lessons learnt
HyFLEET:CUTE	Develop fuel cell buses to reduce the consumption of fuel and energy in the whole transportation system -Develop efficient and sustainable ways to produce hydrogen -Inform the community and key decision-makers about the potential advantages of a hydrogen-based transport system	-more than 2,5 million km travelled -no accidents -Bus availability > 89% -Stations availability >90% -Share of renewable energy used for on-site H2 generation	-Optimizing existing FC buses for energy efficiency -Development and build of next generation of FCEB -Optimizing existing H2 refuelling systems for efficiency and reliability -Create a global hydrogen bus platform for dissemination and exchange of information, forum for debate, education of decision makers -Study the socio and macroeconomic implication of H2 technology -The purchase price of the buses must be significantly reduced to achieve commercialisation
CHIC	Demonstrate: -Operating range >350km -Short refuelling times (<10min) -High fuel efficiency (9kg/100km) for 12m buses -CO2 emissions reduced by 85% compared to diesel buses along the bus life cycle (green hydrogen)	-Operating range equivalent to that of diesel buses (>350km) -Refuelling time <10mins -Satisfaction for end users -6,800 tonnes of CO2 equivalent saved compared to diesel buses -Survey results show that CHIC regional stakeholders, bus drivers and passengers support the technology and a move to zero emission public transport	-Improve bus availability through resolving technical ‘teething’ issues and increasing scale -Reduce bus and hydrogen prices through commercialisation -Harmonise regulations -Importance of green hydrogen – social science research suggested, that hydrogen should be fully sustainable to be fully accepted by society
HIGH V.LO.City and HyTransit	-Increase energy efficiency of buses; -Reduce the total cost	-14 buses in full operation with >85% availability -97% availability of	- Ensure high availability of supply chain - HRS can easily be scaled up

[20] Source: Dolman and Skiker, Presentation of the JIVE Project, May 2019.

	of ownership; -Increase the life time of the fuel cells; -Reduce life cycle costs and more specifically the cost of hydrogen; -Define concrete economic early markets	stations -good customer acceptance -1.5million km driven -9-10 kg hydrogen per 100km	when the fleet is growing and should be located at the bus depot, more efficient if used at full capacity
3Emotion	-Reduce TCO, capex and fuel cost - (<10kg/100km) -Increase lifetime and warranties -Availability > 90%	On going	On going

Table 8: The objectives and achievements of the take-off schemes

4.2. The coordination schemes for the take-off phase: JIVE 1 and JIVE 2

Launched at the World Economic Forum 2017, in Davos, The Hydrogen Council involves 60 major companies. Its mission is to be: "a global initiative of leading energy, transport and industry companies with a united vision and long-term ambition for hydrogen to foster the energy transition". The year 2017 may be considered as a kick-off date for the large-scale commercialization of clean hydrogen solutions across industries world-wide.

Simultaneously, also in 2017, the European Commission launched the Clean Bus Deployment Initiative. This initiative is based on the following 3 pillars:[21]

1. *A public declaration* endorsing a common ambition of cities and manufacturers to accelerate roll-out of clean buses: The signatories commit to jointly deploy 2,000 clean buses by the end of 2019 in the EU
2. *Creating a deployment platform* where public authorities, public transport operators, manufacturers and financial organisations can come together with the aim to:
    - better exchange information,
    - better organize relevant actors and create coalitions,
    - leverage potential investment action,
    - issue recommendations on specific policy topics.
3. *Creation of an expert group* bringing together actors from the demand and supply side. This expert group will benefit from consolidated expertise on technological, financial and organisational issues.

In this favourable context two new schemes dedicated to FCEB were launched, labelled as the Joint Initiative for Hydrogen Vehicles across Europe (JIVE 1 and JIVE 2). Table 9 gives their main

[21] https://ec.europa.eu/transport/themes/urban/cleanbus_en

characteristics. It clearly appears that they have much larger targets than the demonstration programs.

Coordination scheme	horizon	#FCEB	Cities and regions	Funding Total/FCH-JU
JIVE 1	2017-2022	139	London, Birmingham, Aberdeen, Bolzano, Herning, Region Köln, Wuppertal, Region Rhein-Main	106 M€ / 32 M€
JIVE 2	2018-2023	152	Benelux, France, Germany North Italy, Northern and Eastern Europe, UK	225M€ / 25M€

Table 9: The JIVE coordination scheme for powering-up

The JIVE schemes are organized along administrative regional “clusters”. Each cluster coordinates the cities within its region. The management is carried out by associated existing organizations as follows:

- Benelux: Rebel (twynstra Gudde)
- UK: Element Energy
- France: Afhypac & Mobilité hydrogène France
- Germany/ Italy: Energy Engineers & hySolutions
- Northern/ Eastern Europe: Latvian Academy of Sciences

In each cluster, the JIVE coordinator entity will support the participating cities in the initial transition phase and give advice for a long-term FCEB deployment. More specifically, these missions involve:

- Increase the number of affiliated cities within the cluster;
- Support each affiliated city in its development plans for FCEB;
- Facilitate the analysis of their financing needs and the access to subsidies for the first wave of deployments;
- Provide advice and support for the corresponding procurement processes;
- Develop strategies for financing the future deployments beyond the current subsidised phase.

As of 2019 the five regions which cover all Europe (see Figure 2) operate under the overall coordination of Element Energy, an energy consultancy based in the UK, which directly reports to the FCH JU. Element Energy relies on partners (Thinkstep and PLANET) to carry out the performance assessment.

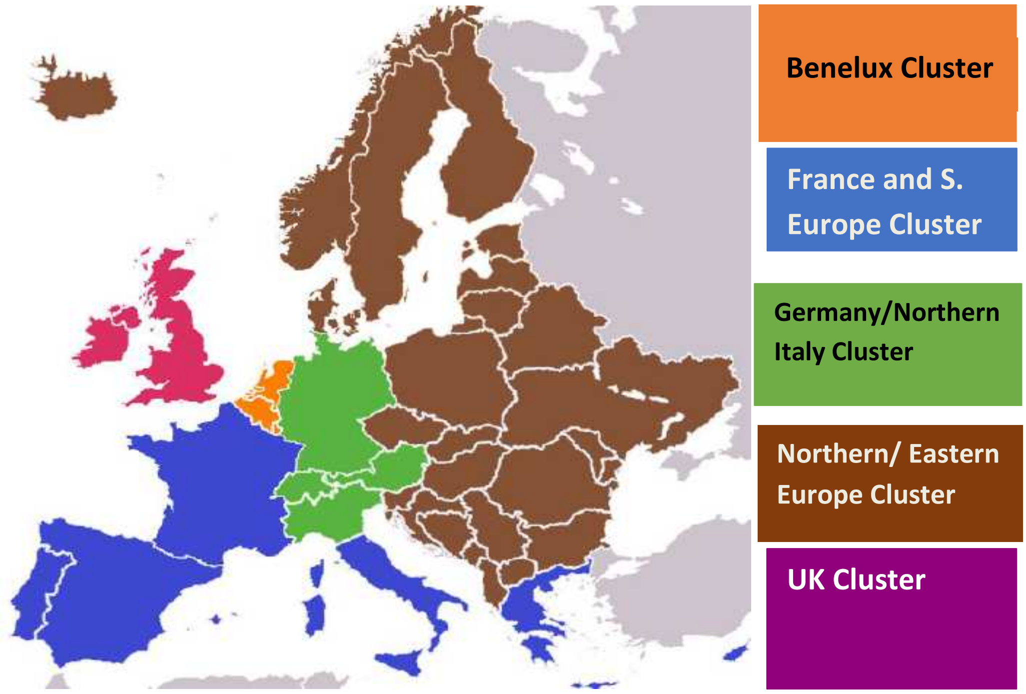

Figure 2: Cluster coordination and location as wished in the future

Moreover, JIVE 2 encourages new entrants in the FCEB market (industry suppliers and HRS) to stimulate technological innovation and large-scale uptake.

We now turn to the evaluation of JIVE.

5. Analysis of the JIVE[22] coordination schemes

The two questions of interest are the following:

- Is the JIVE/2[23] scheme an efficient self-selecting process to elicit the cities that are likely to pursue a sustainable FCEB deployment in the future and eliminate the cities only looking for a short-term financial wind fall profit;
    - in the former case one would expect that the JIVE/2 cities are indeed required to present and detail their plans for the future, in line with the project's work programme, in/after 2020;
    - furthermore, one would expect that these cities would have made earlier commitments to FCEB such as getting involved in demonstration programs and incurring some sunk costs for the provision of green hydrogen;

[22] The JIVE and JIVE2 projects have received funding from the Fuel Cells and Hydrogen Joint Undertaking under grant agreement No 735582 and 779563. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe Research.

[23] For notational simplicity JIVE/2 refers to JIVE and Jive 2.

    - finally, that the JIVE/2 program does provide potential benefits which override its constraints, for instance benefits in relation to the design of the procurements and participation in the exchange of information along the process.
- Is the JIVE/2 process successful enough in terms of volumes to generate substantial learning-by-doing returns leading to reduced prices of FCEBs in the near future?
    - JIVE provides monetary and non-monetary incentives, such as a flat 200 k€ subsidy for the acquisition of a FCEB and assistance to cities with their development plan for FCEB acquisition, their financing, the tender process… Are these incentives strong enough to generate the desired volumes; could these incentives have been designed differently?

Our answer to these questions is based on different sources:

- Quantitative analysis of questionnaires regularly handed out as part of the JIVE/2 process;[24]
- Interviews of representatives from AFHYPAC, Element Energy, EU Commission;
- Interviews of professionals: city officers, managers in companies operating along the value chain (OEMs, Energy providers…), specialized lawyers.

5.1. JIVE/2 as an efficient self-selecting process

Quantitative analysis of questionnaires

The answers have been classified under two categories:

- The reasons for being involved in clean transportation in general, in FCEB in particular, and in JIVE/2;
- The main benefits at this stage.

A total of 13 cities provided answers to the first item. The results detailed in Table 9 confirm that the cities involved in JIVE/2 have a long-term commitment towards clean transportation and FCEB, but joint commitments of their local and national Governments to this technology are a prerequisite. The absolutely vital importance of Government Policy Frameworks that incentivize or mandate Zero Emission public transport is a constant refrain when it comes to cities' willingness to find the funds to subsidize the new technology to encourage transport operators.[25] The cities engage in demonstration projects to gain experience in operating BEBs and/or FCEBs. In particular, they need confirmation of the credibility of both FCEB and HRS. Note that the current price of FCEB is a major concern.

[24] JIVE 1 and JIVE 2 information cited in this paper was gathered by PLANET GbR Engineering and Consulting, thinkstep AG and Fondazione Bruno Kessler on behalf of the JIVE 1 & JIVE 2 Projects. We are indebted to them for their assistance.

[25] The EU Clean Vehicles Directive as revised in spring of 2019 will also be a powerful driver. See https://ec.europa.eu/transport/themes/urban/vehicles/directive_en It requires that a certain share of vehicles bought by the public sector MUST be emission free and that, from 2026, this explicitly means battery or fuel cell electric only (0 g CO2 at the tailpipe).

For the second item we have 16 answers [out of 18 cities involved in the JIVE/2 projects. To date, the benefits from JIVE/2 are accruing through ‘best practice’ information gathered along three stages: Financing, Planning the HRS, Planning the Bus Operations. These results are detailed in Table 10. Access to better information about funding resources at all levels (EU, national including regional/local) is a major benefit for the cities. JIVE/2 also provides enhanced opportunities for exchanges with industry (HRS and bus operators) or with the experienced JIVE/2 project coordinator. Note also there are substantial benefits from exchanges (formal and informal) with other cities involved in JIVE/2 and the dissemination of information from earlier EU programs.

It should be noted however, that interviews suggest that the involvement of cities in JIVE/2 has not been a smooth road for all. Problems relating to sufficient/timely financing and poor industry response to tenders have led to significant delays. Long delays in demonstration projects cannot always be accommodated, while in cities without these constraints, an innovation such as this might be given the time it needs – but without the subsidies of the project environment.

JIVE also opens the opportunity for coordination between regions with experience of FCEB fleets deployments (e.g. Köln) as well as between regions seeking to build their knowledge and experience by demonstrating FC buses in small fleets (e.g. Auxerre, Gävleborg) as long as they commit to extend their fleets, if the initial demonstrations are successful.

Altogether there is a significant number of cities (7 out 18) engaged in JIVE/2 which had gained previous experience in FCEB through earlier EU programs (a striking example being London, see Table 6) while some others are using JIVE/2 to get into a demonstration stage building on the experience of early adopters.

What are the major reasons for the city involvement in clean transportation	
City looking for alternative to current public transport fuel options	77%
City wants cleaner air	62%
City committed to combatting climate change	46%
Part of the City’s general environmental programme	46%
Funds became available from sources outside city	46%

Why selecting FCB			**Is your involvement in FCB part of a national/local plan ?**		**What do you expect from JIVE**	
Will your transportation plan involve both BEB and FCB	100%		Does your national government support a wider deployment of fuel-cell buses?	88%	The refuelling technology will prove to be highly reliable and relatively maintenance free	62%
main drawback of FCB is higher price	77%		Does your local government support a wider deployment of fuel-cell buses?	69%	The bus technology will prove to be highly reliable and relatively maintenance free	54%
main advantage of FCB is range	54%				The city will have a clear idea of future public transport bus	54%
					The city will commit to a future hydrogen fuel cell bus technology in the short term	38%

Table 9: Cities ‘expectations from clean transportation, FCEB and the JIVE programs

What information did you find helpful?						
Financing			***Planning the HRS***		***Planning the Bus Operations***	
Knowledge of European sources of money	94%		Talking to HRS suppliers	94%	Talking to city sites with operating FC Buses	50%
Knowledge of National (including local/regional)	88%		Talking to city sites with operating HRS	75%	Talking to FC bus suppliers	50%
Previous experience in preparing funding proposals	75%		Talking to JIVE/JIVE 2 project coordinator	69%	Talking to JIVE/JIVE 2 project coordinator	44%
A local politician who was committed to the idea	69%		Written resources: NewBusFuel Reports	69%	Written resources: Reports from CHIC	44%
Working with another site to jointly seek finance	13%		Written resources: Reports from other ongoing or completed projects	50%		
			Written resources: Reports from CHIC	31%		

Table 10: Current stage of implementation and main benefits from JIVE

Additional information from cities not affiliated with JIVE/2 either from interviews conducted or from Dolman and Madden (2018) includes:

- EU funding only covers a part of the costs, without national, regional or private investments, it is impossible to commit to sufficient volumes. In the French cluster for example, some cities (Nantes, Rouen, Le Havre, Belfort) are waiting for a net FCEB price below 450 k€ and an effective strategy in place for vehicle maintenance. They will consider purchasing fuel cell buses after 2020.

- Paris is not a member of JIVE/2. RATP, which operates the urban buses, announced an ambitious plan of 4,500 bus renewal before 2025 with 80% electric and 20% CNG. In their ZE original plan FCEBs were not considered due to high costs. RATP considers that if an experiment with fuel cell buses occurs, the feasibility of a whole depot based on hydrogen (200 buses) must also be determined. Nevertheless, the bus routes in Paris have a mileage below 180 km, which is below the mileage suited to FCEBs (300 km). BEBs perform better on mileages below 200 km. So efforts are focused on deployment of this technology.

It can be observed that there is some geographic bias in the cities that benefited from JIVE/2. They are more likely to be part of the Northern clusters (UK, Benelux, Germany…) than the Southern ones (notably France). This problem arises mostly from the selection process for the participating cities. Element Energy organised a call to candidacy, to which the cities can respond within two/three months. This time period is particularly short, and disadvantages cities that are not related to important national OEMs committed to hydrogen (Figure 3 gives the distribution of OEMs among clusters). Van Hool, arguably the leading manufacturer of FCEBs as they get almost 90% of the European FCEBs orders, lobbies a lot of Belgian and Dutch cities, so that their candidacy documents are likely to be better prepared than those of the French cities, which are underrepresented in the project. However, this under representation can also be explained by a different level of maturity of the market between the countries. German, British, Dutch and Belgian cities had previous experiences with FCEBs, whereas France has only more recently shown interest.[26]

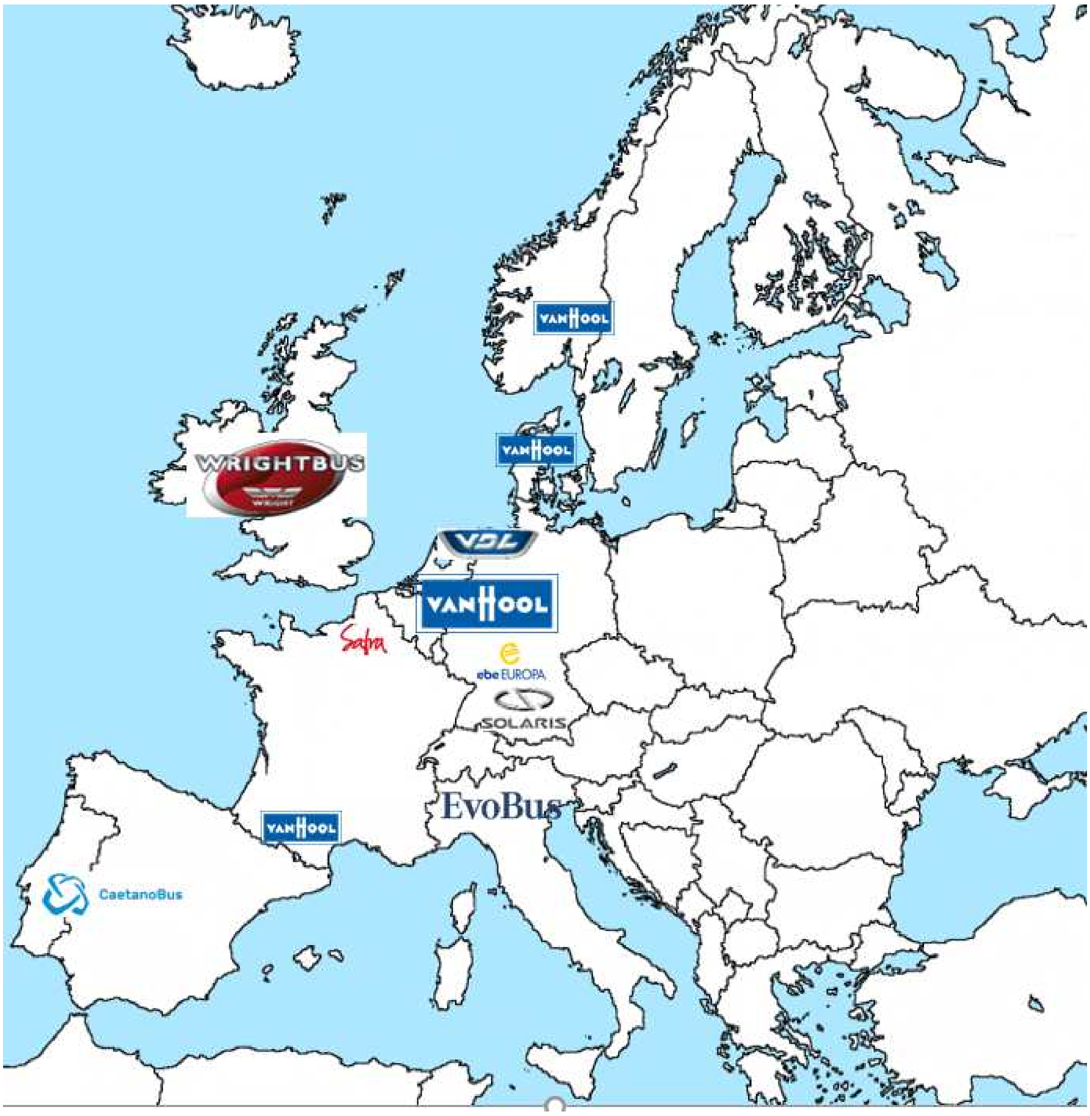

Figure 3: Distribution of European OEMs among JIVE/2 clusters

5.2. JIVE/2 as a scheme to trigger a high demand for FCEB

The level of the demand aggregated by JIVE/2 is detailed in Table 11.

Cluster	#FCEB in JIVE	#FCEB planned after 2020
Benelux	50	136

[26] The so called plan Hulot to deploy hydrogen for the energy transition announced on June 1 2018 provided a strong push for this technology https://www.ecologique-solidaire.gouv.fr/plan-hydrogene-outil-davenir-transition-energetique

France	15	49
Germany/Italy	88	177
N/E. Europe	50	147
UK	88	136
Total	291	645

Table 11: The level of demand directly induced by JIVE/2

Aggregation of the overall demand suggests about 1 000 FCEB to be deployed in the coming years as compared to only 114 FCEB for the demonstration programs. This number is substantial but remains closer to the niche scenario than to the production at scale scenario envisioned by the Roland Berger study (cf. section 2.2). This is confirmed by the observation that the price for standard 12 m single deck buses is expected to be around €650k / €625k in 2020. Still some suppliers have indicated far lower prices (e.g. well below €450k) for customers willing to commit to enough volumes (sustained orders of at least 100 buses per year per OEM).

Figure 4 depicts the relationship between the price evolution and the phasing of the different coordination projects implemented in Europe.[27]

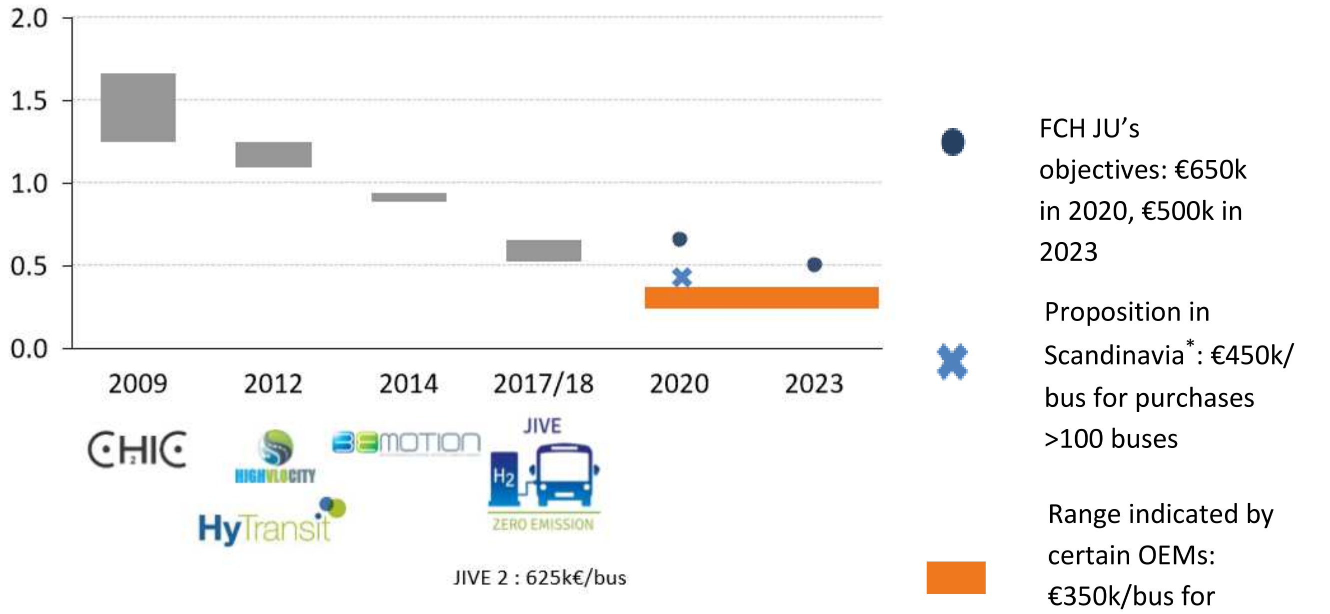

Figure 4: Capex evolution (in €M) for a standard FCEB (12 metre) in Europe without subsidy

Altogether it seems that the JIVE/2 program remains short relative to the objective of triggering a high enough demand, but this conclusion may be wrong. We may just be at the beginning of the powering-up phase and future programs may consolidate FCEB deployment. On the 3rd June 2019,

[27] *Fuel cell bus joint procurement clusters*, Element Energy Ltd, Nov 2017 in FCH JU Stakeholder Forum

*http://hydrogenvalley.dk/white-paper/

the latest deployment program H2Bus Consortium was announced by Everfuel, Wrightbus, Ballard Power Systems, Hexagon Composites, Nel Hydrogen and Ryse Hydrogen. Through this consortium, they are committed to deploying 1,000 FCEBs, along with supporting infrastructure in European cities. In the press release, we can read "the first phase of the project, totalling 600 buses, is supported by €40 million from European funding. This will enable the deployment of 200 hydrogen fuel cell electric buses and supporting infrastructure in each of Denmark, Latvia and the UK by 2023".[28] New EU programs are under way and will take the baton from JIVE. [29]

6. How is the industry responding to the challenge?

The FCEB value-added chain goes from the energy source to produce hydrogen to the assembly of buses. Schematically two segments can be distinguished: (i) production, storage and delivery of hydrogen to refuelling stations (HRS), (ii) production and assembly of bus components involving critical parts such as the fuel cell, the electric drive system and the hydrogen high pressure tank. In each segment the players come different from industry sectors with specific competitive advantages.

Namely for the first segment:

- Traditional fossil fuels producers such as Shell and Total
- Traditional gas producers such as Air Liquide, Linde, Pitpoint
- Traditional energy suppliers such as ENGIE

There are also new entrants which focus on recent advances in electrolysis such as AIR Products, Mc Phy, NEL as well as companies which focus on providing efficient retail stations such as Luxfer, Hydrogenics.

The situation is similar in the second segment:

- Traditional international OEMs with large portfolios such as Toyota, Hyundai, Yutong
- Traditional international OEMs especially active in bus production such as New Flyer, Van Hool.

There are also new entrants such as Caetanobus, EBE Europa, Rampini, Safra, Solaris, Wrigthbus which intend to expand worldwide from their national markets.

Most of these players rely on suppliers for the fuel cell, such as Ballard, Siemens Hydrogenics, and more recently Michelin through its acquisition of Symbio. A company such as Toyota is fully integrated in the sense that it produces its own fuel cells.

It is out of the scope of this paper to provide a systematic analysis of the competitive advantage of the players in this fragmented market.[30] Indeed the current market game is quite open and it is hard to see along which lines some consolidation will take place. Many players are attracted by the

[28] https://www.greencarcongress.com/2019/06/20190604-h2bus.html

[29] See for instance https://www.fch.europa.eu/news/fch-ju-launches-new-call-project-proposals

[30] The competitive analysis should take a world perspective and give due consideration to the developments in China, see for instance Liu et al., 2018.

emerging, potentially highly profitable market associated with green hydrogen. Appendix 1 gives an incomplete panorama of the firms involved with their main geographic markets in FCEB.

We conclude our industry analysis by briefly reviewing the components of the value added chain that may justify a decreasing trend in the costs.

Acquisition cost

Figure 5 give the relative share of the cost components over the period 2016-2020. Since the early deployments in the 1990s, purchasing price for FCEB have fallen by more than 75%.

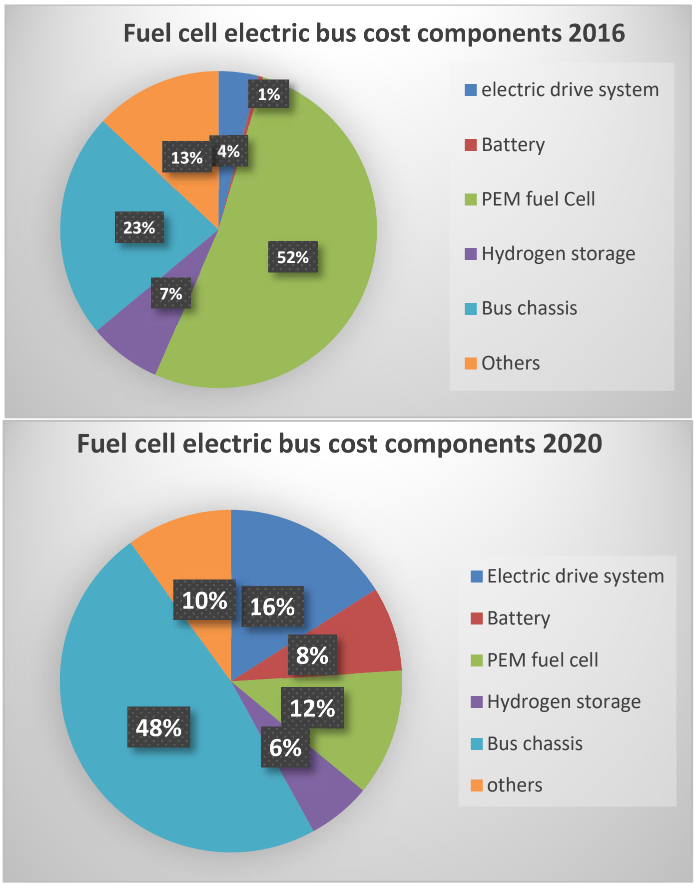

Figure 5. The relative capital cost components of a FCEB

In 2016, the PEM fuel cell comprised about half the cost of a FCEB, but in the projections for 2020, the fuel cell comprises only 13% of the price. This difference is partly due to the rapid evolution of the fuel cell and hydrogen technologies.[31] Another reason is that the fuel cell used in the 2020 projections is only 60kW, whereas in the 2016 costs, the fuel cell used in FCEB are mostly about 100kW. While future costs can be expected to decrease the price tag will still include certain expensive materials necessary for operation of the current technology like the platinum catalyst within the fuel cell stack. In 2020, the price of a FCEB is expected to be below 500,000€.

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[31] Ballard's announced in 2019 that its "next generation of products will reduce fuel cell module volume by 40% and weight by 30% from current versions, reducing constraints and cost around vehicle integration". Actually, "improvement in system integration and volume procurement is driving the price of fuel cell power module towards €1/ Watt" assures Ballard. *Fuel Cell Electric Buses: an attractive value proposition for zero-emission buses in the United Kingdom,* Ballard, November 2016

Maintenance and operating costs

Over time, wear and tear of materials will degrade the performance of the fuel cells. This slow and predictive process will require the fuel cell stack to be re-furbished once during the 12-14-year life of the fuel cell buses. Currently, the cost to refurbish the Ballard's fuel cell stack, FCveloCity®, is €27,000. This cost will be further reduced with the next generation fuel cell power module which will be introduced in 2019.[32] Other maintenance costs involve the replacement of the conventional parts and the maintenance of other powertrain components.

The forecast for 2025 is that the maintenance cost for FCEBs and diesel buses will be aligned, due to increasing volume of FCEBs.

Running cost: fuel production cost

Fuel production cost

The fuel production cost depends on the method used. Steam Methane Reforming (SMR) is a well-developed process in which the cost of hydrogen production is highly dependent on the cost of natural gas. SMR cost is estimated between 1.5€ and 2.5€/kg. To decarbonize the process, the cost can reach 3€ to 4.5€/kg. This process is particularly used to produce large volumes of hydrogen.

The cost of hydrogen produced by electrolysis is determined by the electricity cost, which depends on its production mode (emission-free or not) and the size of the production unit. If we consider that electrolysers have access to relatively cheap bulk electricity, (e.g. €70/MWh), the final cost of hydrogen produced by electrolysis is around €3.7/kg. This cost is very sensitive to electricity prices. Unlike SMR, this process is generally used to produce small volumes of hydrogen.

The price of hydrogen from SMR is currently approximately 20% lower than hydrogen from electrolysis. SMR will play some role in the early years of deployments of FCEBs. In the coming years, SMR is to be replaced by hydrogen produced from electrolysis with renewable energy sources of electricity. Some key suppliers have already installed on-site hydrogen production through electrolysis directly at the hydrogen refuelling station.

Fuel price

For each production option, off-site production with SMR and on-site production with electrolysis, on-site hydrogen storage and refuelling infrastructure are required. Including hydrogen refuelling station costs in the fuel price, the current hydrogen price is approximately €10/kg. The mass-market targeted price is between €6 and €8/kg.

Fuel consumption

The actual hydrogen fuel consumption of FCEBs depends on the bus operation. It should take into account the passenger load, route, speed and heating and cooling requirements. On a flat route around 5kg of H_2/100 km is required to power the bus electric drivetrain. The addition of an auxiliary load, such as heating or cooling and routes topologies, will increase fuel consumption up to 7.5kg of

[32] Ballard concludes its most recent study as "Based on an average of 75,000 km per year and a 12-year bus life time, the fuel cell power module total life maintenance cost is expected to be around €0.15/km, considering preventive and corrective maintenance." Fuel Cell Electric Buses-proven Performance and the way Forward, Ballard, April 2019.

H_2/100 km.[33] Current generation of fuel cell electric buses have demonstrated an average fuel consumption of around 8kg of H_2/100km.

References

Anderson, S., Fischer, C. and Egorenkov, A (2016) Overlapping strategies for reducing carbon emissions from the personal transportation sector, Energy and Climate Conference 14-15 October CESifo, Munich.

Ballard, 2017, *Economic Case for Hydrogen Buses in Europe.* https://cdn2.hubspot.net/hubfs/2007428/Premium%20Content/Economic%20Case%20Hydrogen%20Buses%20Europe/PT-Ballard-Fuel-Cell-Buses-in-Europe-Summary.pdf

Barrett, S. 2018, Climate treaties and the imperative of enforcement, *Oxford Review of Economic Policy*, 24-2, 239–258

Barrett, S. 2014, *Why have climate negotiations proved so disappointing?* www.pas.va/content/dam/accademia/pdf/es41/es41-barrett.pdf

Creti, A., Kotelnikova,A., Meunier, G and Ponssard, J-P. 2018. Defining the Abatement Cost in Presence of Learning-by-doing: Application to the Fuel Cell Electric Vehicle. *Environ Resource Econ*, *71(3), 777-800 (2018).* https://doi.org/10.1007/s10640-017-0183-y

Dolman, M., Skiker, S., 2017, *Fuel cell buses: a flexible and zero emission public transport – Fuel cell buses in Europe* https://www.fch.europa.eu/sites/default/files/selection.pdf

Dolman, M., Skiker, S., 2019, *Presentation of the JIVE Project – Joint Initiative for hydrogen vehicles across Europe,* https://www.fch.europa.eu/sites/default/files/documents/ga2011/4_Session%201_JIVE_Michael%20Dolman%20%28ID%204811591%29.pdf

Dolman, M. Madden, B., 2018, *Strategies for joint procurement of fuel cell buses – a study for the FCH JU,* https://www.fch.europa.eu/sites/default/files/Strategies_%20for_joint_procurement_of_FCEBuses_final_report.pdf

Elshurafa A. M., Albardi S. R., Bigerna, S., Bollino, C., A. 2018. Estimating the learning curve of solar PV balance–of–system for over 20 countries: Implications and policy recommendations, *Journal of Cleaner Production*, Volume 196, 122-134.

Eudy, L., Post, M. 2019, *Fuel Cell Buses in U.S Transit Fleets: current status 2018,* National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy19osti/72208.pdf

[33] *Fuel Cell Electric Buses – Proven Performance and the Way Forward*, Ballard, April 2019, https://info.ballard.com/fuel-cell-electric-buses-proven-performance-white-paper

Frost and Sullivan. 2013, *Strategic Analysis of Global Hybrid and Electric Heavy-Duty Transit Bus Market* (NC7C-01). Frost & Sullivan Publication. https://fr.slideshare.net/FrostandSullivan/strategic-analysis-of-global-hybrid-and-electric-heavy-duty-transit-bus-market

Hua T, Ahluwalia R, Eudy L, Singer G, Jermer B, Asselin-Miller N, Wessel S, Patterson T, Marcinkoski J, 2014, Status of hydrogen fuel cell electric buses worldwide, Journal of Power Sources, 269, 975-993.

Littlejohn, C., and Probst, S., 2019, What Role for Electric Vehicles in the Decarbonization of the Car Transport Sector in Europe?, CESifo Working Paper Series 7789, CESifo Group Munich.

Liu, Z., Kendall, K., Yan X., 2018, China Progress on Renewable Energy Vehicles: Fuel Cells, Hydrogen and Battery Hybrid Vehicles, *Energies,* 12, 54, 1-10.

Mahmoud, M., Garnett, R., Ferguson, M., Kanaroglou, P., 2016. Electric buses: A review of alternative powertrains. *Renewable & Sustainable Energy Review* 62, 673-684, DOI: 10.1016/j.rser.2016.05.01

Meunier, G., Ponssard, JP., 2018, What policy should be adopted to encourage deployment of hydrogen vehicles in France? http://www.chair-energy-prosperity.org/en/publications-2/politique-encourager-deploiement-vehicules-a-hydrogene-france/

Meunier, G., Ponssard, JP., 2019, Optimal Policy and Network Effects for the Deployment of Zero Emission Vehicles,
https://www.researchgate.net/publication/334041717_Optimal_Policy_and_Network_Effects_for_the_Deployment_of_Zero_Emission_Vehicles

Morgenstern, R. D., 1991, Towards a Comprehensive Approach to Global Climate Change Mitigation *The American Economic Review* Vol. 81, No. 2, 140-145.

Nylund N-O, Koponen K. 2012, Fuel and Technology Alternatives for Buses – Overall Energy Efficiency and Emission Performance. https://www.vtt.fi/inf/pdf/technology/2012/T46.pdf

Quinet E., 2013, L'évaluation socioéconomique des investissements publics, Tome 1, page 45.

Reuter, B., Faltenbacher, M., Schuller, O., Whitehouse, N., Whitehouse, S., 2017, *New Bus ReFuelling for European Hydrogen Bus Depots*

http://newbusfuel.eu/wp-content/uploads/2017/03/NewBusFuel_D4.2_High-level-techno-economic-summary-report_final.pdf

Roland Berger GmbH, 2015, *Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe,* A Study for the Fuel Cells and Hydrogen Joint Undertaking,
https://www.fch.europa.eu/sites/default/files/150909_FINAL_Bus_Study_Report_OUT_0.PDF

Stempien J.P., Chan S.H , 2017, *Comparative study of fuel cell, battery and hybrid buses for renewable energy constrained areas*, Journal of Power Sources 340, 347-335.

Transport & Environment, 2018*, Electric buses arrive on time*
https://www.transportenvironment.org/publications/electric-buses-arrive-time

Zhou, Y. and Li, S. (2018). Technology adoption and critical mass: The case of the us electric vehicle market, The Journal of Industrial Economics 66(2): 423-480.

Acronyms

BEB = Battery Electric Bus

CEF EU = Connecting Europe Facility

FCEB = Fuel Cell Electric Bus

FCEV = Fuel Cell Electric Vehicle

FCH JU = Fuel Cell and Hydrogen Joint Undertaking

HRS = Hydrogen Refuelling Station

JIVE = Joint Initiative for hydrogen Vehicle across Europe

OEM = Original Equipment Manufacturer

PEM =Proton Exchange Membrane

SMR= Steam Methane Reforming

TCO = Total Cost of Ownership

ZEV = Zero Emission Vehicle

ZE = Zero Emission

Appendix 1: The main players for the FCEB market

The production, storage and delivery of hydrogen

From the energy source to produce hydrogen to its storage in the bus roof tanks, here is an overview of the fuel cell electric bus supply chain.[34]

[34] *Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe, A Study for the Fuel Cells and Hydrogen Joint Undertaking*, Roland Berger, September 2015

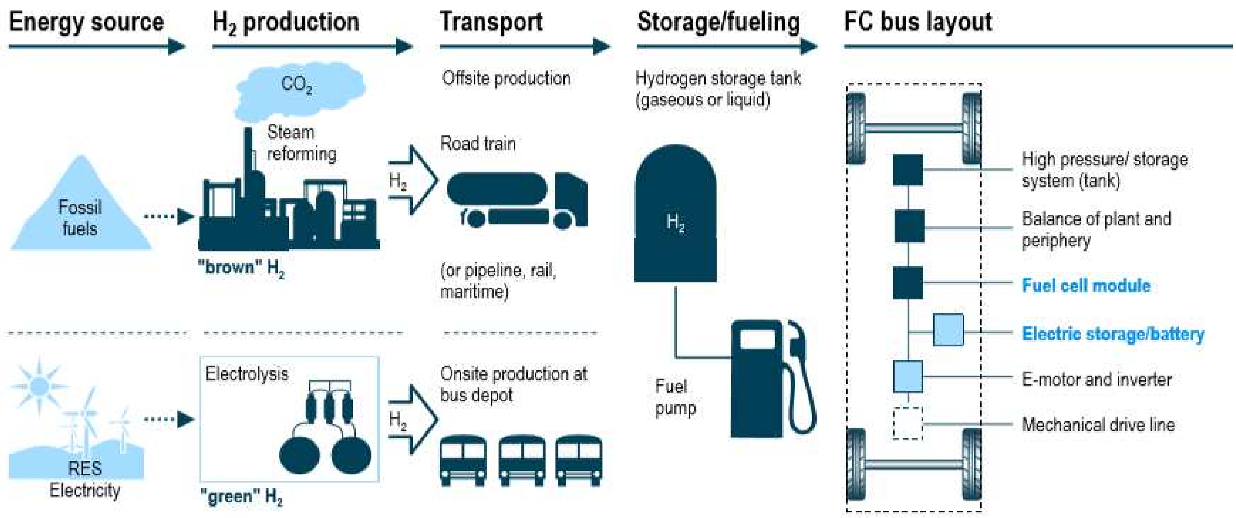

Figure 7: Hydrogen value chain and FCEB layout

Hydrogen can either be produced onsite or offsite and then delivered via tanker or pipeline in either gaseous or liquid form. Off-site production includes large-scale hydrogen production, as well as facilities where hydrogen is produced as a by-product. Hydrogen refuelling stations (HRS) are used for transferring hydrogen from stationary H2 storages to on-board vehicle storage tanks to be used as a fuel in a FCEB"[35]. These stations can be configured in different ways, depending on the source of hydrogen.

Currently, there is a total of 152 HRS, distributed over 14 European countries. With 60 hydrogen stations, Germany is the leading country in Europe.

The production of HRS as an industrial process remain subject to a few technological, economic and legal issues. These issues are summarized in the appendix 2.

The main suppliers for production, storage and delivery of hydrogen

	Relevant experiences/ Facts	Places where HRS are installed
INTERNATIONAL LEVEL		
AIR LIQUIDE Creative Oxygen **(FR)**	Designed and installed over 100 H_2 stations around the world. Part of the H_2 mobility consortium, SWARM consortium	Saga, Aalborg, Dubai, Copenhagen, Düsseldorf, Rotterdam, Aargau Paris, Oslo, Kawasaki, Tokyo, Los Angeles, Whistler in Canada
AIR PRODUCTS **(BE)**	Offer an extensive patent portfolio in hydrogen dispensing technology and involved in over 200 hydrogen fueling projects in the United States and 20 countries worldwide, including China (*SmartFuel* station)	London, Cologne, California, Texas, Pennsylvania, Florida, Missouri, Illinois, Washington, Tennessee, Beijing (chosen to support China's first, commercial-scale liquid hydrogen-based fuelling station)
THE LINDE GROUP Linde **(DE)**	Build the largest HRS in the UK (Abeerdeen) and one of the most powerful HRS with a capacity of up to 200kg/h in Berlin	Aberdeen, Milan, Bolzano, Arlanda Airport in Stockholm, Hamburg, Berlin and Munich, Vienna, Amagasaki City in Japan, Shanghai Anting in China + USA

[35] *New Bus ReFuelling for European Hydrogen Bus Depots,* B. Reuter, M. Faltenbacher, O. Schuller, N. Whitehouse, S. Whitehouse, March 15th 2017

Shell (UK-NE)	In Germany, Shell is part of a joint venture with industrial gas manufacturers Air Liquide and Linde, car manufacturer Daimler and energy companies Total and OMV, to develop a nationwide network of 400 hydrogen refuelling stations for new hydrogen car models by 2023.	Cobham, Beaconsfield (Southeast of England) The Netherlands, Germany (Frankfurt, Berlin Los Angeles, Citrus Heights (California), Vancouver
LUXFER (UK)	Luxfer's G-Stor H2 products are the leading line of lightweight high-pressure hydrogen-storage cylinders used by OEMs to manufacture compressed hydrogen-storage systems for fuel-cell electric vehicles.	Europe, Australia, India, Russia, New Zealand
HYDROGENICS SHIFT POWER | ENERGIZE YOUR WORLD (Canada)	Global provider of H_2 fuelling stations (HySTAT™) and fuel cell systems. Participated in the CUTE program, deliver first green Hydrogen production station to New Zealand, and world's largest Hydrogen electrolysis plant in Canada	Dunkerque, Hamburg, Stuttgart, Brussels, Istanbul, Oslo, Brügg (Switzerland), Los Angeles + Barcelona, Stockholm and Amsterdam for CUTE
NATIONAL LEVEL		
PITPOINT CLEAN FUELS (NE)	International provider of clean fuels. Design, build, and operate service public or private fuelling stations for LNG, CNG, bio-methane, hydrogen, as well as electric charging points.	Chemie Park Delfzijl in the Netherlands
McPhy Driving clean energy Forward (FR)	Designed, manufactured and integrated the first hydrogen system in France, combining an innovative high energy-efficient electrolyser with a hydrogen station with a capacity of 40 kg per day.	Sarreguemines, Rovaltain (France) Ivry-sur-Seine (inaugurated during the COP21) Berlin Airport
engie (FR)	Will supervise through its subsidiary GNVERT the construction and exploitation of HRS for the first hydrogen bus line in France (Pau). Founder member of the H hydrogen Council. Inaugurated the first multi-fuel station in France	Pau, Rungis International Market, Member of the Rhône Alpes H2 plan
Everfuel (DK)	Establishes green hydrogen distribution – and production operations, installs and operates HRS directly at bus depots. Member of the consortium H2bus.	
nel (NO)	hydrogen company delivering technologies to produce (electrolysers), store and distribute energy. Member of the consortium H2bus.	

Fig8: Non exhaustive list of hydrogen supplier and HRS manufacturer

The manufacturing of fuel cell buses and the main players

Only a limited number of European OEM committed resources to the FC bus market. Bus suppliers had to respond to changing requirements in the global market over the past decade, for example with the introduction of increasingly stringent European emission standards, demands for hybrid vehicles (of various types), other alternative fuels, and fully zero emission buses. In this context, battery electric buses have emerged as the favoured zero emission technology for some OEMs and fuel cell buses are perceived as a few years behind in terms of commercial readiness, due to the current high cost of fuel cell drivetrain components and uncertainties around the fuelling infrastructure.[36]

It is worth detailling the components of a FC bus.

Components of a FC bus[37]

Bus Chassis

The body style of FCEBs are very similar to traditional buses. The composition of the bus frame often depends on the proposed application and route for the bus being manufactured. Generally, frames are comprised of a mixture of stainless steel, carbon steel, and various aluminium alloys. Bus manufacturers are responsible for designing, building and servicing the buses based on the contract with operators.

Electric Drive System

An electric drive system converts electrical energy into mechanical motion. Within a fuel cell hybrid bus, the principal aim of the electric drive system is to control the energy transfer from the fuel cell and battery with maximum efficiency. The electric motor, as well as all other electric accessories contained in the vehicle (the communication and computer systems, the lighting, etc) operate with electricity delivered by the fuel cell.

Sensors and software monitor the drive system to ensure that it properly integrates fuel cell and battery operation, that it functions efficiently and that it relays safety information to the driver. The software system and the inverter coupled to the electric motor are particularly fundamentals device in the FCEB layout. The software system plays a central role as it communicates within the electric drive system and manages the electrical load to respond to the changing power requirements of the electric motor.

In the fuel cell hybrid bus industry, the two most prominent electric drive system integrators are Siemens and BAE.

Proton Exchange Membrane Fuel Cell

The leading fuel cell type for automotive applications is the Proton Exchange Membrane (PEM), also called Polymer Electrolyte Membrane fuel cell (PEMFC), because it deploys a solid polymer membrane sandwiched between an anode and a cathode. Its quick startup time, low operating temperature and good power-to-weight ratio make it an appropriate fuel cell for transportation. Moreover, PEM fuel cells only require a supply of pure hydrogen, ambient air and a method to remove the waste heat generated by the cells' electrochemical reactions. The PEM fuel cell has many subcomponents, including bipolar plates, catalysts, gas diffusion layers and membrane electrode assemblies (MEA) which is its most critical component.

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[36] The NewBusFuel project collects engineering studies on large-scale hydrogen refuelling at bus depot to define optimal designs, hydrogen supply routes, commercial arrangements and practicalities for HRS capable of providing fuel to fleets of fuel cell buses (75–260 buses). Source: New Bus ReFuelling For European Hydrogen Bus Depots, Guidance Document on large scale hydrogen bus refuelling, B. Reuter, March 15th 2017

[37] Hydrogen storage tanks, balance of plant which includes the software managing the energy system…

The main players

European OEMs	Production sites	Relevant experience/ product[38]	Clients for FCEB (non-exhaustive)
INTERNATIONAL LEVEL			
ALEXANDER DENNIS **(UK)**	UK, Germany, Hong-Kong, Singapore, Malaysia, New Zealand, Mexico, USA, Canada	hydrogen-powered Enviro400 double deck	
EvoBus **(DE)**	Germany, France, Spain, Czech Republic	Demonstrated 17 FCEB in the CHIC project, tens of FC bus produced to date.	Aargau, Bolzano, Hamburg, Milan
VAN HOOL **(BE)**	Belgium	Market Leader, more than 40 FCEB operating in Europe (since 2007) and the US (since 2005). About to deliver 30 buses for Köln and 10 for Wuppertal (largest order for FCEB in Europe). New A330 FC hydrogen bus **+** Van Hool Exqui.City 18 FC bus, which will be on the road from the end of 2019 in Pau, France => the first BRT system in Europe running on hydrogen.	Köln, Wuppertal (JIVE 2) Pau Aalborg (Denmark) RET in Rotterdam Oslo
VDL **(NL)**	The Netherlands	Delivered the first 18-metre FCEB, named Phileas, to Köln and Amsterdam	Amsterdam, RVK in Köln, Eindhoven, Riga
NATIONAL LEVEL			
rampini **(IT)**	Italy	Built the "H80" FC Bus in 2007. Plans to produce tens of FCEB over the coming years	
ebe EUROPA **(DE)**	Germany	"Blue City Bus" (10, 12 and 18 m)	ÖPNV Deutschland (Wiesbaden, Mainz and Frankfurt am Main)
Safra **(FR)**	France	Developing an FC version of plug-in hybrid electric buses of the "businova" platform (10.5 – 12 m)	Arthois-en-Gohelle
SOLARIS **(PL)**	Poland	Solaris Urbino 12 H_2, the continuation and development of two articulated electric buses (Solaris Urbino 18,75) powered with H_2 fuel cells as range extenders, should be released in 2019	Hamburg (CHIC project)
SOLBUS **(PL)**	Poland	First FCEB delivered to Syntus (Dutch bus operator) in mid-2016	Syntus
WRIGHTBUS **(UK)**	Northern Ireland	Single and double deck FCEB available for order from 2017: StreetDeck FCEV. Order of 20 buses from TfL	London (CHIC project & JIVE), Brighton, Birmingham, Aberdeen (JIVE)
CAETANOBUS GRUPO SALVADOR CAETANO **(PT)**	Portugal	Received fuel cell systems from Toyota with the aim to become the first company in Europe to implement the Toyota technology. First FCEB will deploy in autumn 2019	

[38] *Zero emission public transport – Fuel cell buses in Europe*, Element Energy Ltd, September 2017

Fig.9 Non exhaustive list of EuropeanFCEB manufacturers

Non-European OEMS	NEW FLYER (Canada)	TOYOTA (Japan)	HYUNDAI (South Korea)	TATA (India)	YUTONG (China)

Fig.9 Non exhaustive list of Non-European FCEB manufacturers

	International Position	Relevant experiences/ products	Clients
BALLARD **(Canada)**	Canada, USA, China, Mexico, Europe (UK, Denmark, Norway, Belgium, Germany)	Leading global provider of fuel cell solutions through Heavy Duty Modules (FCveloCity), Fuel Cell Stack (FCgen, FCvelocity)	Daimler, Solaris, Van Hool, Wrightbus in Europe, New Flyer,ElDorado in the USA, King Long, Yinlong & Feichi in China, Toyota in Japan, ..
elringklinger **(DE)**	Germany, France, India, South Korea, Spain, Turkey	produces metallic bipolar plates, casings, end and media modules for PEM	
SIEMENS **(DE)**	Europe (Germany, Denmark, Austria, Rumania, France), Canada, China, India, USA	Developed the SILYZER portfolio, a PEM electrolysis using wind and solar energy + part of Hydrogen Mobility Europe	Leading 3 projects: H2Future in Austria, HY4LL in France and NEWBUSFUEL in the UK
PM Fuel Cells · Power Systems **(DE)**	Germany	Produces HyRange®-extender for battery-electric commercial vehicles and buses. Committed with Skoda Electric to develop at least ten FCEBs (using the HyRange system) per year from 2020.	

Fig.10: non exhaustive list of key sub suppliers

Appendix 2: Some pending issues for the production, storage and delivery of hydrogen

Optimal pressure

Refuelling many buses, typically with storage tank sizes of 30 – 50 kg of H2, requires significantly more hydrogen than refuelling passenger vehicles that usually carry about 5 kg of H2. Moreover, FCEB can carry more weight and greater volumes than light-duty vehicle. This means that the on-board hydrogen storage for buses commonly operates on a lower pressure level than the one for passenger cars. Two standards dispensing pressures have been adopted globally, 350 bar for buses and 700 bar for cars. The lower pressure provides several advantages as it reduces cost and increases overall reliability. Hydrogen compression up to 700 bars requires more energy than the compression up to 350 bars and is more costly.

Hydrogen storage

Hydrogen storage is necessary to balance the hydrogen supply, both from on-site or off-site production, and the hydrogen demand. The size of a storage decreases, and the cost of the station increases as gaseous hydrogen is stored at higher pressure levels. Two main storage concepts are used currently: the constant pressure storage and the cascade storage which uses overflow filling from different pressure banks. Optimizing these technologies implies, among others, using the entire amount of hydrogen in the storage without requiring any storage overcapacities. Another important challenge is that the lifetime of a storage tank is limited by a maximum number of pressure load changes. To increase the lifetime of the hydrogen storage, additional overcapacities may be installed in order to reduce the pressure load variation within the storage[39]. To date, the maximum refuelling capacity is for about 10 FCEBs[11].

Refuelling process and dispenser

During the refuelling process, the successive rebounds and compressions lead to temperature fluctuations, which represent important security issues. This problem requires an optimization of the hydrogen mass flow in order to limit the energy losses, especially during a fast refuelling.

Sizing issues

The sizing issues are related to the hydrogen regulation, which was made for an industrial application and is not suited for mobility. This regulation must change to conform with new uses of hydrogen. In order to simplify the deployment of FCEB in Europe and globally, this regulatory evolution must be done through process standardization between countries.

It is important to mention that the main legal obstacle on the deployment of FCEBs concerns the hydrogen refuelling station operating with electrolysis. To produce hydrogen via SMR, there is a well-established legal base, but for the production via electrolysis, there is a whole legal environment to create.

Legal issues

At the European level, the Industrial Emission Directive (IED) plans precautionary measures regarding the production of hydrogen in industrial volumes. All these particularly constraining measures are enforced as soon as there is an industrial production of hydrogen. All the nuance of the legal issue is to define "industrial quantity". The legal battle fought by many hydrogen associations is to show that the electrolysis does not produce hydrogen in industrial quantities, as long as it only concerns small electrolysers intended to recharge an HRS. Moreover, the IE Directive is not relevant for hydrogen production via electrolysis, insofar as there is no pollutant emissions (industrial emissions in the directive refer to pollutant emissions).

[39] *New Bus ReFuelling for European Hydrogen Bus Depots – Guidance Document on Large Scale Hydrogen Bus Refuelling,* Dr B. Reuter, M. Faltenbacher, O. Schuller, N. Whitehouse, S. Whitehouse, March 15th 2017