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Cities coordination for a decarbonized mobility

Application for the deployment of fuel cell electric buses

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Executive summary

The development of new technologies to address the challenges of decarbonized mobility in cities, such as hybrid, battery or fuel cell technologies, suffer from low market shares. As identified by Meunier and Ponssard (2019), two externalities are responsible for problems in the early stages of commercialisation: networks and initial costs. To solve this chicken-dilemma related to infrastructure and fleets and to drive down high initial costs, a public intervention in the form of subsidies is necessary. In the past decade, the European Commission chose to distribute his fund earmarked for green mobility through a coordination process between different clusters of cities.

This report empirically tests the effectiveness of the coordination and financing mechanisms set up in clusters based on the development of fuel cell electric buses (FCEB). We aim to assess the role they play in the dissemination of the fuel cell technology. In order to establish as precise a diagnosis as possible of the relevance of such public intervention, we cover and highlight the several economical, technological and legal aspects of the fuel cell electric bus deployments in Europe, as well as around the world, and how they are handled by the clusters.

FCEB development is currently in the latter half of the technology demonstration phase and is about to enter in a few years in the mass uptake phase thanks to the joint action of industry and the public sector. The joint ventures initiated by the cluster have proven to be essential to demonstrate the technical and economic feasibility of FCEBs, and thus reassure investors.

Intended to pave the way to commercialization of FCEBs by coordinating procurement activities to unlock economies-of-scale and reduce costs, Europe's funding program succeeded in having the initial costs dropped from about €1,000,000 to €600,000. They demonstrated the technical readiness of FCEBs and outlined the lack of economic attractiveness to private investors and policy makers. A difference of €1.4 per km in the total cost of ownership between diesel buses and FCEBs results indeed in an average abatement cost of around 1000€/tCO₂ eq and thus make FCEBs less cost effective than diesel buses. In order to achieve enough orders of FCEBs to enter the mass market phase and become competitive with diesel, the clusters need to find a way to integrate more cities in their deployment programs. Convincing more than twice as many cities to adopt hydrogen technology for their bus fleets would result in the deployment of more than 8,000 buses by 2025. Conditions to support hydrogen deployment are numerous and concern regulation, changes in law, public transport financing, and incentives for OEMs.

Since the economic viability of hydrogen buses is only a matter of time, recommendations for a successful mass market phase are simple. Procurements should be easier, insofar as the coordination structure should mirror typical arrangements between OEM and bus operator without transport authority being involved. It is furthermore essential to ensure understanding of the technology and its benefits, in order to facilitate the social acceptance of hydrogen as an energy carrier.

Most of the investigation concerning hydrogen buses in this report can be used to find synergies with other emerging heavy-duty hydrogen vehicle applications such as trucks, dump trucks and train. Hydrogen is an energy solution of today, and not only of tomorrow. That is why it is very important to re think a structure for the mass market phase, when the cluster coordination and the funding program will no longer be needed, to ensure the sustainability of the fuel cell technology.

Table of contents

Acknowledgements	3
Executive summary	4
Introduction	7
1- Technical characteristics of Fuel cell electric buses	8
The fuel cell technology	8
The 100% battery-powered technology	10
Comparison between BEB & FCEB	10
Performances	10
Energy efficiency	11
Environmental Efficiency	13
2 – The supply Chain of Fuel cell electric buses	15
H ₂ Production & Storage/ refuelling stations	15
FCEB Layout	18
produces metallic bipolar plates, casings, end and media modules for PEM	20
3 - Comparison in the total cost of use and future trends	21
Total Cost of Ownership	21
Acquisition cost: Bus manufacturing	21
Maintenance & operating costs	23
Running cost: fuel production cost	23
Discount rate	26
Costs evolution & future trends	27
Acquisition cost	27
Fuel production cost	28
Cost evolution of TCO	29
Abatement costs	31
4 – The potential market	32
European market	32
Case study: London	34
International market	36
China	36
USA	37
5 – Main national and international deployment programs for FCEBs	39
Stakeholders involved in Fuel Cell Electric Bus deployment	39
National Level	39
European Level	40

International level	40
Coalition of Fuel Cell Electric Bus stakeholders	41
Benefits of FCEB coalitions	41
The different coalitions supported by the FCH JU.....	41
Organisation of the coalitions	43
Funding methods.....	45
JIVE's project.....	46
JIVE I.....	46
JIVE II.....	46
How do JIVE operate?	47
Risks, challenges, and lessons learnt.....	48
After JIVE.....	52
Conclusion	54
References.....	55

Introduction

As local air pollution has become a major health issues in big cities around the world, public authorities are testing new pathways towards a green mobility. Transportation, and especially mass transit, plays a crucial role, insofar as it is the sector where global greenhouse gas emissions (GHG) are increasing most quickly¹. To respond to the growing demands for greening public transport systems, alternative engines have become available in the market: biofuels (biodiesel and biogas), hybrid, battery and fuel cell bus models.

However, those new technologies suffer from a low rate of penetration. According to Meunier and Ponsard (2019), a high price of zero emission vehicle and the range anxiety due to the absence of an adequate infrastructure of refuelling stations are the main reasons to explain a low rate of penetration. Those two externalities, reflecting the network and high initial costs issues, are the main arguments advanced to justify a public intervention and coordination mechanisms in order to break the classical chicken-egg dilemma and drive down initial investments required thanks to learning-by-doing.

Barrett (2008) asserts that climate treaties must enforce both participation and compliance. But as international climate negotiations proved disappointing in addressing the urgent issues of global warming and air pollution (Barrett, 2014), solutions promoting cities coordination have raised in the last decade. One of the most famous cities network, C40 cities, has the ambition to connect, inspire and advise city peers based on experience with similar projects and policies.

These networks are particularly committed to promoting green mobility. In March 2015, the C40 Clean Bus Declaration of Intent, signed by twenty cities, was a milestone that reflected the cities' concern on local air pollution. Through this commitment, cities hope to show the example towards a decarbonized mobility. The Declaration aims to incentivize and help manufacturers develop strategies to make these clean technologies more affordable and economically viable for cities.

In this report we investigate the interest of cities coordination within deployment programs, subsidised by public fund, to solve the problems related with the first stages of deployment. We are particularly interested in the coordination mode within clusters, whether through joint venture, or through captive fleets. The main objective of these clusters is to avoid dispersed, unpredictable purchases, and then to reduce the incertitude concerning the potential demand. The different deployment strategies aim to move from the take-off phase to the powering up phase, to finally secure the cruising phase. These three archetype configurations are introduced by Meunier and Ponsard (2019) to help policy guidance.

To evaluate the efficiency and the relevance of the coordination mode implemented to encourage large scale deployment of green transportation, we chose to study the fuel cell technology applied to city buses. When produced sustainably, hydrogen offers a variety of advantages and makes a suitable solution to decarbonize the public transport, especially buses. The fuel cell technology's start of operation is in line with the European Union's commitment to transforming its transport as part of a future low carbon economy.

The commercialisation of FCEB can also support the systematic linking of energy and transport systems, as it can give a push to establishing hydrogen as a storage medium for electricity from renewable energy sources, which is by nature intermittent. As a clean energy carrier, hydrogen represents a flexible way to balance electricity grids. This is called the "power-to-gas" solution. It is maybe ambitious, but definitely realistic to consider fuel cell electric bus as the gateway for a hydrogen economy.

¹ https://ec.europa.eu/eurostat/statistics-explained/index.php/Climate_change_-_driving_forces

1- Technical characteristics of Fuel cell electric buses

To improve air quality through mobility management, cities around the world show growing interest in adopting clean bus technologies. Zero-emission buses imply many drivetrain technology options. In the marketplace today, there are four zero-local-emission bus powertrain options available: hydrogen fuel cell, trolley, opportunity-charging battery electric and overnight charging battery electric, as summarized in figure 1.



Figure 1 Different types of electric bus technologies

2

The fuel cell technology

The fuel cell power module on-board the bus efficiently generates electric energy through an electro-chemical reaction between hydrogen and dioxygen leaving only water and heat as by-products.

Within the hydrogen fuel cell category different levels of hybridization are available, from full fuel cell powered propulsion to varying combinations of fuel cells with energy storage devices. There are actually three types of hydrogen powered buses: the internal combustion hydrogen bus, the Fuel Cell Bus (FCB) and the hybrid Fuel Cell Electric Bus (FCEB). The first one is a modified diesel or natural gas bus that combusts hydrogen to propel the bus. FCB use a powerful fuel cell instead of an internal combustion engine. Among FCEB, the construction can be **fuel cell dominant**, where the battery serves the purpose of load balancing, peak traction power and energy recovery through braking, (e.g. Toyota Mirai) or **battery dominant**, where the fuel cell is a mere range extender that keep the batteries charged (e.g. Kangoo Fuel Cell).

Used together, fuel cell and battery technologies overcome the limitations of each technology on its own. Batteries support regenerative braking and buffer peak load demands, allowing the fuel cell to operate as close to optimally as possible, improving efficiency and lifetime. Fuel cells provide significantly better range on challenging transit routes at a lower weight, maximizing passenger load

² Battery-Fuel Cell Hybrid Electric Buses – Optimized solutions for zero-emission transit, Ballard, April 2019

and reducing fuel consumption. In addition, heat can be captured for cabin heating to further improve efficiency.

Our study will be focusing on FCEB with a fuel cell dominant construction.

Fuel cell dominant construction is mapped below³.

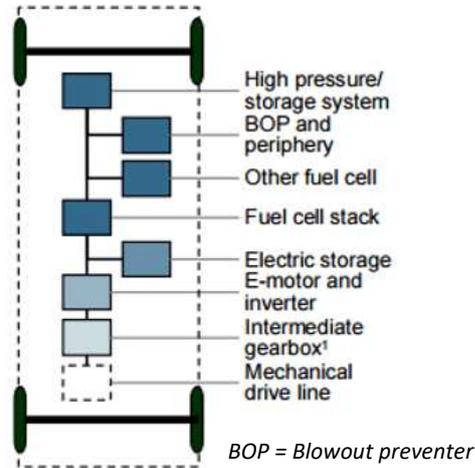


Figure 2: Fuel cell dominant electric bus powertrain schematic (source: FCH JU)

The electricity generated by the fuel cells powers the hybrid electric motors and charges the energy storage system. When more power is required than the fuel cell system can produce, the lithium-ion battery provides the energy to fill this gap. Conversely, when the power produced by the fuel cell system is more than what is needed by the drive system, the surplus electricity is used to re-charge the battery. High pressure tanks located on the roof of the bus store hydrogen fuel, providing sufficient range for a full day of operation, over 16 to 18 hours, as mapped below⁴.

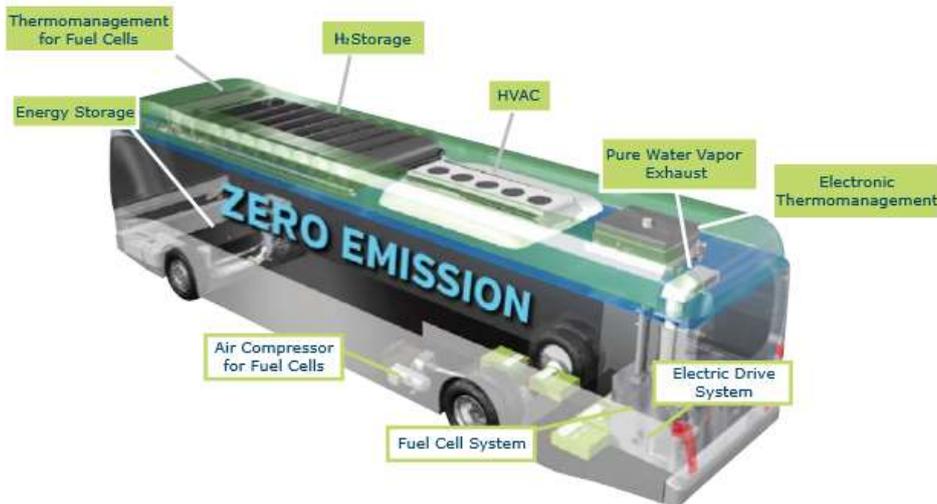


Figure 3: Fuel Cell Electric Bus Composition

³ Battery – Fuel Cell Hybrid Electric Buses – Optimized solutions for zero-emission transit, Ballard, April 2019

⁴ Fuel Cell Electric Buses: an attractive value proposition for zero-emission buses in the United Kingdom, Ballard, November 2016

The 100% battery-powered technology

A battery electric bus (BEB) stores energy on-board the vehicle in a battery, which is charged from the electric grid and which powers an electric traction motor. Overnight-charging battery electric buses carry sufficient batteries to drive the entire assigned route and fully recharge only nights at the bus depot, whereas opportunity-charging battery electric buses charge on-route at passenger stops or dedicated charging stations. These buses are less flexible than overnight-charging buses, because they are tied to the specific route where the chargers are located.

Electric buses employ regenerative braking. When the bus is braking, the drive motor becomes a generator and recovers energy by converting kinetic to electrical energy and storing the regenerated energy in the batteries.

The comparison between FCEB & BEB configuration is mapped below⁵.

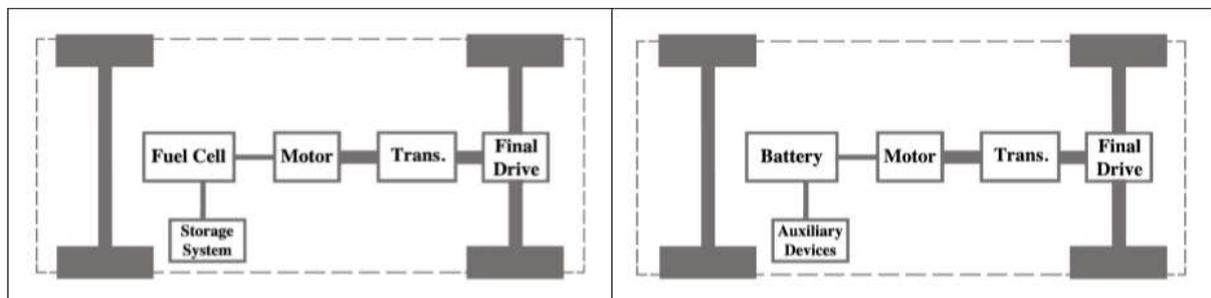


Figure 4: FCEB and BEB configuration

Comparison between BEB & FCEB

All the data⁶ presented below are only mean, and can vary for one bus model to another.

Performances

	Bus range ¹	Fuel Cell Durability	Fuel consumption (MJ/km)	Refuelling/ recharging time (min)
FCEB	350 – 500km	30,000hrs ²	9 – 16	7 - 10
BEB- overnight	200 - 250 km	N/A	5- 6	180 - 300

¹Optimal renages of 12m buses, which means measurements are taken during ideal conditions: the batteries/ fuel cell are at beginning of life, the bus is operating on a flat route, seated passengers only and no cabin heating or cooling.

²without stack replacement/ refurbishing

⁵ 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

⁶ Fuel Cell Electric Buses – Proven Performance and the Way Forward, Ballard, April 2019

Battery/ Fuel Cell Characteristics for a 12m bus

	Energy density (MJ/kg)	Battery size (kWh)	Fuel Cell Size (kW)
FCEB	2.3	60	120 - 200
BEB	0.6	200	N/A

Hydrogen higher energy density compared to electrical storage system is the reason for longer range.

Energy efficiency

Hydrogen production

Hydrogen is produced using different methods that include:

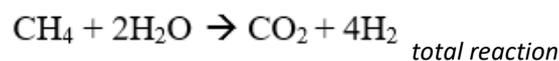
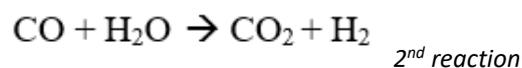
- Renewable energy (electrolysis)
- Natural gas steam reforming (NSGR)
- Gasoline steam reforming
- Coal (gasification)
- On-board Auto Thermal Reforming (ATR)

Unlike electricity, the efficiency of hydrogen depends on both the production method and delivery pathway.

The most efficient hydrogen production method is on-board ATR, while NSGR is the most efficient fossil fuel-based hydrogen production method, and the most commonly used today accounting for 75% of world hydrogen production. However, the only way to have zero-emission FCEB on a well-to-wheel basis is to use renewable sources through electrolysis.

Steam methane reforming (SMR)

SMR is a process in which a catalytic reaction between steam and lighter hydrocarbons such as methane or biogas takes place to produce hydrogen and carbon monoxide. Syngas reacts further to give more hydrogen and carbon dioxide.



The main disadvantage of this reaction is that around 10kg of CO₂ is emitted per kg of H₂ produced.

Electrolysis of water (alkaline electrolysis)

In the electrolysis of water, the passage of an electric current lead to the decomposition of water into oxygen and hydrogen.



Using electrolyzers is a way to convert the surplus energy into hydrogen. Surplus is when supply of solar or wind energy exceeds demand, which means that the marginal value of a kilowatt hour of electricity can become negative. Renewable energies are intermittent, and the storage of big quantities are only possible through hydrogen. Having the possibility of capturing the surplus electricity, converting it into a green fuel as energy storage, and then using that zero emission fuel to power transportation creates real value to the existing infrastructure.

In order to compare the energy efficiency of a FCEB and a BEB, it is important to consider the production efficiency of electricity and hydrogen, as indicated below⁷

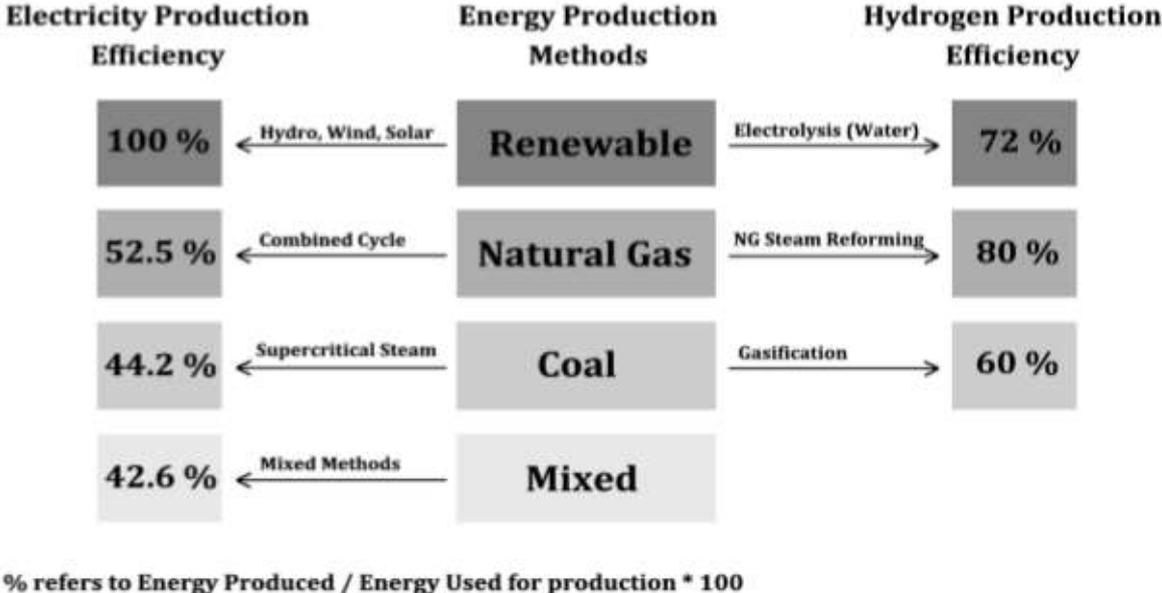


Figure 5: Production efficiency of electricity and hydrogen

One of the advantages of BEBs over FCEBs is their efficiency on a well-to-wheel basis considering only clean energy production methods. Hydrogen production efficiency of water electrolysis (72%) combined with the fuel cell efficiency (50%) gives a total efficiency of 35% for FCEBs against 90% for BEBs. However, cold weather operation is particularly challenging to batteries. Relative to performance at 25°C, some lithium battery chemistries deliver only 75% of that energy at -30°C, 80% at -20°C, and 90% at 0°C⁸. In this case, FCEBs performance is better than BEB’s one.

On a tank-to-wheel basis, BEBs provide the highest energy efficiency with fuel consumption of 7 MJ/km, against 11 MJ/km for FCEB. However, this result needs to be qualified as energy consumption varies significantly due to driving conditions (congestion, number of stops, geography, etc...)

⁷ 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
⁸ *Fuel Cell Electric Buses – Proven Performance and the Way Forward*, Ballard, April 2019

Environmental Efficiency

In order to compare the environmental efficiency between FCEB and BEB, it is important to distinguish: well-to-tank, tank-to-wheel, and well-to-wheel GHG emissions.

1) Well-to-tank

Well-to-tank assessment provides quantified measures of GHG emissions during energy production (i.e fossil fuel, renewable or biofuel) and distribution (i.e road, rail, pipeline, on site). Identification of energy production methods, feedstock, and the distribution pathways are thus keys considerations.⁹

	Hydrogen		Electricity
Well-to-tank GHG emissions (gCO₂ eq/km)	NGSR 320	Electrolysis (RES – grid) 0 - 305	720 (EU- mix) ¹

fig.6 well-to-tank GHG emissions of BEB and FCEB

¹EU-mix = mean emissions considering electric grid GHG emissions in different european countries.

2) Tank-to-wheel

Tank-to-wheel assessment of GHG emissions estimates the local emissions produced during bus operation. Both FCEBs and BEBs operate with zero local GHG emissions.

3) Well-to-wheel

Since there is no tank-to-wheel GHG emissions for FCEB and BEB, well-to-wheel emissions are equal to well-to-tank emissions.

It is clear that water electrolysis is crucial for greening mobility on a WTW basis as it offers a means of hydrogen production with electricity from renewable energy sources such as wind and solar power.

4) Battery/ Fuel Cell recycling

Rechargeable electric batteries (Li-ion, Ni-Zn, Ni-Cd) can be recycled. However, global consumption of lithium and cobalt is growing faster than its production due to increase demand of Li-ion batteries. 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 manufacturers, 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.”⁶ Ballard fuel cell stacks use no cobalt, lithium or rare earth materials.

⁹ Nylund N-O, Koponen K. Fuel and Technology Alternatives for Buses – Overall Energy Efficiency and Emission Performance. VTT TECHNOLOGY 462012.

To summarize, FCEBs present many advantages:

They provide all the benefits of a battery bus: zero emission, low noise, high performance, and improved passenger comfort with key advantages:

- Extended range (> 300km)
- Significant reduction in vehicle weight (more passengers)
- Faster refuelling (no change to operational processes)
- Route flexibility (no roadside infrastructure)
- Operation from -30°C to + 50°C ambient temperature
- Excellent fuel cell stack durability (> 30 000 hrs)

This is why FCEBs can operate on long routes with steep grades and a frequent service, whereas BEBs excel for agencies with short flat routes and moderate schedules. And contrary to electric batteries, which are known to excel in warm, moderate temperatures, the FCEB performance is consistent during all seasons.

For all these reasons, fuel cell electric buses have demonstrated to be a 1:1 replacement to conventional buses, allowing transit agencies to migrate their fleet to zero emission without affecting service or current operation processes.

The central decision of many transit agencies is the choice of zero-emission technology: fuel cell electric buses (FCEBs) or battery electric buses (BEBs)—or a combination of both. In most cases, the decision will be based on the routes served (how long, how flat or hilly); the existing infrastructure (electrical capacity, hydrogen availability); and the bus depot constraints. Although FCEBs and BEBs are sometimes represented as competing technologies, they are actually **complementary**.

2 – The supply Chain of Fuel cell electric buses

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.¹⁰

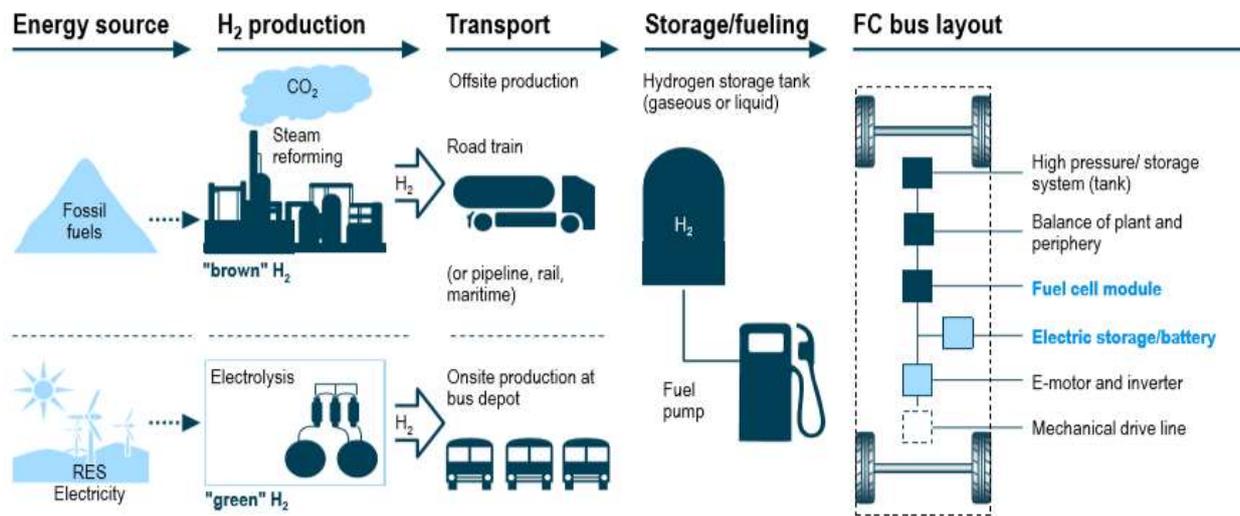


Figure 7: Hydrogen value chain and FCEB layout

H₂ Production & Storage/ refuelling stations

“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”¹¹. These stations can be configured in different ways, depending on the source of hydrogen, which 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.

During the refuelling process, gaseous hydrogen is dispensed to the vehicle storage tank until a maximum pressure is reached. This pressure threshold is determined by the vehicle storage tank and influenced by the ambient temperature and the temperature of the hydrogen contained in the vehicle tank.

Even though it is now possible to manufacture HRS, the production is still far from an industrial production. Many technological improvements are still required. In this section, we will only present the most challenging ones. It has to be noted that we only consider on-site production using electricity from renewable sources, in order to have a carbon-neutral hydrogen production.

1) Optimal pressure

The design and construction of hydrogen refuelling stations is not a completely new challenge since a growing number of HRS already exist, but most of them provide hydrogen to a relatively small number of passenger vehicles. Yet, refuelling a large number of 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 are capable of carrying more weight and greater volumes than light-

¹⁰ *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

¹¹ *New Bus ReFuelling for European Hydrogen Bus Depots*, B. Reuter, M. Faltenbacher, O. Schuller, N. Whitehouse, S. Whitehouse, March 15th 2017

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 standard 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 thus costlier.

2) 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 storage¹². To date, the maximum refuelling capacity is for about 10 FCEBs¹¹.

3) 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.

4) 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 has to 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. For the production of hydrogen via SMR, there is a well-established legal base, but for the production via electrolysis, there is a whole legal environment to create.

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 electrolyzers 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).

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

¹² *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

	Relevant experiences/ Facts	Places where HRS are installed
 (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
 (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 (<i>SmartFuel</i> 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)
 (DE)	Build the largest HRS in the UK (Aberdeen) 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
 (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
 (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.	<i>Chemie Park Delfzijl in the Netherlands</i>
 (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
 (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 Hydrogen Council. Inaugurated the first multi-fuel station in France	Pau, Marché International de Rungis
 (UK)	Luxfer's G-Stor H ₂ 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
 (DK)	Establishes green hydrogen distribution – and production operations, installs and operates HRS directly at bus depots. Member of the consortium H2bus.	
 (NO)	Dedicated hydrogen company delivering technologies to produce (electrolysers), store and distribute energy. Member of the consortium H2bus.	
 (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

Fig8: Non exhaustive list of hydrogen supplier and HRS manufacturer

FCEB Layout

In this section, we will only focus on the key components of a FCEB and their key suppliers.

1) 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. Below is a non exhaustive list of different European OEM.

2) 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 fundamental devices 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.

3) 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.

	International Position (production only)	Relevant experience/ product ¹³	Clients for FCEB (non-exhaustive)
 (UK)	UK, Germany, Hong-Kong, Singapore, Malaysia, New Zealand, Mexico, USA, Canada	hydrogen-powered Enviro400 double deck	
 (DE)	Germany	“Blue City Bus” (10, 12 and 18m)	ÖPNV Deutschland (Wiesbaden, Mainz and Frankfurt am Main)
 (DE)	Germany, France, Spain, Czech Republic	Demonstrated 17 FCEB in the CHIC project, tens of FC bus produced to date.	Aargau, Bolzano, Hamburg, Milan
 (IT)	Italy	Built the “H80” FC Bus in 2007. Plans to produce tens of FCEB over the coming years	
 (FR)	France	Developing an FC version of plug-in hybrid electric buses of the “businova” platform (10.5 – 12 m)	
 (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)
 (PL)	Poland	First FCEB delivered to Syntus (Dutch bus operator) in mid-2016	Syntus
 (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
 (NL)	The Netherlands	Delivered the first 18-metre FCEB, named Phileas, to Köln and Amsterdam	Amsterdam, RVK in Köln, Eindhoven
 (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)
 (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	

¹³ Zero emission public transport – Fuel cell buses in Europe, Element Energy Ltd, September 2017

Non-European OEMS	 NEW FLYER (Canada)	 TOYOTA (Japan)	 HYUNDAI (South Korea)	 TATA (India)	 YUTONG (China)
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Fig.9 Non exhaustive list of key FCEB manufacturers in Europe

	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

To conclude, one explanation for the low levels of fuel cell related activity amongst bus OEMs is the fact that engineering resources in many of these organisations are limited, especially in the smaller, privately owned companies. Bus suppliers have had to respond to changing requirements in the 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. 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).

3 - Comparison in the total cost of use and future trends

Total Cost of Ownership

The total cost of ownership (in €/km), which reflects the costs incurred by a product, has often been described as one of the main barriers for the implementation of fuel cell electric buses. The TCO can be decomposed into four categories:

- Acquisition cost (unit price)
- Maintenance & operating cost
- Running cost (fuel cost)
- Disassembly cost (end-of-life cost)

The latter was not successfully determined. However, it is very likely that the disassembly cost does not vary significantly between diesel and FCEBs. It also has to be noticed that there is a lot of uncertainty in the estimation of TCO, mostly because its calculation is highly dependent on operational and logistics aspects.

Acquisition cost: Bus manufacturing

Fuel cell electric bus capital pricing has decreased considerably as the volumes have grown. Since first deployments in the 1990s, purchasing costs for FCEB have fallen significantly by more than 75%¹⁴. Funding provided by the European Fuel Cells and Hydrogen Joint Undertaking (FCH JU) as well as several projects have contributed to increase deployment volumes.

Currently, the target price for a 12meter fuel cell electric bus is €650,000. Funding from the FCH JU contributes €200,000, resulting in a purchase price of €450,000, whereas a diesel bus costs currently €300,000 and a battery electric bus €550,000. The expected price without subsidy is below 500,000€ by 2020.¹⁵

Cost reductions expected between the fuel cell electric bus components in 2016¹⁶ (Fig11.) and in 2020² (Fig12.).

In order to further calculate the TCO, it is important to take into account the annual mileage and the bus lifetime while considering the acquisition cost. Due to actual performances of fuel cell electric buses, it is reasonable to consider 12-year lifetime and an annual mileage of 70,000 – 75,000km.

¹⁴Roland Berger GmbH "Fuel Cell Electric Buses - Potential For Sustainable Public Transport In Europe" München The Fuel Cells and Hydrogen Joint Undertaking, 2015. Web. November 1, 2016.

¹⁵ *Fuel Cell Electric Buses: an attractive value proposition for zero-emission buses in the United Kingdom*, Ballard, November 2016

¹⁶ CALSTART (2016)

Fig11. Fuel cell electric bus components cost in 2016

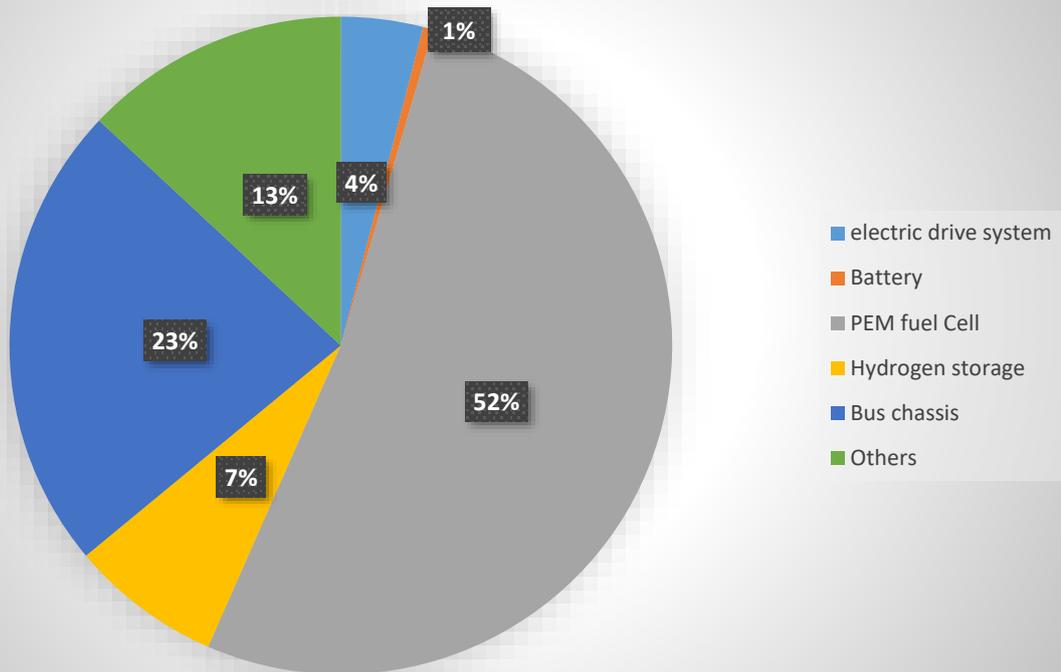
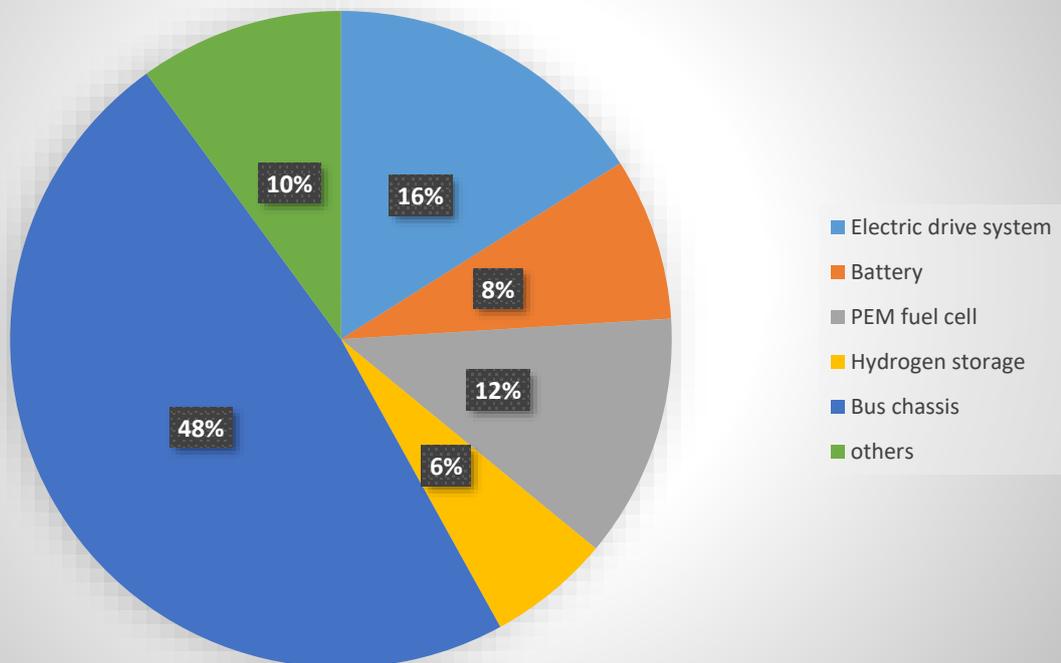


Fig12. Fuel cell electric bus component cost estimate with 60kW fuel cell power module (2020 projections)



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. 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". These improvements should be responsible for a lower fuel cell module total life cycle cost. Actually, "improvement in system integration and volume procurement is driving the price of fuel cell power module towards €1/ Watt" assures Ballard. 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.

However, while economies of scale can drive down costs, 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.

Maintenance & operating costs

Maintenance costs are comprised of the fuel cell module and the fuel cell stack replacement, maintenance of the conventional parts and maintenance of other powertrain components. This includes a midlife overhaul process called fuel cell stack refurbishment. With 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 one time 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.

Although maintenance costs are dependent on multiple variables including vehicle age, duty cycle, topography or fleet maintenance practices, we can affirm that maintenance cost per kilometre are in average 0.40€/ km for FCEB and €0.30/km for Diesel bus. This is based on data collected from the latest generation of buses currently in operation in Europe and the US¹⁷.

The forecast for 2025 shows cost for FCEB aligning with diesel buses, due to increasing volume. This future decreasing is partly explained by the next generation of products to enter service by 2020. Ballard concludes its most recent study saying "Based on an average of 75,000km 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."¹⁸

Running cost: fuel production cost

Fuel production cost

The fuel production cost depends on the method used. The price of hydrogen from SMR is currently approximately 20% lower than hydrogen from electrolysis. That's why, from an economic point of view, SMR plays a central role in the early years of deployments and commercialisation of FCEB. Then, in the long run, it can be replaced by hydrogen produced from electrolysis with renewable energy sources electricity to reach full carbon neutrality from a well-to-wheel perspective. However, some manufacturers and key suppliers committed to a green supply chain, from hydrogen production to FCEB operation. They installed on-site hydrogen production through electrolysis directly on the hydrogen refuelling station.

¹⁷ *Fuel Cell Buses in U.S Transit Fleets: current status 2017*, National Renewable Energy Laboratory, Eudy, L., Post, M.

¹⁸ *Fuel Cell Electric Buses – Proven Performance and the Way Forward*, Ballard, April 2019

SMR

Since Steam Methane Reforming (SMR) is a well-developed process, 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 big volumes of hydrogen.

Electrolysis

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 its production unit. That's why costs are very variable.

If we consider that electrolyzers have access to relatively cheap bulk electricity, (e.g. €70/MWh), the final cost of hydrogen produced by electrolysis is €3.7/kg (at least!). This price is extremely receptive to electricity costs. Unlike the SMR, this process is generally used to produce small volumes of hydrogen.

Fuel price

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

Fuel consumption

The actual hydrogen fuel consumption of FCEB depends on the bus operation and takes into account the passenger load, route, speed and heating and cooling requirements. On a flat route around 5kg of H₂/100 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 as presented in table below¹⁹.

Fuel consumption	kg/100 km
Drive train on flat routes	5
Hill impact (3% hill on route)	2
Auxiliary / hotel load	0.5 per kW

Figure 13: Hydrogen fuel consumption

Today's current generation of fuel cell electric buses have demonstrated an average fuel consumption of around 8kg of H₂/100km.

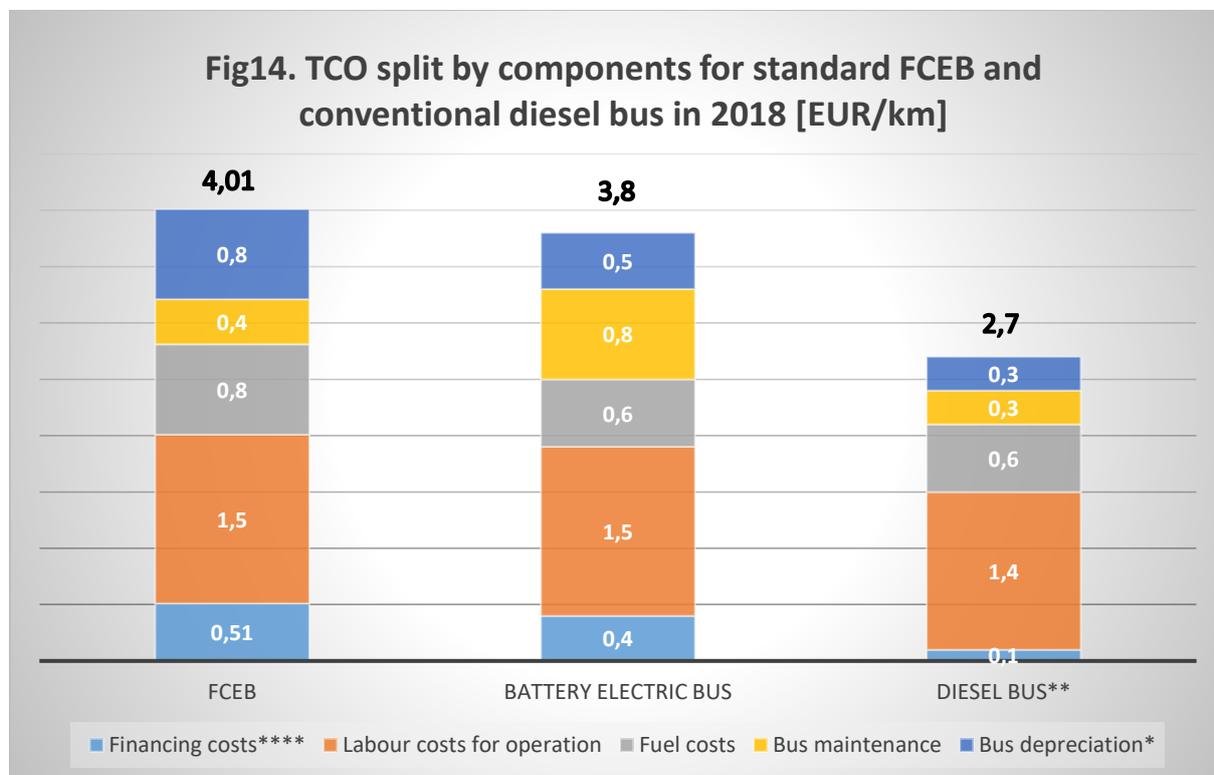
Hydrogen refuelling infrastructure costs are covered through to per-kilogram payment. So the fuel price considered in the TCO analysis covers all costs associated with generating, distributing and dispensing hydrogen.

To calculate the TCO we consider the bus depreciation (i.e. purchasing price), maintenance and fuel costs (described in the above section), as well as labour and financing costs, whose data have been collected from the Roland Berger's study "Fuel Cell Electric Buses – Potential for Sustainable Public

¹⁹ Fuel Cell Electric Buses – Proven Performance and the Way Forward, Ballard, April 2019

Transport in Europe". We then compare the TCO of standard FCEB, battery electric bus²⁰ and conventional diesel bus. It should be noted that the data used for battery electric buses is a mean including overnight charging e-bus and opportunity charging e-bus.

In the following section "Cost evolution and future trends", we will compare our results with future TCOs calculated for different production scenario.



* Bus depreciation calculated for a 12-years lifetime and an annual mileage of 70 000km

**Diesel bus data are drawn from Roland Berger's study "Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe"

***We assume a diesel price of €1.35/L, a fuel consumption of 10kg of H₂/km and a fuel price (including infrastructure cost) of €8/kg for FCEB, and an electricity price of 0,112€/km (Eurostat 2017, electricity prices for non-household consumers) for an efficiency of 1,3kWh/km (NREL 2017)

**** A Weighted Average Cost of Capital (WACC) of 7% is considered

Bus depreciation and fuel costs constitute the largest share of FCEB bus-specific TCO, since labour costs are equally applicable to the diesel bus. The higher depreciation and financing costs of the FCEB against the standard diesel bus are evidences that a higher purchasing price will remain the largest difference between the two types of buses. However, cost-efficient hydrogen prices are also required to achieve competitive operational costs for FC buses compared to diesel buses.

Consequently, the bus purchase price and the hydrogen production cost can drive the price gap between FCEB and diesel buses. They are the two aspects stakeholders need to focus on, so that the TCO does not become a barrier for the implementation of fuel cell electric buses.

The same observation can be made for battery electric buses. The purchase cost remains higher than a diesel bus, but lower than a FCEB. BEBs also have the highest maintenance costs, due to the

²⁰ *Electric buses arrive on time*, Transport & Environment, November 2018

sensitivity of the different electric components to the utilisation level of service. However, the biggest advantages of BEBs over FCEBs and diesel is their reliance on electricity, which is cheaper and more efficient than imported fuel or from electrolysis produced hydrogen.

Discount rate

➤ $r = 5\%$

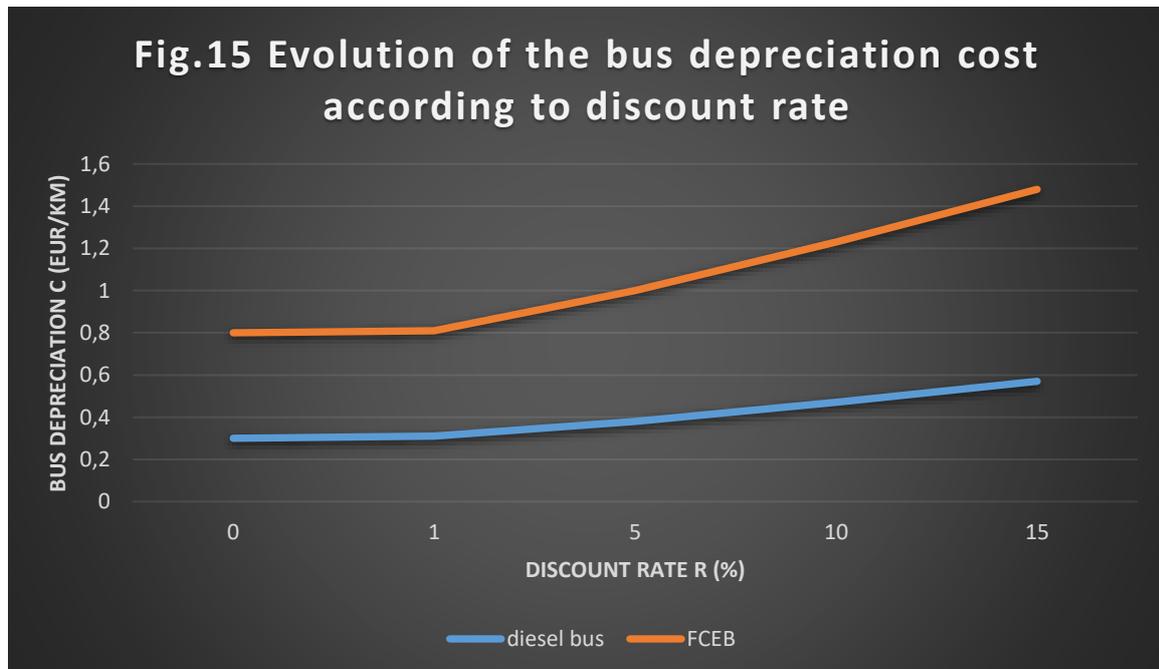
$I = €650\,000$; $D = 12$ years; $a =$ annuity (€/ year)

$$I = \sum_{t=0}^{D-1} \frac{a}{(1+r)^t}$$

Considering 70,000km per year, the bus depreciation cost is €1 (against €0.8 without discount rate).

➤ $r = 10\%$

With a discount rate of 10%, the bus depreciation cost becomes 1,23€.



As long as FCEB's capex is higher than the one of diesel buses, a higher discount rate will increase significantly the TCO difference between the two types of buses. FCEBs are at a disadvantage when the discount rate raises.

Costs evolution & future trends

Acquisition cost

A significant decrease in the purchase price of FC buses has been made since the introduction of first prototypes in the 1990s. In order to enable a sustainable market-based commercialisation, the FCH JU supports deployments projects intended to bridge the gap towards commercialisation by reaching scale effects and reducing current costs. In this section, we will present the costs evolution due to large-scale implementation of FCEB.

The evolution of fuel cell bus costs in Europe is correlated to the evolution of different large-scale demonstration projects implemented in several European clusters, as presented below.²¹

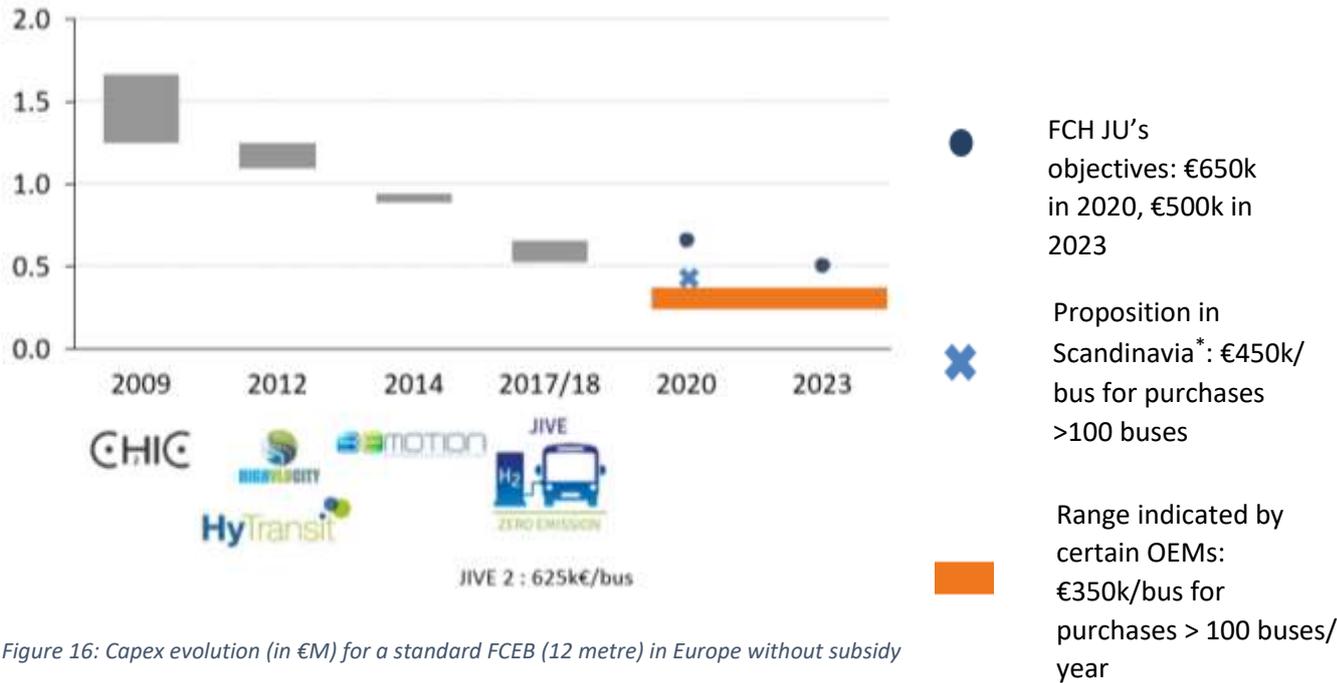


Figure 16: Capex evolution (in €M) for a standard FCEB (12 metre) in Europe without subsidy

To complete and expand Element Energy’s data, which reflect the FCH JU’s achievements and objectives, let’s focus on the "niche scenario" and the "production-at-scale scenario" from the Roland Berger’s study mentioned previously. Those two scenarios depend on efficiencies and economies of scale achieved with varying market sizes and the related overall technological progress.

The nice scenario is characterized by a cumulative number of 1,200-1,800 FC buses deployed on Europe’s roads in total until 2025. The production-at-scale scenario requires a total cumulative volume of 8,000-10,000 FC buses until 2025. 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.”

²¹ Fuel cell bus joint procurement clusters, Element Energy Ltd, Nov 2017 in FCH JU Stakeholder Forum
 * <http://hydrogenvalley.dk/white-paper/>

On the fig.17, presented in Roland Berger’s study, we can clearly note that the purchase price of FCEB in 2030 is expected to significantly decrease to approximately €490k - €520k in the niche scenario and to €400k- €450k in the production-at-scale scenario, and will thus align with diesel hybrid buses.

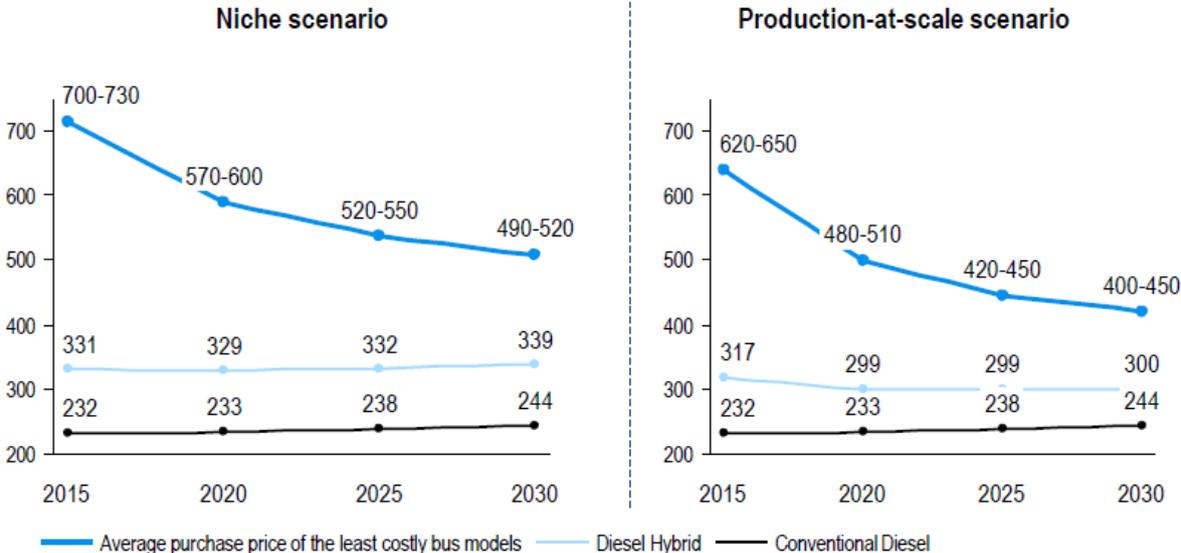


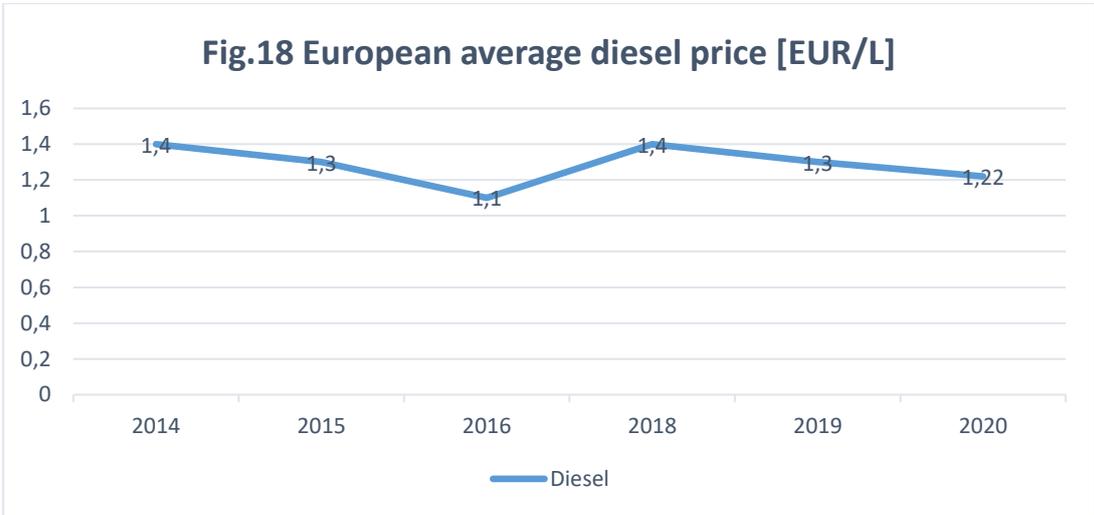
Figure 17: Purchase price development of standard FCEB according to different scenarios in the heavy-duty pathway [€ x10³]

Most recently, the journalist G. Topham reported in *the Guardian* the transport for London (TfL) has ordered 20 hydrogen-powered double-decker buses, which costs around €550,000 each. This is the target price announced by Roland Berger for 2020 in the niche scenario. Recently, some suppliers have indicated far lower prices are possible – well below €450,000 – with sustained orders of around 100 buses per year per OEM.

Fuel production cost

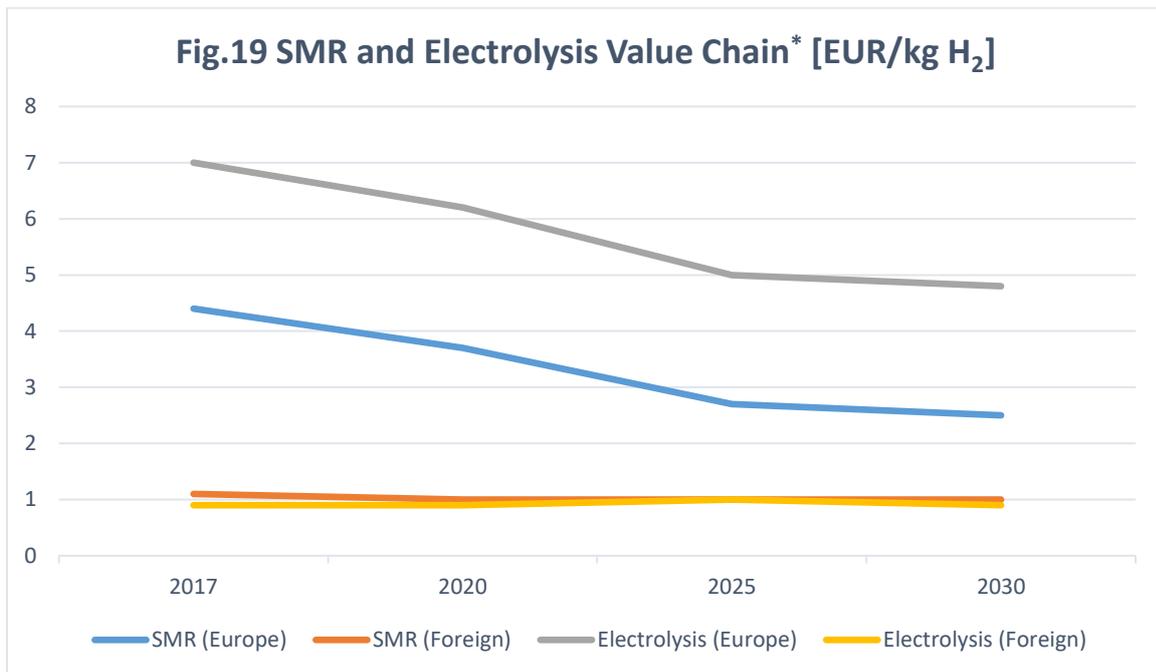
We suppose that current tax regimes for diesel remain and that no new taxation for hydrogen is being introduced.

Diesel price evolution



Source: Weekly oil bulletin from the European Commission for the past data. Estimation results from the Global Petrol Prices models

Hydrogen price evolution

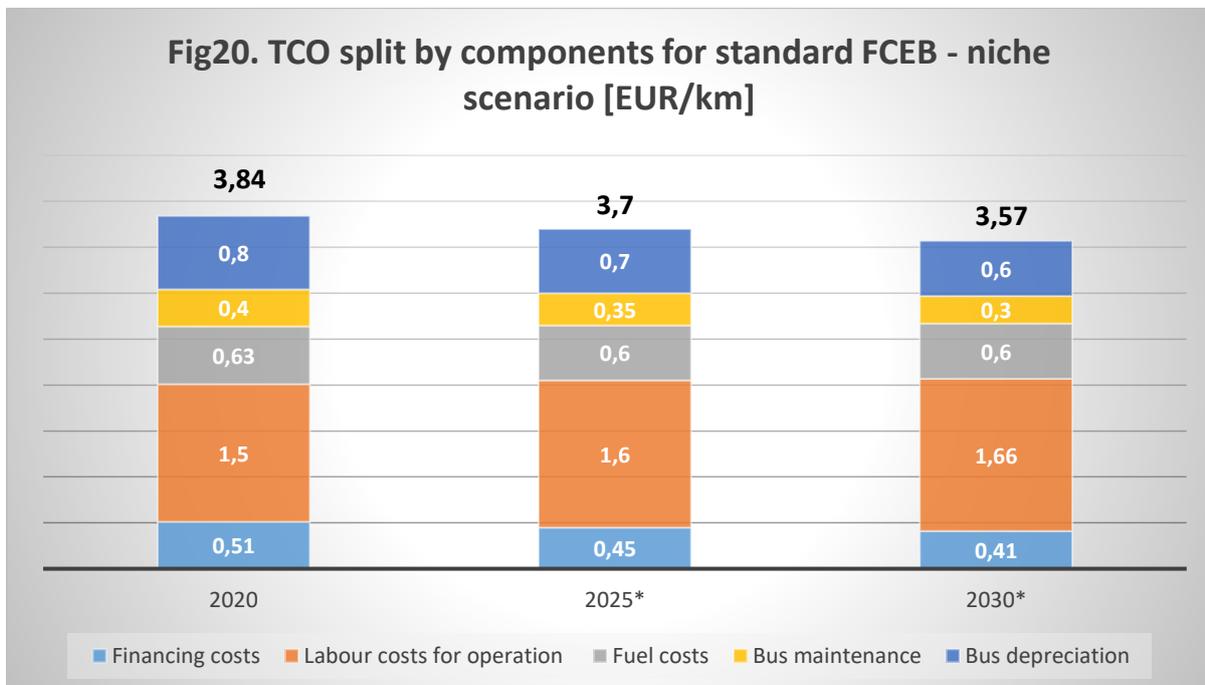


Source: *Economic Case for Hydrogen Buses in Europe, Element Energy Ltd, May 2017*

*assumed 50% of hydrogen production by SMR and 50% by electrolysis. Include aggressive production cost reductions and utilisation improvements for all technologies.

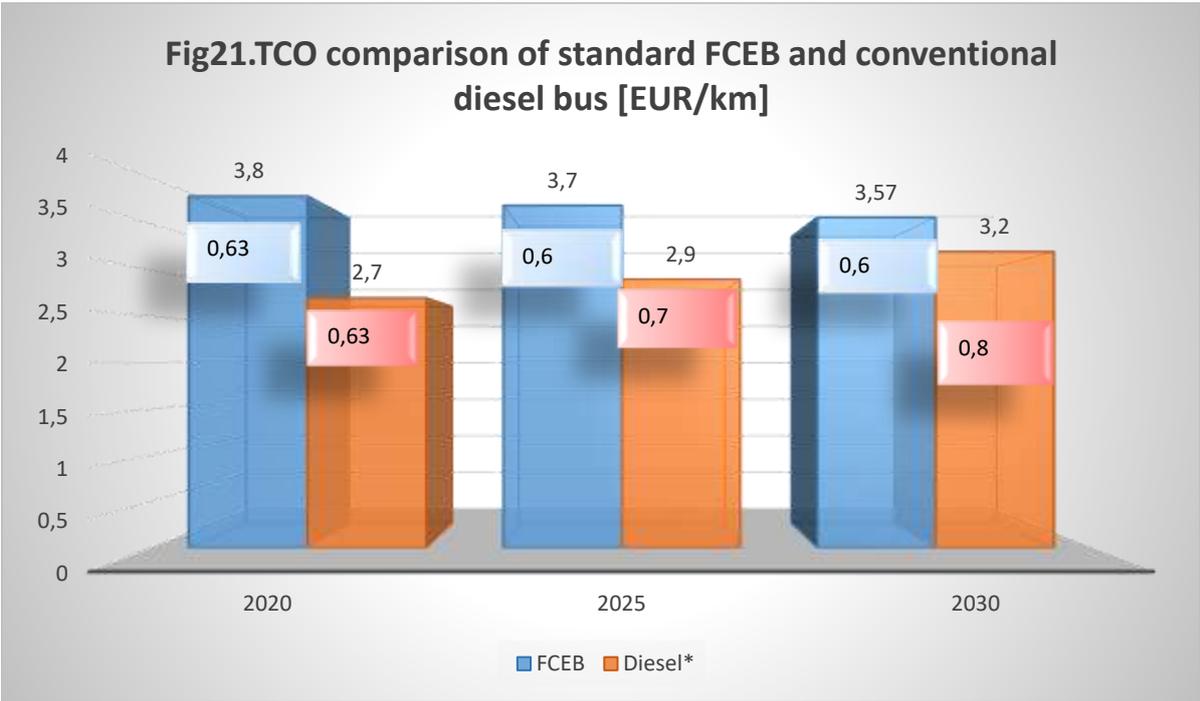
As we can see on the graphs above, the fuel cell electric bus TCO is expected to significantly decrease as the bus capex and hydrogen prices trend is to align with diesel.

Cost evolution of TCO



*data are drawn from Roland Berger's study "Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe"

Considering all European projects for FCEB deployments (from CUTE to JIVE, see part 5), and the current market maturity, the niche scenario seems to be the most realistic until 2030.



* data are drawn from Roland Berger’s study “Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe”
 ** the highlighted part of the bin categories indicates the fuel price in €/km

As deployments of fuel cell electric buses is ramped up, significant decreases in the bus capex and the hydrogen prices are expected. Combined with a TCO augmentation of diesel buses due increasing diesel prices, FCEBs could be more cost-effective in the future than diesel buses. It is important to underline that these results are obtained under the main assumption that current tax regimes for diesel remain and that no new taxation for hydrogen is being introduced.

With low interest rates, some public operators should be able to achieve lower Weighted Average Cost of Capital (WACC) and thus lower financing costs, which can further reduce TCO. In addition, certain manufacturers claim that FCEB’s lifetime could be extended to 18 years, which would help closing the gap to the diesel bus.

Future improvements may also be considered, as a longer stack life time, promised by Ballard will increase fuel cell stack durability beyond 30,000hrs, which in turn will lower TCO.

A few reliable data can be found on the TCO estimations for BEBs. However, the study conducted by Mahmoud and al. (2016) suggests that with a TCO of **€2,7/km in 2030**, the BEBs with opportunity charging should become the most cost-effective zero emission technology for buses.

Abatement costs

TCO [€/km]: data drawn from fig.21

Emissions [gCO₂ eq/km]: data for FCEB drawn from fig.6 (part1).

For diesel emissions, we will consider 1222gCO₂ eq/km²².

$$a = \frac{\text{TCO FCEB} - \text{TCO diesel}}{\text{diesel emissions} - \text{FCEB emissions}}$$

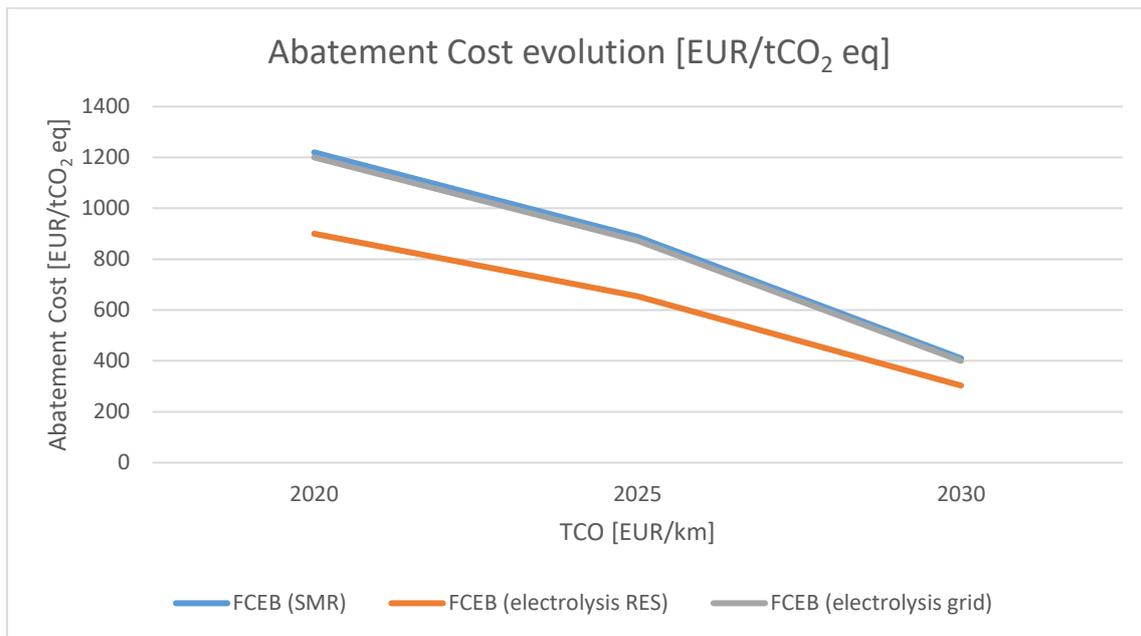


Figure 22: Abatement cost evolution [EUR/tCO₂ eq] according to different hydrogen production methods

Today, the average abatement cost of FCEB is around 1000€/tCO₂ eq, same order of magnitude as for fuel cell electric vehicle as the Toyota Mirai. The slight difference observed between a hydrogen production through SMR and through electrolysis with grid electricity is due to a low variation of the CO₂ emissions between the two methods. This implies that the grid electricity is mostly supplied by carbonised sources

To conclude, the total cost of ownership analysis suggests that the gap between FCEB and diesel buses will narrow over the coming decade. Overall costs for FCEB are expected to decrease, until being competitive with conventional diesel buses on a per kilometre basis in the year 2030. This important decrease results partly from reductions in the bus maintenance costs, and the bus capex. Hydrogen fuel costs are also assumed to be even lower than diesel costs on a per kilometre basis. Exceeding this “fossil parity” is a necessary condition for hydrogen technology to become more viable.

²² 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

4 – The potential market

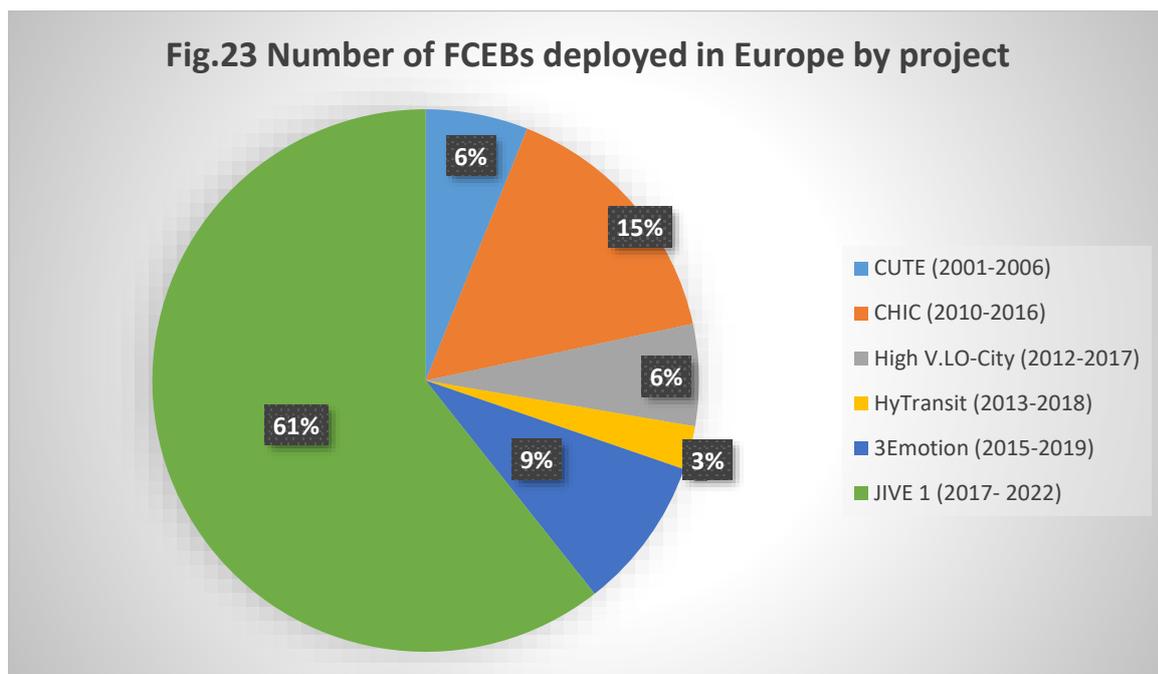
The previous part made clear that the cost evolution of fuel cell electric buses depends on its market size. This part studies the EU potential market compared to others geographic areas. The estimations made in this part are mostly based on cities official declarations. The market's drivers (European programmes) will be presented in the following section.

European market

Thanks to recent zero-emission regulations imposed by national governments and by the European Commission²³, many European cities are looking to convert their fleets to 100% zero-emission. So far, very few have deployed zero-emission buses on a large scale.

Since 2015, a total of 35 European cities are committed to assessing FCEB rollout options. 12 countries are thus represented: Portugal, France, Italy, Hungary, Germany, Switzerland, Belgium, Holland, United Kingdom, Norway, Estonia and Latvia.

The fuel cell bus commercialisation in Europe is developed through deployment programs funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU). Those programs have taken turns since 2001 and are now responsible of 231 FCEB deployed all across Europe. Most of these FCEBs are supported by one of the most recent programs: JIVE 1. Further details on this programs can be found in the following part "Policy instruments".



Existing and planned projects are expected to deliver 350 – 400 FCEBs by the early 2020s. But considering all cities across Europe which are planning to phase out diesel buses, the demand for FCEB could be bigger as expected. The following map²⁴ indicate the potential demand for FCEB in different countries and cities.

²³ CO₂emission performance standards for new heavy duty vehicles - Amendments adopted by the European Parliament on 14cNovember 2018 on the proposal for a regulation of the European Parliament and of the Council setting CO₂ emission performance standards for new heavy-duty vehicles (COM (2018)0284 –C8-0197/2018 – 2018/0143(COD))

²⁴ Mayor of London's Transport Strategy – draft for public consultation, June 2017



Figure 24: Cities across Europe planning to phase out diesel buses and their objectives

This map, dated from 2017, is not exhaustive. Since 2017, others cities have committed to ambitious green mobility policies. For example, the local transport operator for the Cologne Region, RVK, decided to convert its entire fleet to alternative powertrains by 2030, while the Oslo/Akershus Region aims at running its entire public transport bus from renewable energy sources only by 2020. Those two goals are achievable through fuel cell technology.

To estimate the potential demand, we need to consider the following aspect:

- Current fleet size
- Market expected growth
- Zero-emission objectives
- H₂ / 100% electric / CNG share among the zero-emission fleet

The current fleet size is indicated on the map. The total across these cities/ countries is 47,750 buses, which represents 10% of the 2017 estimated total bus fleet in the EU 28, Switzerland and Norway²⁵. Assuming a standard bus lifetime of 12 years, approximately 4,000 buses need to be replaced annually in the bus fleets.

In addition, the total bus market in Europe is expected to grow about 3-5% annually until 2020²⁶.

However, the share of zero emission powertrains is difficult to estimate, because it depends on several important factors, including regulation policy, public transport financing, and technology cost

²⁵ Estimation based on Eurostat data and European Commission: Study of passenger transport by coach (2009). Eurostat data indicates that size of bus fleet overall remained stable since 2009. Estimation excludes coaches.

²⁶ *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

evolution. That's why an estimation of the potential demand can only be properly estimated on cities through specific case studies.

Case study: London

Currently, approximately 30% of London's carbon dioxide emissions are generated by transportation, making it an ideal industry of focus for reductions.

Former London's 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, delivers in his *Mayor's Transport Strategy 2018* his vision to improve air quality, which ensures among others that London's entire transport system is 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 actively working towards this objective: 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 website²⁷, it is 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 all 9,200 buses across London.**

Through the *Healthy Streets Approach*, the Mayor supports his strategy to re-shape the bus network and meets the 2037 goal. This strategy includes 12 Low Emission Bus Zone 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.

Share of hybrid, electric and hydrogen in zero-emission fleets²⁸

- Hybrid: over 3,000 diesel-electric hybrid buses currently run through the capital, making up **30%** of TfL's bus fleet.
- 100% electric: over **150 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.
- **Hydrogen:** London wants to be a world leader in hydrogen and fuel cell activity. Currently, **10 hydrogen buses are operating in London**, but the city ordered 20 double decker fuel cell buses from Wrightbus in May 2019 – they will be delivered in 2020. This was one of the cheapest bus purchase since the technology development (£500,000 each bus).

²⁷ <https://www.london.gov.uk/what-we-do/transport/green-transport>

²⁸ Bus Fleet Audit, 31 March 2018

Below²⁹ is London roadmap to clean his bus fleet and meet the objectives described previously.

		NOW	2020	2025	2030	2035	2037
Bus procurement and retrofit		Retrofit of existing double decks to Euro VI standards	TfL will buy only electric or hydrogen single decks	TfL will buy only electric or hydrogen double decks			
		TfL will buy only hybrid double decks					
Bus fleet in central London			All single decks electric or hydrogen				All TfL buses electric or hydrogen
			All double decks Euro VI and hybrid			80% of double decks electric or hydrogen	
Bus fleet in inner and outer London				50% of single decks electric or hydrogen	90% of single decks electric or hydrogen	All single decks electric or hydrogen	
			All double decks meet Euro VI standard as a minimum	More than 85% of double decks hybrid, electric or hydrogen	60% of double decks hybrid; 40% electric or hydrogen	20% of double decks hybrid; 80% electric or hydrogen	

Figure 25: London’s roadmap towards a zero-emission bus fleet in 2037

Roland Berger’s study “Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe”, published in 2015, states that a “total cumulative volume of 8,000-10,000 FC buses is required until 2025 to reach the cost projections of the production-at-scale scenario.” This scenario, presented in the previous part on FCEB’s cost evolution, was the most optimistic one. We consider that on average 30 cities have been or are participating to FCEB deployments programs (from CUTE to JIVE), and that these cities are committed to deploy all in all 300 to 400 buses until 2020. In the production-scale scenario, it is also assumed that “pioneering locations deploy 20 FC buses each in 2021”. This would sum up to 3,900 FCEBs in 2025. Consequently, in order to reach the target number of 8,000 and achieve the “production-at-scale” scenario, it is necessary to engage further locations willing to deploy FCEB.

²⁹ Mayor of London’s Transport Strategy – draft for public consultation, Figure 13, p.97 (June 2017).

The graph below³⁰ summarizes the ramp-up scenario for FCEBs in Europe.

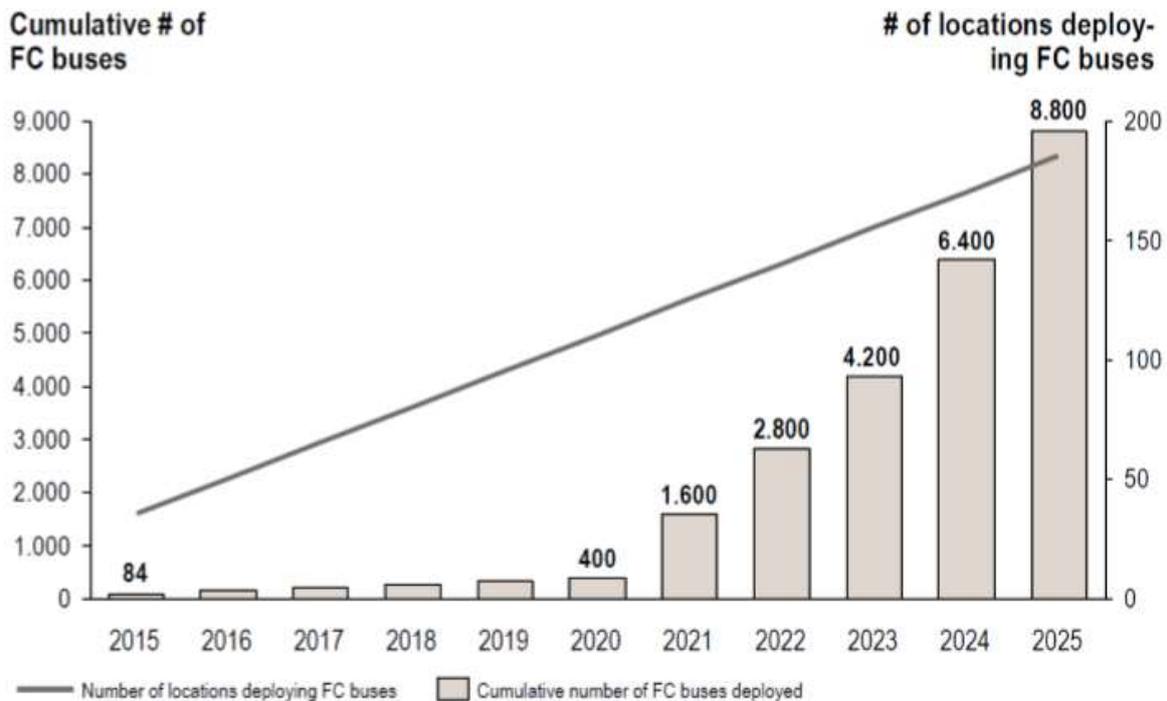


Figure 26: Ramp-up scenario for FCEB in Europe

International market

On a global level, the study “Hydrogen Scaling Up” (Nov 2017) from the Hydrogen Council reveals their vision for the hydrogen economy in 2050: 6Gt of annual CO₂ abatement, 18% of final energy demand, \$2.5tr of annual sales (hydrogen and equipment). However, to realize these objectives, “more than 15 million buses (~25%) running on hydrogen need to be in operation by 2050 in the world”. This target share “would imply a 10% share of sales by 2030 in priority markets, for annual sales of about 20,000 buses globally”.

China

China created the largest hydrogen fuel cell battery bus project in the world, located at Yunfu Industry site close to Foshan in Guangdong Province of South China. Chinese bus production has now overtaken that in EU, USA and Japan combined. 300 fuel cell electric buses have been produced by the company Synergy, in order to operate in all the city of Foshan in 2019³¹, where more than 10 hydrogen stations are about to be put into operation soon. The project’s strength rests in the complex of factories located at the same place: A Feichi bus manufacturing facility capable of building 5000 vehicles per year, a fuel cell stack production line using Membrane Electrode Assemblies (MEAs) from Ballard, a fuel cell module assembling line with fuel cell stacks produced by the Synergy-Ballard Joint Venture, a Research Institute and a hydrogen refuelling station. In 2017, only two years after the agreement between

³⁰ Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe, Figure 29, p.48, Roland Berger for the FCH JU (2015)

³¹ Liu, Z., Kendall, K., Yan X., China Progress on Renewable Energy Vehicles: Fuel Cells, Hydrogen and Battery Hybrid Vehicles, 25 December 2018

Synergy and Ballard, the Yunfu project overtook the EU hydrogen bus program. Then, by end of May 2018, the 300 planned 8.5 m buses were built and were beginning to run without passengers. By 2020, it is anticipated that 20 stations will be installed in Foshan, with more than **1000 buses** running.

USA

Although the United States government decided in 2009 to reduce funding for research into fuel cells and the hydrogen economy, the transportation industry and especially the Federal Transit Administration (FTA) have continued to invest into the technology by funding several programs, such as:

- the National Fuel Cell Bus Program (NFCBP): a \$180 million, multiyear, cost-shared research program for demonstrating commercially viable fuel cell technology for transit buses established in 2006.
- Transit Investments for Greenhouse Gas and Energy Reduction (TIGGER): \$225 million for capital investments that would reduce greenhouse gas emissions and/or lower the energy use of public transportation system. Most of the buses funded are battery electric buses.
- Low or No Emission Vehicle Deployment Program (Low-No Program): FTA’s newest program with \$271 million in funding to transit agencies for capital purchases of zero-emission and low-emission transit buses that have been largely proven in testing and demonstration efforts but are not yet widely deployed. At least 385 buses will be deployed through the program including FCEBs, BEBs, and hybrid electric buses. However, the FCEB projects only include 17 FCEBs.

In August 2018, 32 FCEBs were in operation at several locations throughout the USA³². Figure 27 lists the location and bus operators using these FCEBs.

Bus Operator	Location	Actives Buses	Funding program
AC Transit, ZEBA	San Francisco, Bay Area, CA	13	NFCB
SunLine Transit Agency	Thousand Palms, CA	10	NFCB & TIGGER
University of California at Irvine (UCI)	Irvine, CA	1	ND
Orange County Transportation Authority	Santa Ana, Ca	1	NFCB
the Stark Area Regional Transit Authority (SARTA)	Canton, OH	6	NFCB & Low-No Program
Flint Mass Transportation Authority	Flint, MI	1	TIGGER

Figure 27: Fuel Cell Transit Buses in Active Service in the United States

35 others fuel cell transit buses are planned in the United States and should be put in operation between end of 2018 and 2020, depending on the projects.

³² Eudy, Leslie and Matthew Post. 2018. Fuel Cell Buses in U.S. Transit Fleets: Current Status 2018. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-72208

According to the study “Electric Buses: a Review of Alternative Powertrains”³³, electric buses will dominate the North America market in 2020. However, this market penetration will be driven mainly by hybrid technology as shown in the graph below, drawn from the study.

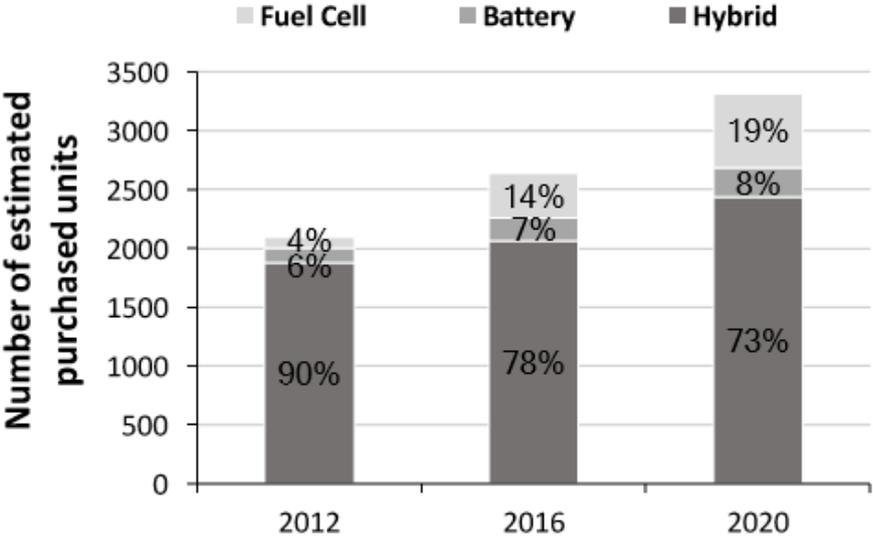


Figure 28: North America electric bus market profile

To conclude, it can be claimed that the market share of fuel cell electric buses has featured steady growth in recent years. Frost and Sullivan’s study “Strategic Analysis of Global Hybrid and Electric Heavy-Duty Transit Bus Market”³⁴ estimate that electric buses will hold 15% of global market in 2020. Asia Pacific regions, mainly China and India, are expected to dominate this market. However, the share of FCEB among electric buses should not exceed 30%.

As mentioned for the European and American market, the market trend for fuel cell electric buses is strongly affected through the national deployment programs and the funding associated with the different clusters. The following part “Main local, national and international policy instruments” will analyse the European projects. We will assess their mechanisms and coordination mode to expand the FCEB market.

³³ 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
³⁴ Frost & Sullivan. Strategic Analysis of Global Hybrid and Electric Heavy-Duty Transit Bus Market (NC7C-01). Frost & Sullivan Publication 2013.

5 – Main national and international deployment programs for FCEBs

Ensuring a stable and long-term deployment of FCEB requires to overcome numerous obstacles, mentioned in the previous part of this report, that only a concentrated effort of all players can overcome. Thus, the different stakeholders come together in consortium and joint ventures in order to share their vision and their strategies towards a future hydrogen mobility. This part of the report is dedicated to the coalition of stakeholders, their operation and coordination mode, thought to ensure a rapid and solid deployment of FCEB.

Stakeholders involved in Fuel Cell Electric Bus deployment

In this section, we will present the key stakeholders of the hydrogen mobility at different levels of authority.

National Level

Germany



The H2 Mobility and Consortium has a plan to build a German-wide network of hydrogen refuelling stations by 2020. It has committed to building 100 stations by the end of 2019, regardless of the number of Fuel cell electric vehicle (FCEV) sold in the country. This commitment represents the initial phase, which should be followed by the construction of another 300 stations to provide full coverage of the country, contingent on FCEV sales. Oil retailers, gas and automotive companies have

joined forces to overcome the disadvantage of being the first movers who invest in infrastructure that is not currently being used. Building a network of hydrogen stations while not yet having cars on the market is indeed a costly process.

France



The AFHYPAC federates French fuel cell and hydrogen stakeholders: companies, research institutes and laboratories, competitiveness clusters, territorial communities and regional association. Its ambition is to accelerate the deployment of hydrogen solutions for the benefit of the energy transition. To achieve this ambition, AFHYPAC communicates on the challenges of the 'hydrogen society', contributes to unlock deployments projects in France and influences the legal framework.

European Level



The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) is a “public private partnership supporting research, technological development and demonstration (RTD) activities in fuel cell and hydrogen energy technologies in Europe. Its aim is to accelerate the market introduction of these technologies. The three members of the FCH JU are the European Commission, fuel cell and hydrogen industries represented by Hydrogen Europe and the research community represented by the research grouping Hydrogen Europe Research”³⁵. It is the result of a long cooperation between representatives of industry, scientific community, public authorities and civil society in the context of the

European Hydrogen and Fuel Cell Technology Platform, launched under the 6th Framework Programme for Research (FP6).

For the period 2014 – 2020, the FCH JU have a budget of €1.33 billion. Its second phase (the “FCH 2 JU”) should last until 31 December 2024 and aims to demonstrate on a large scale the readiness of the technology to enter the market in the fields of transport (cars, buses and refuelling infrastructure) and energy (hydrogen production, storage, distribution).



Hydrogen Europe is the European Hydrogen and Fuel Cell Association. It currently represents more than 100 industry companies, more than 68 research organizations as well as 13 National Associations. It is based on three pillars: Industry, Research, and National Associations. The Industry and Research

division are both involved in the FCH JU, whereas the National Association pole is intended for trade association activities.

International level



The Hydrogen Council, launched at the World Economic Forum 2017 in Davos, is a global initiative of leading energy, transport and industry companies to accelerate the investment in the development and commercialization of the hydrogen and fuel cell sectors. It is the largest industry-led effort to develop the hydrogen economy. The growing coalition is comprised

companies such as Air Liquide, Alstom, Engie, Total, BMW, Daimler, Linde, Toyota, Honda, Hyundai, Kawasaki and Shell.

³⁵ <https://www.fch.europa.eu/>

Coalition of Fuel Cell Electric Bus stakeholders

This part will deal with the framework of the commercialisation initiative supported by the FCH JU. We will look in details into the different programs of deployment and then analyse their organisation and funding methods. Finally, we will focus on JIVE, the latest FCH JU program, to better understand its coordination mode.

Benefits of FCEB coalitions

The idea of these FCEB coalitions, that constituted the different programs supported by the FCH JU, was to bring together the demand side (bus operators, local governments of the cities, associations) and the supply side (bus manufacturers, technology providers, hydrogen suppliers). Both sides benefit from the experiences and lessons learnt through the coalition. The demand side gets transparency on costs and specification of future product characteristics with OEMs. On the other hand, the supply side has a privileged way to cooperate with customers in order to assess large-scale deployment solutions and define technical specifications and performance of future FCEBs. The coalition highlights the operational requirements, as well as the cost-down potential of a FCEB market.

A key challenge of the fuel cell bus commercialisation effort is to “stimulate interest from more bus OEMs, while simultaneously provide each OEM with sufficient order volumes to bring about the required cost reductions via economy of scale effects”³⁶. The hydrogen sector requires indeed a wider range of product offerings and increased competition. Once the bus costs reach a level at which the need for subsidy is eliminated by a sufficient demand, the coalitions would no longer be needed, as the market will be self-contained.

Nevertheless, it should be outlined that (at least) the first European programs that emerged were essentially intended to prove the feasibility of the FCEB and of their operation. The mass market introduction objective was, in practice, not a priority.

The different coalitions supported by the FCH JU

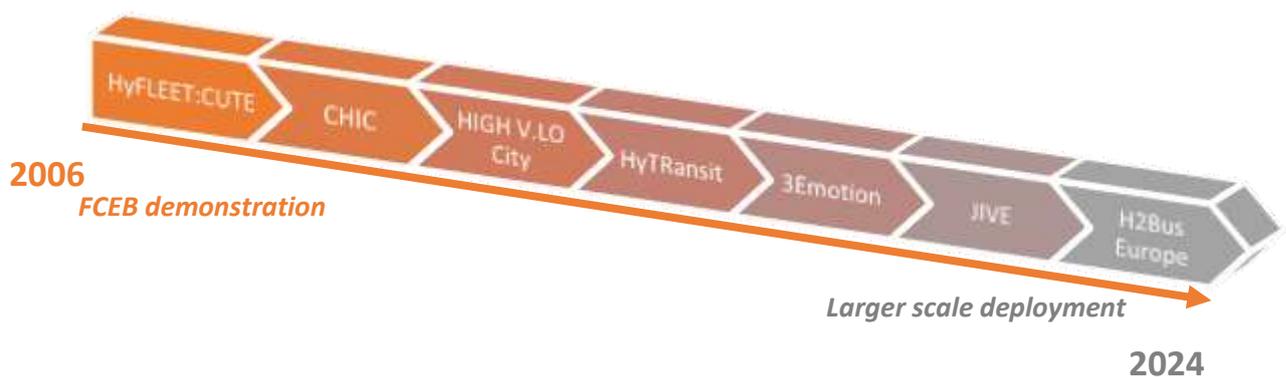


Figure 29: Timeline of the different FCEBs deployment programs from 2006 until 2024

³⁶ Strategies for joint procurement of fuel cell buses – a study for the FCH JU, Element Energy, 2018 DOI: 10.2843/459429

HyFLEET:CUTE (2006 -2009) has involved the operation of 47 hydrogen powered buses in regular public transport service in 10 cities: Amsterdam, Barcelona, London, Luxembourg, Madrid, Hamburg, Berlin, Reykjavik, Beijing and Perth. This project was co-funded by the European Commission through the Commission’s 6th Framework Programme. It helped demonstrate major developments in the FCEB technology.

CHIC₂

CHIC project (Clean Hydrogen in European Cities) from 2010 to 2016, embeded the knowledge and experience from HyFLEET: CUTE project and aimed to “intensively test the technology to generate learning for the final steps towards commercialisation by operating a minimum of 26 hydrogen buses in medium sized fleets in normal city bus operation, and substantially enlarging hydrogen infrastructure in 5 European regions.”³⁷ The project concerned 7 cities for a total of 56 buses (+ 20 buses in Canada). The main drawback of this project was the expensive capital cost of each bus (€600,000) due to a still too small production.

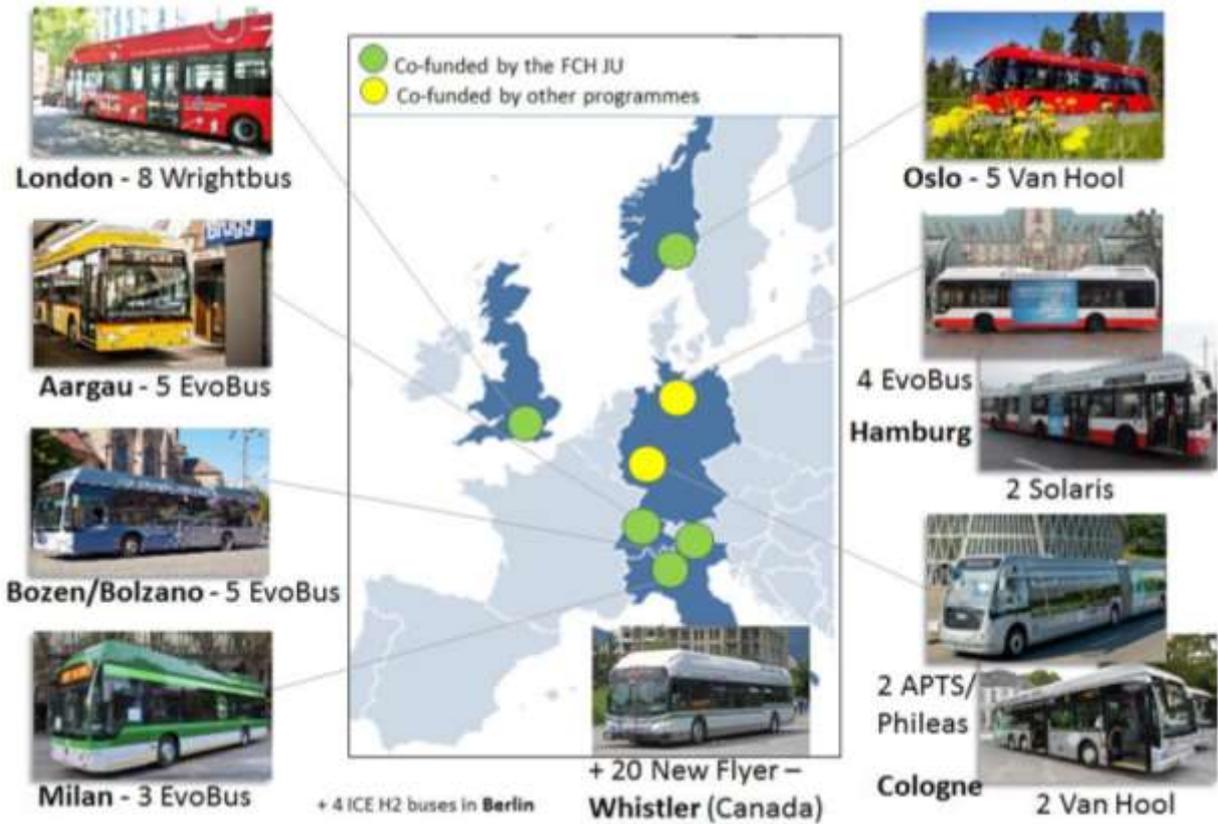


Figure 30: Location and number of FCEB ordered through CHIC. Source: CHIC Emerging Conclusions

³⁷ <https://hydrogeneurope.eu/project/chic>



High V.LO-City (2012-2017) concerned 4 cities (Antwerp (BE), Aberdeen (UK), San Remo (IT) and Groningen (NL)) for a total of 14 buses. The project sought to further broaden and consolidate the network of successful bus operators that implemented FCEBs. The generation of FCEB in the High V.LO-City project reaches efficiency levels that go far beyond those tested in previous fuel cell bus projects. The newness of this project compared to the previous one was to evaluate the entire life cycle costs of buses from their productions up to the final operation.



HyTransit (2013- 2018) aimed to introduce FCEBs and hydrogen infrastructure to Scotland. It planned 6 buses in Aberdeen. The implementation in Aberdeen had to test the economic and environmental benefits of hydrogen fuel cell transit technologies.



3Emotion (Environmentally Friendly, Efficient, Electric Motion) from 2015-2019 presents the deployment of 21 new fuel cell buses throughout Europe: Rotterdam (NL), Aalborg (DK), London (UK), Rome (IT), Versailles and Pau (FR). Its goal is to bridge the gap between current fuel cell bus demonstration projects and larger scale deployments by increasing the bus lifetime and availability and integrating the latest technologies to lower the TCO. The consortium comprises 7 public transport operators, a refuelling station operator, a bus manufacturer, a fuel cell manufacturer, a knowledge centre for evaluation and local authorities.



JIVE (Joint Initiative for hydrogen Vehicles across Europe) comprised to phases. The first one runs for six years from January 2017 and have a budget of €32 million to deploy 139 new FCEB and associated refuelling infrastructure across 5 countries: United Kingdom, Italy, Denmark, Germany and Latvia. The second phase (JIVE 2) started in January 2018 to deploy 152 others FCEB. Combined, the JIVE projects will deploy nearly 300 fuel cell buses in 22 cities across Europe by the early 2020s, which represents the largest deployment in Europe to date. JIVE should mostly address issues of cost of ownership and availability.

Organisation of the coalitions

One of the main thing that all these projects have in common is their organisation in clusters. In each cluster, the coordinator works with bus suppliers and customers to overcome difficulties related to the high costs of FCEBs implementation. On one hand, OEMs are waiting for large orders before reducing costs, while, on the other hand, public transport authorities are waiting economic fuel cell buses before placing large orders.

The cluster coordinators missions are multiple:

- Support the on-going procurement activity for coordinated purchase of FCEB
- Increase the number of cities participating in each cluster
- Support each partner in the development plans for FCEB
- Work with cities to understand their financing needs for the first wave of deployments
- Develop strategies for financing many hundreds of buses beyond the current subsidised phase.

Thus, their role is to accompany the participating cities in the transition phase, but also to give them the keys to a long-term FCEB deployment.

The clusters differ (in size and in location) from a program to another, and tend to get bigger.

The group of cluster coordinator is coordinated by Element Energy, a specialist energy consultancy, which reports directly to the FCH JU. The following figures are drawn from the report *Strategies for joint procurement of fuel cell buses*, Element Energy, July 2016.

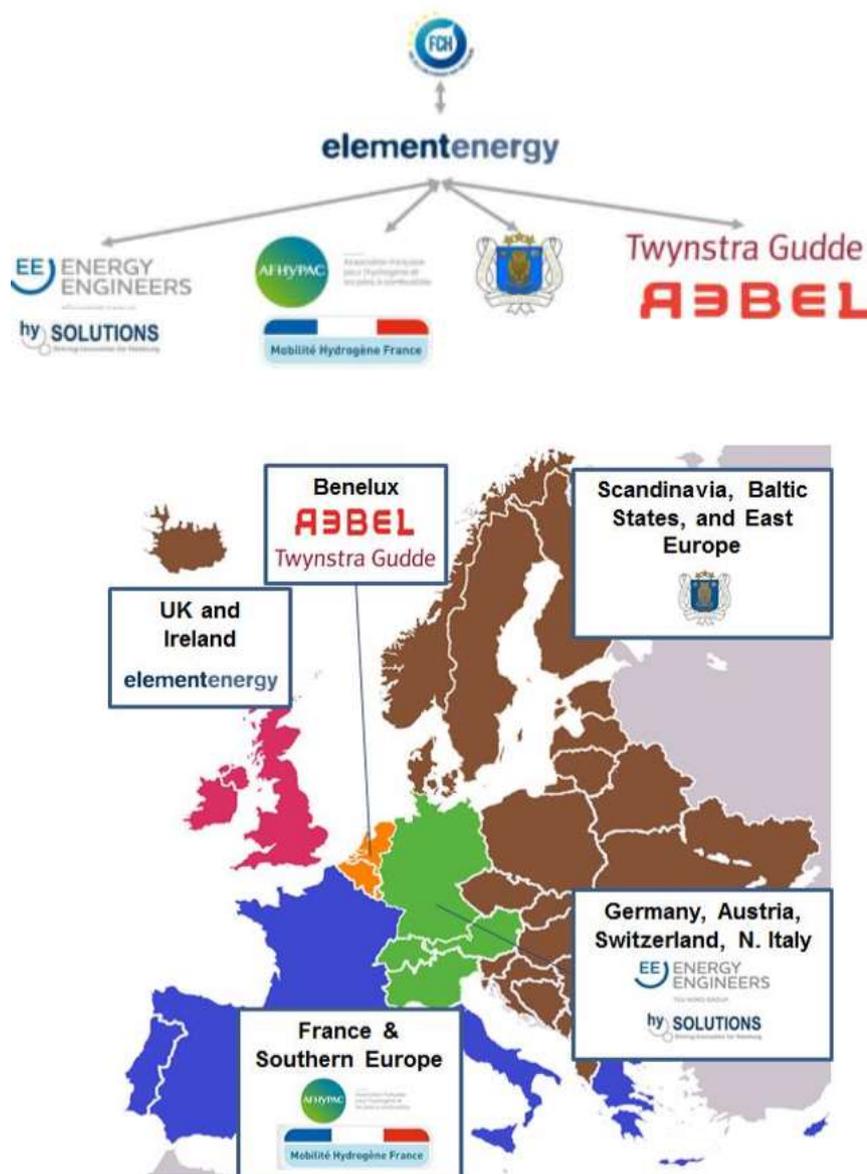


Figure 31: cluster coordination and location

Funding methods

The funding granted to the different deployment projects mentioned above should cover all the costs related to the bus purchase, fuel and maintenance. The majority of FCEBs projects planned are public sector led. The figure³⁸ below illustrates the structure of a typical funded FCEB demonstration project.

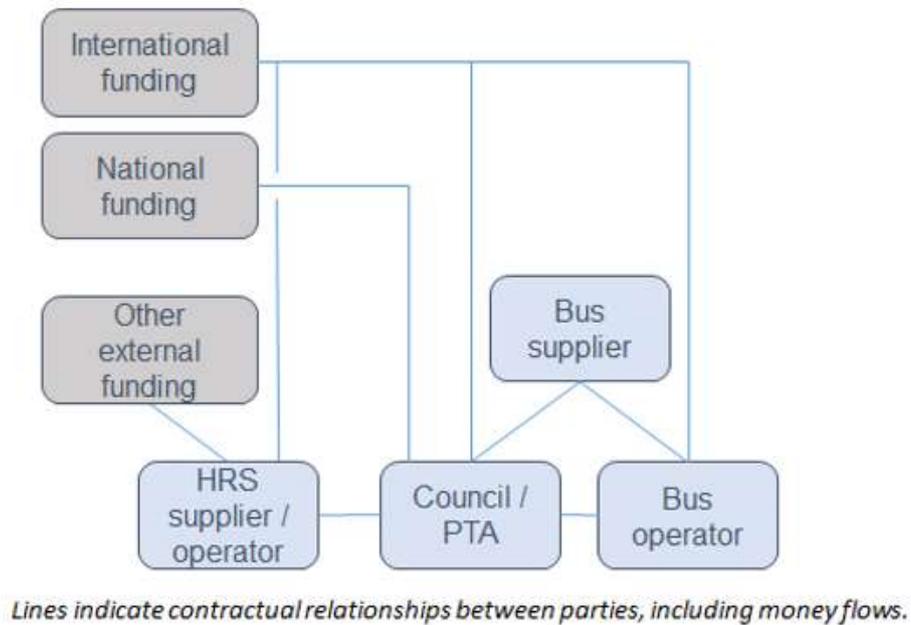


Figure 32: Structure of a typical fuel cell bus demonstration project

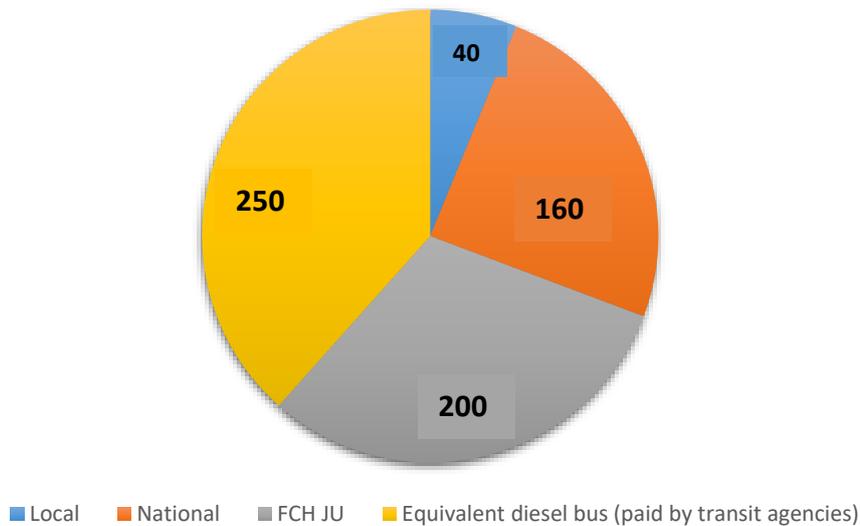
In the case where the public transport authority contracts directly with the bus supplier, the bus ownership remains with the public sector organisation. And then the buses are “leased to the operators for a rate dictated by the cost of leasing conventional diesel buses + diesel fuel + diesel bus maintenance allowance”⁴. The HRS can also be leased through a contract with the Council or directly with the bus operators.

The Council plays a major role, as it takes on responsibility for underwriting the project. The objective is indeed to limit the exposure faced by bus operators and suppliers to not put a brake on FCEBs deployment. Consequently, the risks are borne by the public sector.

According to the “Presentation of the JIVE Project – Joint Initiative for hydrogen vehicle across Europe” by Michael Dolman and Sabine Skiker, on a price ceiling of €650,000, “the funding per vehicle cannot exceed €200,000 per standard bus, provided they are equipped with a full power FC system of at least 50kW”. This meant that projects in each participating city had to secure additional funding from other sources. The distribution suggested in JIVE is the following:

³⁸ Strategies for joint procurement of fuel cell buses – a study for the FCH JU, Element Energy, 2018 DOI: 10.2843/459429

Fig33. Bus initial cost (in €k)



JIVE's project

The JIVE (Joint Initiative for hydrogen Vehicle across Europe) projects will demonstrate nearly 300 FCEBs in over 20 different cities across Europe, the largest European deployment to date. This project is divided in two phases: JIVE 1 and JIVE 2.

JIVE I

Duration: 5 years (2017 – 2022)

Costs: 106 M€ (32 M€ subsidy)

Coordination: Element Energy Limited

The first phase should deploy **139 FCEBs** in order to reach 30% of costs reduction compared to the current market. The clusters are:

- United Kingdom: 56 in London, Birmingham and Aberdeen
- Italy: 15 in South Tyrol
- Denmark: 10 in Slagelse
- Leetonia: 10 in Riga
- Germany: 51 in Cologne, Wuppertal and Rheine Mainz

The buses ordered in this phase should be operational this year.

JIVE II

Duration: 6 years (2018 – 2024)

Coordinated by Element Energy

Supported by a €25M grant from the Fuel Cells and Hydrogen Joint Undertaking (FCH JU)

The objective is to deploy **152 FCEBs across 14 European cities** throughout five clusters:

- Benelux: 50
- France: 15

- Germany/Italy: 88
- Northern/ Eastern Europe: 50
- United Kingdom: 88

For now, no buses have been delivered yet.

The figure³⁹ below summarizes the number of buses that should be put in operation within JIVE's framework.

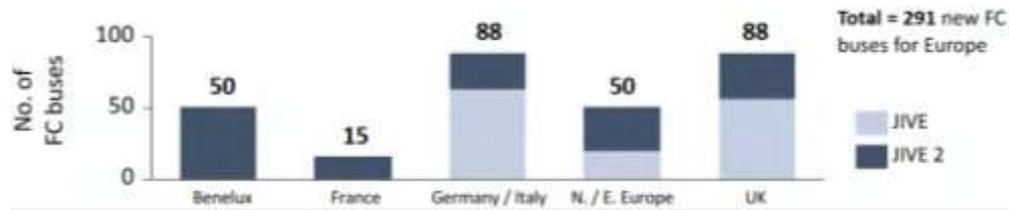


Figure 34 : number of FCEB to be put in operation in JIVE 1 and 2 by clusters

JIVE 1 and 2 have common objectives, listed below⁴⁰:

- Achieve a maximum price €625k-€650k for a standard fuel cell bus thanks to economies of scale – or lower
- Foster joint procurement processes, encourage manufacturers to develop and refine their fuel cell bus offers
- Validate large scale fleets in operation and encourage further uptake, showcasing that fuel cell buses represent a viable alternative for public transport authorities, offering the same operational flexibility as diesel buses.
- Deploy largest hydrogen refuelling stations in Europe and operate them at near 100% reliability
- Share data and best practice to support the adoption of the technology and provide evidence of the suitability of fuel cell buses for wider roll-out

However, JIVE 2 has the specificity to enable new entrants to trial the technology more easily and to stimulate further large-scale uptake. The second phase also involves as well regions with experience of FCEB fleets deployments (e.g. Cologne) as regions seeking to build their knowledge and experience by demonstrating FC buses in small fleets for the first time (e.g. Auxerre, Gävleborg). All deployment locations in JIVE 2 share the ambition to extend their fleets, if the initial demonstrations are successful. That is why these locations will certainly be the first locations chosen for larger scale roll-out of the technology in the 2020s.

How do JIVE operate?

Organisation and coordination mode

As indicated in fig. 2, Element Energy is the project's general coordinator. The energy consultancy firm identifies all the cities' candidacies et filters the most relevant ones, based on rigorous criteria like:

- the number of bus ordered
- the experience with other zero emission solutions

³⁹ Presentation of the JIVE Project – Joint Initiative for hydrogen vehicles across Europe, M. Dolman, S. Skiker, May 2019

⁴⁰ <https://www.fuelcellbuses.eu/projects/jive>

- the ambition of the investments in the hydrogen technology
- the willingness of operators to further expand the fleets after the projects

The selected candidacies are then handled at the national level by the cluster coordinators. Element Energy has also the responsibility to monitor all the JIVE project, which means it collects data, then reports to FCH JU and make sure that the deliveries are correctly executed. Moreover, there is an annually reporting period, where Element Energy gathers all information reported by cities and provide FCH JU with a financial and technical report.

The FCH JU decided to call on an energy consultancy firm for several reasons. First, the FCH JU wanted a company with early, solid and growing practice in hydrogen energy, and that could use its influence to push hydrogen in the UK and then in Europe. Element Energy had also the particularity to have accumulated experience in managing EU projects and applicant consortium. Finally, Element Energy presented the capacity to make relevant comparison between hydrogen and competitive clean tech due to other clients.

The FCH JU organises working meetings and others events to help the participating cities share their feedbacks. Element Energy also favours director opportunities to exchange ideas and share experiences, such as zero-emission conferences. The cities are requested by the cluster coordinators, themselves requested by Element Energy. Similarly, when cities need to report to the FCH JU, they call on the cluster coordinator, which then call on Element Energy. This coordination mode applies equally to participating cities and to cities wishing to participate to the JIVE project.

Call to candidacy and tender process

To launch the tender process, the communities get information from the different OEM, prepare a cost estimate for their project and then submit it to Element Energy. If the FCH JU gives the go-ahead for the project, a classic tender offer is launched.

Engagement of the participating cities

Participating to the JIVE projects involves some responsibilities for the cities. Beyond demonstration of the technology, the participating cities are expected to engage in communication of their efforts to partner cities/regions in Europe and beyond through various channels like dissemination campaign, series of international Zero Emission Bus Conferences, etc.

Risks, challenges, and lessons learnt⁴¹

The risks, challenges and lessons learnt presented in this section are drawn from a presentation made by M. Dolman (Element Energy) and S. Skiker (Hydrogen Europe) in May 2019. Therefore, their data and conclusions are the latest that can be found on JIVE's progress.

Risks

One of the biggest risks associated with JIVE for the deployment of FCEB is that joint procurement exercises are not always the most appropriate model to facilitate the commercialisation of these buses given the number of stakeholders involved. The multiple sources of funding mean that FCH JU funding is well leveraged, but this adds complexity and timescale challenges.

⁴¹ *Presentation of the JIVE Project – Joint Initiative for hydrogen vehicles across Europe*, M. Dolman, S. Skiker, May 2019

Challenges

Costs and technologies are evolving constantly so that relatively limited operational data for latest generation buses is available. This lack of data leads to challenges in planning and budgeting for whole-life costs.

Besides driving initial costs drastically down, one of JIVE's main challenges is to be able to procure sufficient H₂ supplies in parallel with buses. As demonstrated in the TCO comparison of standard FCEBs and conventional diesel bus (fig.21), fuel costs are a critical element for FCEBs to be cost-effective. The cost of hydrogen at small scale deployments is thus an issue that need to be tackle in priority. It is necessary that the hydrogen supply industry recognises that the bus industry will need low cost hydrogen to be competitive.

It is also important to remind that technical challenges remain, notably providing sufficient range and passenger carrying capacity for double deck buses.

Finally, JIVE' challenges is also about reducing the uncertainty over lifetime costs in order to attract more early adopters that will be able to commit to ordering larger fleets.

Lessons learnt

According to *the Presentation of the JIVE Project* by M. Dolman and S. Skiker, the lessons learnt can be divided in four categories: bus operator engagement, early market engagement, tender development and contract award.

Bus Operator Engagement	Early Market Engagement
Early engagement with operators is critical	Identify the challenge to be overcome
Agree selection process on how a FCEB operator will be appointed	Identify suppliers/OEMs who have the potential capability to meet the challenge
Obtain their preferred approach to operating and maintaining the vehicles	Engage with potential suppliers/OEMs to explore their ability to mobilise, their product offers
Set and agree roles, responsibilities and expectations of all parties	Use this as an opportunity to test assumptions and align expectations
Identify potential deployment garages and routes	Ensure the output of this aligns to the procurement approach and specification
Tender Development	Contract award
Agree standard specifications with bus purchaser and operator	Re-evaluate the operators' requirements in terms of specification of the bus and approach to maintenance
Lean on organisations with wider experience in the sector	Respect the timescales

All these lessons learnt highlight the crucial role of coordination between the different stakeholders, especially between bus suppliers and bus operators (text in bold). Aligning expectations, notably by well-establishing the tender process, is a necessary condition for a long-term agreement between bus operators and bus suppliers. This is the only way to secure further purchases and to achieve the production-at-scale scenario.

JIVE first emerging conclusions outline an important aspect, which is often underestimated. As all innovative technologies, fuel cell buses require appropriate staff training and new mechanical skills

compared with diesel buses. That's why enough time should be dedicated for training. However, it has been proved that adaptation has been easier for staff already trained on hybrid buses. It is important to explain to the staff the benefits they contribute to in order to increase their motivation, which is a key to the project's success.

Finally, as the sector expands, it becomes clearer that the fuel cell bus will need to be financed like most buses today, which implies leasing products for the buses and stations installed at the expense of the hydrogen suppliers.

Success until JIVE

Project	Success	Lessons learnt
CHIC	-Operating range similar to that of diesel buses (>350km) -Refuelling time <10mins -Satisfaction for end users	-Improve bus availability through resolving technical issues and increasing scale -Reduce bus and hydrogen price through commercialisation -Harmonise regulations
HIGH V.LO.City	-14 buses in full operation with >85% availability -97% availability of stations -good customer acceptance	- Ensure sufficient supply chain in place - HRS can easily be scaled up when necessary and should be located close to bus depot

In the *Presentation of the JIVE Project* by M. Dolman and S. Skiker, the lessons learnt from other preceding projects, as well as their successes, are mentioned. It enables us to understand the evolution of the different phase, from demonstration and technical targets to economically viable deployments.

JIVE's success

Even if not all FCEBs have been delivered, OEMs and bus operators announcement prove that key players are getting serious. Responses to the procurement exercises suggest indeed a growing interest in offering fuel cell buses from suppliers worldwide. They seem to have been successful in aggregating demands and stimulating the supply side.

The ceiling price objective of €650k / €625k for standard single deck buses has been reached. Some suppliers have indicated far lower prices (e.g. well below €450k) for customers willing to commit to sufficient volumes (sustained orders of at least 100 buses per year per OEM). If those low prices are confirmed, fuel cell buses could become the lowest cost zero emission option.

OEMs announcements in JIVE's framework:

"Bavarian fuel cell specialist Proton Motor Fuel Cell GmbH of Puchheim near Munich announced the receipt of a confirmed order from ebe EUROPA GmbH [...] The Memmingen-based integrator and distributor of electric buses has ordered 15 hydrogen powered fuel cells with 60 kW generated power. The ultimate customers are four German city councils (Frankfurt am Main, Mainz, Muenster and Wiesbaden). The order, which includes service and maintenance contracts as well, is a result of the first tender of European funded JIVE PROJECT".⁴²

"Ballard Power Systems has announced a purchase order from Wrightbus [...] These initial 20 double-decker buses – part of the 55 buses ultimately planned for the U.K. cluster under JIVE I – will be deployed

⁴² <https://www.proton-motor.de/gb/millionenauftrag-fuer-puchheimer-unternehmen-proton-motor-elektrobushersteller-ebe-europa-bestellt-15-wasserstoff-brennstoffzellen/>

*on three routes with Transport for London (TfL) [...] All the Ballard modules in this order are expected to ship by end-2019 and all related buses are expected to be deployed with TfL by the end of 2020.*⁴³

Limitations of JIVE

Several dysfunction or friction influences JIVE's coordination.

Element Energy organises a call to candidacy, to which the cities can respond in two months. This time period is particularly short, and is at the disadvantage of cities, that are not related to important national OEMs committed to hydrogen. Van Hool is the leader of FCEBs, as it gets almost 90% of the European FCEBs ordered. The famous Dutch OEM lobbies a lot of Belgian and Dutch cities, so that their candidacy documents were better prepared than the Spanish or French cities ones, which are underrepresented in the project. However, another reason for this misrepresentation is a different maturity of the market. German, British, Dutch and Belgian cities had previous experiences with FCEBs, whereas France and Spain have more recent interest. The more the project goes by, the more cities wish to be involved in FCEB deployments. The reserve list of cities waiting for funding from the FCH JU grows longer.

The organisation in cluster, itself, creates problems, as cities interest can differ within the same cluster. This cluster organisation was intended to facilitate the communication, but also the choice of the OEM, since cities prefer to select a national manufacturer. So, each tender process depends on each cluster. However, it is not always simple. For cluster including several countries, it is sometime harder to find compromises about the manufacturer and among one country, cities can be very different and thus have different expectations.

Finally, the number of stakeholders involved in the joint procurement lead to delays in its implementation.

What JIVE needs to achieve to satisfy large scale validation and prepare the commercialisation phase

Deployment programs are not only necessary to drive down initial costs, stimulate OEMs or to prepare the bus operator's staff to deal with a new technology, they also aim to reach a large scale validation, which means setting up global standards in order to ease the transition towards a fully commercialized product.

The buses deployed within the JIVE project should have a high level of standardization and learning from previous projects reflects significantly in the availability of the buses. The buses are considered to be close to commercial readiness from both a technical maturity and an economic perspective if the following requirements are accomplished⁴⁴:

- Buses can be fuel cell-hybrid or with a fuel cell system as the dominating power source, but at least half of the energy required for performing their expected duty cycle should be provided from hydrogen.
- The minimum operational period for any bus demonstrated in the project is 24 months, whereas in all cases arrangements for extending operation after the end of the project are expected and should be documented in the proposal as a matter of key importance
- >20,000h vehicle operation lifetime initially, minimum 25,000h lifetime as project target

⁴³ <https://newpowerprogress.com/no-jive-london-buses-fuel-cells/>

⁴⁴ <https://cordis.europa.eu/programme/rcn/700891/en>

- Availability >90% on a fleet basis after an initial 6-month ramp-up phase (to be measured in available operation time excluding scheduled preventive maintenance)
- Tank-to-wheel efficiency >42%
- Maximum price (for the customer): 650,000€ for a standard bus and less than 1,000,000€ for articulated buses

After JIVE

What happens after JIVE? The commercial phase from 2020.

All the deployments programs presented previously, from HyFLEET:CUTE to JIVE are characterised by relatively high costs, short durations, and large public subsidies. It is important to be well aware that these deployment programs are unsustainable in the medium term, as there is not sufficient funding available to support an increasing roll-out of buses at these levels. The more FCEBs are progressing from a deployment phase to a commercial phase, the more financial risks will need to transition away from local authorities and back towards the operators and their technology suppliers. That's why we need a new approach to continue the roll-out of FCEBs for the post-2020 period.

The three keys for a successful commercial phase are: scale of bus demand, scale of demand at a depot and access to low cost energy.

Planning beyond the subsidised phase requires to push for an increasing number of cities trusting and adopting the hydrogen technology to meet their objectives of zero emission mass transit. OEMs have made it clear that they need continuity of demand in order to maintain low prices. According to Element Energy's *White Paper on commercialisation of fuel cell buses*, "with a regular demand of around three buses per week (per manufacturer) it becomes possible to introduce a new dedicated fuel cell bus production line and to obtain significant price advantages from suppliers by offering regular long-term supply contracts".

Which future for the cluster in the commercial phase?

Most of the cities involved in clusters "have declared their willingness to expand their bus fleets in the medium term and to make further and more intensive use of the hydrogen infrastructure being installed to fuel the initial fleets of buses"⁴⁵.

Even if some dynamic players are beginning to develop their own initiatives to accelerate the hydrogen sector, it seems relevant to continue the coordination of FCEB demand, at least in the early phases of the commercialisation, to ensure confidence amongst all stakeholders around the robustness of the demand. There is no doubt that the cluster leader will have a lot of work to do before the market of FCEB becomes completely self-sustained: work with national level policy makers to propose subsidy schemes that suit the demand of the commercialisation phase, provide unbiased market data to help support commercial propositions, define the most appropriate hydrogen production and distribution options for each region, help the regulatory framework to become more suited to bus hydrogen consumption, etc...

⁴⁵ *Strategies for joint procurement of fuel cell buses – a study for the FCH JU*, Element Energy, 2018 DOI: 10.2843/459429



On the 3rd June 2019, the latest deployment program **H2Bus Consortium** were 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.”

To conclude, the FCH JU has supported a range of initiatives designed to move the hydrogen technology for buses from the development phase to the mass market phase, where they can fulfil their potential as a mainstream zero emission vehicle for public transport. From real-world pre-commercial demonstration projects (CHIC) to cluster coordination initiatives (JIVE), the pathway towards a commercialisation of FCEBs in Europe have been supported by a wide variety of stakeholders.

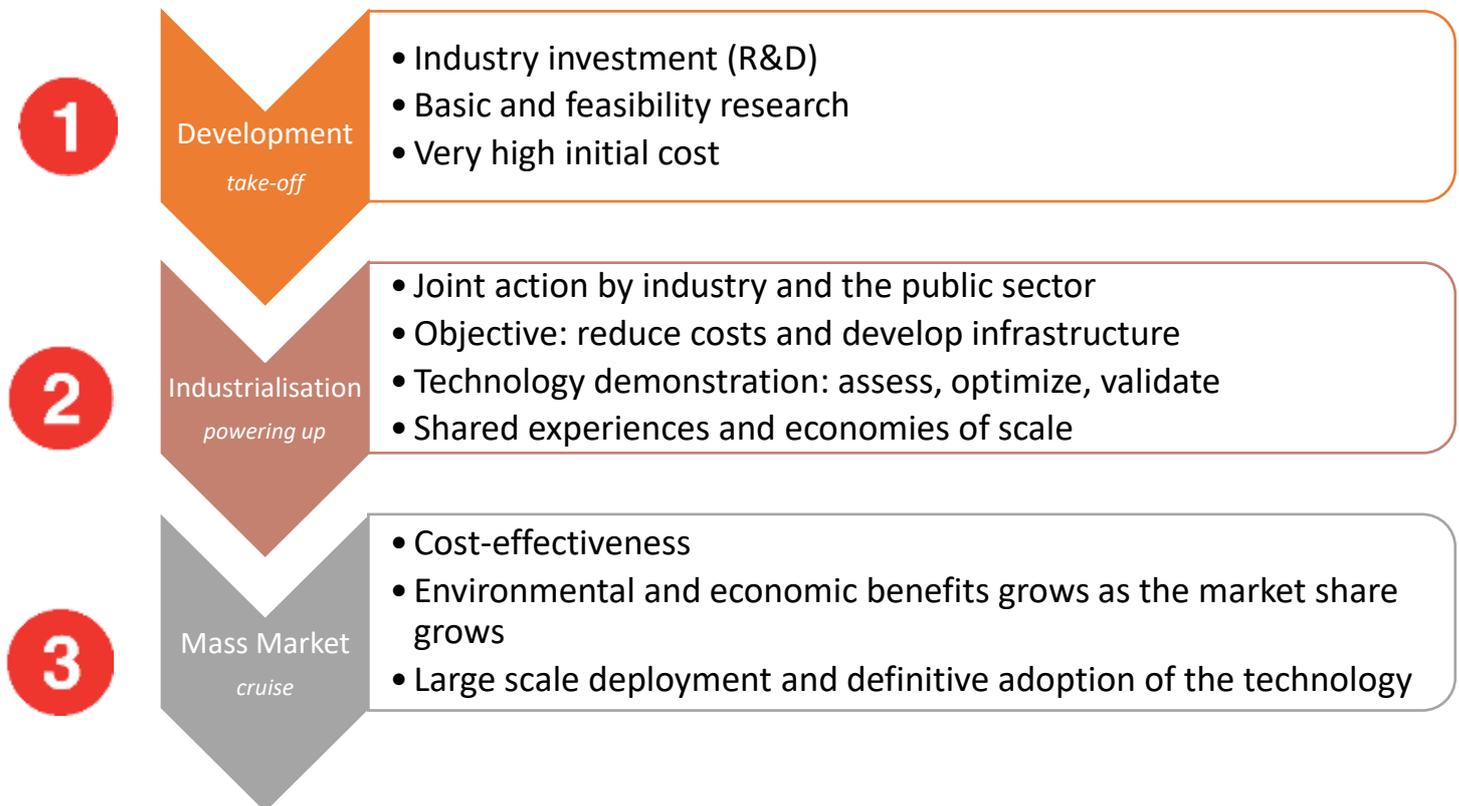


Figure 35: Representation of the commercialisation process developed for FCEBs

Conclusion

Beginning of 2019, with more than 15 years on the road and millions of miles in passenger service, fuel cell electric buses have proven their performance and their suitability to mass transit. If there are still some technical obstacles to overcome, notably concerning the hydrogen-refuelling structure, the current generation of FCEBs is now being deployed to provide a 1:1 replacement to conventional buses, allowing bus operators to migrate their fleet to zero emission without affecting service.

From an economic point of view, the organisation in clusters succeeded in reducing the initial costs and stimulating the OEMs interests. From the first European funded deployment program in 2006 to more recent program JIVE, the bus initial costs dropped from about €1,000,000 to €600,000. Regarding the total cost of ownership, FCEBs are not cost-effective compared to conventional buses. A difference of €1.4 per km, which results in an average abatement cost of around 1000€/tCO₂ eq. However, this situation could reverse once the fossil parity reached for sustainable hydrogen.

Concerning the second externality, hydrogen refuelling station (HRS) deployment projects, such as Hydrogen Mobility Europe, are part of international hydrogen development networks led by the Hydrogen Council internationally and by Hydrogen Europe in Europe. There are currently a total of 152 HRS in Europe, 136 in Asia and 78 in North America. Considering that some of them are only intended for private use, further HRS development is needed to sustain a potential fleet of 1,000 FCEBs in Europe by 2025.

The cluster's joint procurements made it possible to move beyond the take-off phase and to enter in the powering up phase. However, the objectives recommended by Roland Berger for a "production-at-scale" scenario (similar to cruise phase) are still unachievable. The clusters need to find a way to integrate more cities in their deployment programs. Despite new OEMs entering the market, the number of FCEBs available remains relative limited, compared to battery electric buses, which seem to remain the solution cities favour when it comes to zero emission mass transit.

Effective government policy, as well as consortium of industries, institutes, local authorities and associations are also necessary to spur private investments into fuel cell technology. These different stakeholders empower and amplify their actions in the framework of deployment programs to create incentives on both the supply and demand side of the sector.

As a conclusion, we can highlight the importance of framework conditions to support hydrogen deployment: regulation, changes in law, public transport financing, incentives for OEMs. As an example, London developed Low Emission Bus Zone to support zero emission buses. However, a good momentum is not enough to ensure a long-term deployment. Some aspects seem to be left out by the clusters: the legal and social aspect of FCEBs deployment. Those two aspects are yet essential for the cruise phase. The regulators need to understand that a less conservative legal approach concerning hydrogen production through electrolysis is necessary to deploy fuel cell mobility. But, even if the strict regulation of industrial hydrogen becomes more flexible, the social acceptance of the hydrogen technology depends on the public trust in FCEB safety.

The plans of a number of cities to ban the diesel through the use of zero emission solutions will create a significant market within which the fuel cell bus can be competitive. This is a momentum that deployment program need to seize and take advantage of by increasing their efforts to maintain a sufficient offer from OEMs and interest from cities. Promoting hydrogen mobility by setting it in a "power-to-gas" context would help the clusters overcome the remaining obstacles.

Hydrogen is an energy solution of today, and not only of tomorrow, as it opens gateways to tackle the issues of the "after battery" and of the seasonal storage need. It is still time for Europe to become a leader in this sector and overcome its Asian neighbours. After the creation of the Battery Airbus between France and Germany to catch up the technology and economic gap of Europe, why not creating a Hydrogen Airbus to gain a competitive edge over Asian?

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