Roland Berger

50 navigating complexity

Development of Business Cases for Fuel Cells and Hydrogen Applications for Regions and Cities

FCH Buses

FCH

Brussels, Fall 2017

This compilation of application-specific information forms part of the study ***"Development of Business Cases for Fuel Cells and Hydrogen Applications for European Regions and Cities"*** commissioned by the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH2 JU), N° FCH/OP/contract 180, Reference Number FCH JU 2017 D4259 .

The study aims to **support a coalition of currently more than 90 European regions and cities** in their assessment of fuel cells and hydrogen applications to support project development. Roland Berger GmbH coordinated the study work of the coalition and provided analytical support.

All information provided within this document **is based on publically available sources** and reflects the **state of knowledge as of August 2017**.

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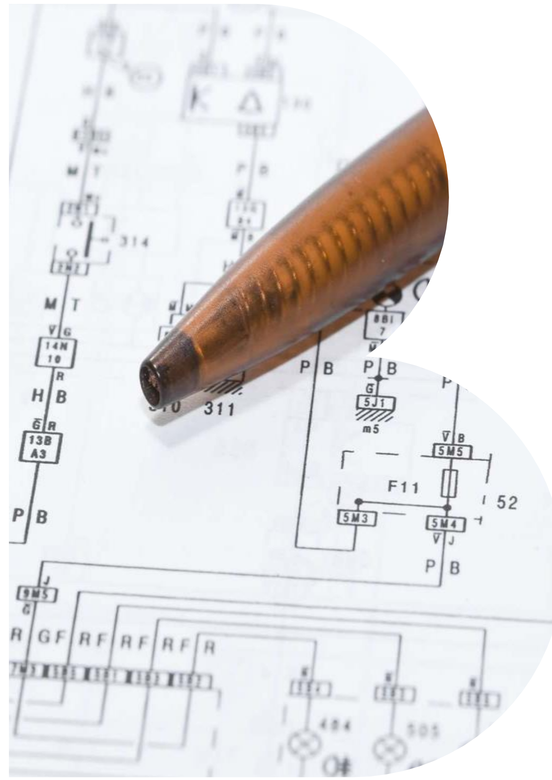
A. Technology Introduction



Fuel cell electric buses offer an technologically advanced, zero-emission alternative to the diesel combustion engines

Fuel cell electric buses

Brief description: Fuel cell electric buses built on a conventional chassis (12-18m) use compressed hydrogen gas as a fuel to generate electricity via the fuel cell (FC dominant powertrains). Other hybrid vehicles e.g. with plug-in batteries or FCH range extenders (larger battery, smaller FC) as well as minibuses are pursued as well

Use cases: Regions and cities can use/promote fuel cell electric buses in all fields of urban public road transport where diesel buses are used today; regions and cities can stipulate zero-emission vehicles through tender requirements for new bus fleets

Fuel cell dominant electric buses (FCEBs)[1]

Key components	Fuel cell module, tank, balance of plant and periphery, battery, e-motor and inverter, mechanical drive line
Output	>100 kW
Efficiency; consumption; range	51-58%; 8-14 kg H_2 /100 km; 250-450 km
Fuel	Hydrogen, 350 bar, ca. 45 kg tank (e.g. total of 3 tanks)
Passenger capacity	Ca. 75-105 (dep. on size and layout)
Approximate unit cost	Approx. EUR 625,000 (upper limit, FCH2 JU JIVE2)[1]
OEMs (selection)	Daimler EvoBus, Van Hool, VDL, Solaris, Toyota, Wrightbus
Fuel cell suppliers (selection)	Ballard, Hydrogenics, UTC Power, NuCellSys (selection)
Typical customers	Municipal public transport operators, (public or private) bus service operators
Competing technologies	Diesel, diesel-hybrid, biofuels/biomethane, CNG, battery EV

1) Range-extender fuel cell electric buses exist as well
2) Recent industry-based analyses led by the FCH2 JU outline production-at-scale scenarios which see average purchase prices fall to approx. EUR 400,000 over the next ca. 10 years
Source: Roland Berger

There are already large scale deployments of FCH buses in Europe, enabling the transition to a fully commercial application

Fuel cell electric buses

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Overall technological readiness: As one of the most advanced FCH applications, fuel cell electric buses are in a pre-commercial phase with large scale transit-based demonstration projects being currently under way and expected to continue over the coming years

TRL*

1 Idea | 2 | 3 Tech. formulation | 4 | 5 | 6 Prototype | 7 | 8 Fully commercial | 9

Demonstration projects / deployment examples (selection)

Project	Country	Start	Scope	Project volume
Joint Initiative for Hydrogen Vehicles Across Europe (JIVE)		2017	Large scale deployment of 140+ fuel cell buses across 9 European locations in cooperation with FCH JU; coordinated bus procurement activities	EUR 106 m
3EMOTION		2015	Deployment of 21 new and 8 existing FC electric buses in several countries all over Europe including the refuelling infrastructure. 6 public transport operators	EUR 41 m
Integration of Hydrogen Buses in Public Fleets (HIGH V.LO-CITY)		2012	Large scale demonstration of FC buses and refuelling infrastructure addressing key environmental and operational issues, commercial fleets in 3 EU regions	EUR 29.2 m
Clean Hydrogen in European Cities (CHIC)		2011	Flagship zero emission bus project demonstrating readiness of FC electric buses for widespread commercial deployment	EUR 81.8 m

Recent products / systems (selection)

Name	OEM	Product features	Country	Since	Cost
Citea Electric	VDL	Within the framework of H2busses Eindhoven, deployment of 2 18m tri-axles VDL buses with a trailer where formic acid is split into hydrogen		2017	n.a.
Urbino 18.75	Solaris	Deployment of first Solaris Urbino electric buses with fuel cell range extender; deployed on Hamburgs "innovation line"		2014	n.a.
A330	Van Hool	Deployment of 10 13m tri-axles hydrogen buses in Aberdeen, with 50 kg storage capacity, part of strategy to create a hydrogen economy in the region		2014	n.a.

Source: Roland Berger

*) Technology Readiness Level ≤ 5 6-7 8-9

Fuel cell electric buses could help reduce carbon and noise pollution and increase standard of living in urban areas

Fuel cell electric buses

Use case characteristics

Stakeholders involved

- Customers (public transport operators, bus service operators etc.)
- OEMs and FC manufacturers, H_2 -suppliers
- Public authorities (vehicle approval, regulatory framework for emissions etc.)

Demand and user profile

- Same service of routes and service hours as diesel buses (different topographies, route lengths, total distance travelled p.a.) incl. necessary reliability of operations (e.g. up to 95%) to meet schedules and have full-day continuous operation away from the depot

Deployment requirements

- Hydrogen refuelling station infrastructure – also permitting of inner city refuelling stations close to residential neighborhoods very complex
- Maintenance & repair infrastructure
- Permitting and licensing of commercial operation

Key other aspects

- -

Benefit potential for regions and cities

Environmental

- Depending on production of hydrogen, zero tailpipe emissions of pollutants (esp. NO_x) and greenhouse gases (esp. CO_2)
- Low noise pollution (depending on speed and track conditions almost no noise emissions at all)

Social

- Public health benefits (esp. in urban areas), overall higher standard of living
- Lower adverse impact on residents adjacent to major inner-city logistics routes, e.g. retail pedestrian areas

Economic

- With CAPEX reduction, increases in efficiency and affordable supply of hydrogen, potential to reduce TCO[1] below battery EV, biofuel and even diesel buses

Other

- High passenger comfort based on deployment experience
- Generally high public / every-day visibility as "urban" FCH use case, FCH flagship potential for regions and cities

1) Total Cost of Ownership

Source: Roland Berger

Roland Berger

As large scale deployments are ongoing, further improvement of technology and reduction of CAPEX/OPEX expected

Fuel cell electric buses

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Hot topics / critical issues / key challenges:

> **Reduction of CAPEX,** mainly through further large scale deployments across Europe

> **Technical performance,** reduction of bus downtimes for costly maintenance (increase of overall bus availability) in order to increase overall utilisation of fleet, efficiency improvements

> **Hydrogen infrastructure,** i.e. distribution logistics, local storage, refuelling stations and respective costs

> **Well-to-Wheel emissions,** reduction potential largely depends on resources used for hydrogen production

> **System integration and range extension,** enlargement of operation range or further development of hybrid operation with battery powered power train for extension

> **Cost of hydrogen,** strongly influences the competitiveness towards benchmark technologies

Further recommended reading:

> FCH2 JU, 2017 – Fuel cell electric buses demnonstation projects deployed in Europe

> FCH2 JU, 2016 – Strategies for joint procurement of fuel cell buses

> FCH2 JU, 2015 – Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe

> EC DG Mobility and Transport, 2017 – Declaration of intent on promoting clean buses deployment

Key contacts in the coalition:

Please refer to working group clustering in stakeholder list on the share folder

https://sharefolder.rolandberger.com/project/P005

Source: Roland Berger

Roland Berger

Fuel cell minibuses are a smaller, zero-emission alternative to large urban FCH buses with a variety of potential use cases

Excursus: Fuel cell electric minibuses

Brief description: Fuel cell minibuses are a hydrogen-fuelled transport application, using compressed hydrogen gas as fuel to generate electricity via a converter (a low-temp. PEM fuel cell) to power a electric engine – FCH minibus concepts are generally based on FCEV (i.e. car) technology

TRL*

1 Idea 2 3 Tech. formulation 4 5 6 Prototype 7 8 9 Fully commercial

Use cases: Cities and regions can deploy or incentivise the deployment of FCH minibuses for example in shuttle services (e.g. airports, hotels, resorts, etc.) and public transport (e.g. bus lines with fewer passengers or routes through small villages or inner cities with narrow streets) to increase efficiency and decrease local emissions (pollutants such as NO_x, CO_2, noise)

Existing prototypes and demonstration projects (selection)

Project/product	Country	Since	Specifications
Hyundai H350 Fuel Cell Concept		2017	Hyundai presented this concept vehicle at the IAA 2016 in Hannover with 2 times 700-bar high-pressure tanks comprising a storage of 7.05 kg of hydrogen and powered by a 100 kW electric motor. The vehicle reaches speeds of up to 150 km/h
Dolomitech Fuel		n.a.	This vehicle is produced by Dolomitech s.r.l. and is based on an IVECO Daily model and was developed with several partners, including Linde. It is equipped with a 80 kW electric traction motor fuelled by a 7 kg hydrogen tank with hydrogen stored at 350 bar

i For additional information regarding fuel cell powered minibuses, please contact our Roland Berger team directly

Source: Roland Berger

*) Technology Readiness Level ≤ 5 6-7 8-9

B. Preliminary Business Case

Fuel cell buses are a highly flexible zero emission option for public transport; they can in principle be operated like diesel buses

Value propositions of fuel cell hydrogen buses

High daily ranges

… of up to 400 km without refuelling – range extension possible

Full route flexibility

… not bound to any required infrastructure on the route

Strong performance

… comparable to diesel buses, e.g. acceleration or gradeability

Fast refuelling

… down to 7 min per bus possible – several refuelling cycles per day possible as well

High passenger comfort

… due to reduced noise levels and smooth driving experience

Close to full technological maturity

… with nearly 15 years and 10 million km of operational experience in Europe

Note: for a comparison of different alternative powertrain solutions, please refer to the FCH study "Urban buses: Alternative powertrains for Europe", 2012

Source: Roland Berger

B

We considered the deployment of 20 new buses from one depot, covering a typical distance of ~200 km per day and bus

Use case assumptions and exogenous factors in two scenarios – SIMPLIFIED

Use case

> Bus operator renews (part of) his fleet out of the same depot: deployment of ~20 new buses with routes of each ~200 km per day, i.e. annually ~65,000 km per bus

> Financing costs of bus operator: 5% p.a.

> Labour costs: based on 2 FTE per bus with average Western European wages of each EUR ~32,000 p.a.

> CAPEX for refuelling stations: one HRS at depot for FCH buses as well as substation, central transformer and cable charging infrastructure for BE buses; no additional investment considered for counterfactual diesel bus deployment

> Resulting hydrogen consumption (considering the assumptions on the next slide): ~15-20 kg per day (bus), ~350 kg per day (fleet)

Exogenous factors[1)]

> Cost of hydrogen for operator: 8.00 / 4.00 EUR/kg H_2

> Cost of diesel: 1.01 / 1.30 EUR/l

> Cost of electricity: 0.14 / 0.12 EUR/kWh

> CO_2 intensity of "grey" hydrogen: 9.00 kg / kg H_2

> CO_2 intensity of diesel: 2.64 kg/l

> CO_2 intensity of electricity: 0.51 / 0.30 kg/kWh

> NO_x intensity of diesel: 4.00 g/l (~1.5 g NO_x / km)

Strongly dependent on specific regional circumstances

1) Two scenarios: "CURRENT" / "POTENTIAL"

Source: FCH2 JU, Roland Berger

Draft for Discussion – Confidential

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Within our analysis we benchmark FC buses with electric as well as conventional diesel buses in a current and a future scenario

Application-related assumptions in two scenarios – SIMPLIFIED

CURRENT / POTENTIAL	FCE Bus	BE Bus[1]	Diesel Bus
Technical specifications	FCH-dominated powertrain	Overnight charging BE	Full diesel powertrain
	12 m; ~35-40 seats	12 m; ~35-40 seats	12 m; ~35-40 seats
	Holding period: 12 years	12 years	12 years
	Availability: 85% / 95%	90% / 95%	95% / 95%
CAPEX ('000 EUR)			
Purchase price	~620 / ~400[2]	~450 / ~350	~230 / ~250
Refuelling station	~2,400 / ~2,000	~1,000	-
Fuel			
Fuel type	Hydrogen (350 bar)	Electricity	Diesel
Consumption (per km)	0.086 / 0.065 kg	1.5 kWh	0.4 l
Maintenance costs (EUR)			
Bus per km	0.37 / 0.26	0.30 / 0.26	0.26 / 0.26
Refuelling station p.a.	~80,000	~30,000	~10,000
Replacements[2]	~60,000 / ~30,000	~90,000 / ~60,000	-

1) Guaranteed year-around ranges for BE buses will only become apparent through ongoing European procurements (2017-18), assumed range of 200 km/d in this use case is still TBC (potentially no feasible alternative in the "current" use case for ranges of 200 km)
2) Assuming production-at-scale scenarios for bus OEMs as per "Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe" (FCH JU, 2015)
3) One FC stack or battery pack replacement during lifetime

Source: FCH2 JU, Roland Berger

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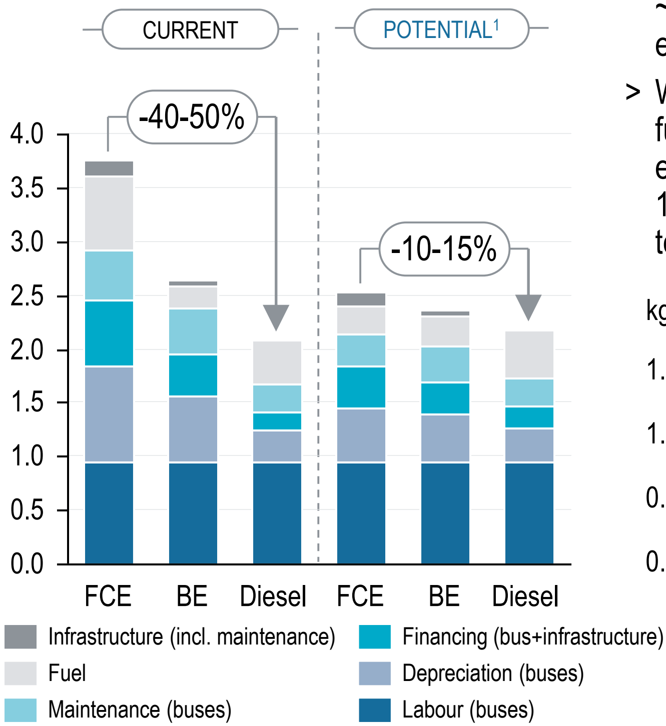
The cost premium of hydrogen buses might decrease significantly in the medium run, emissions can be drastically reduced

Business case and performance overview in two scenarios – INDICATIVE

Economic

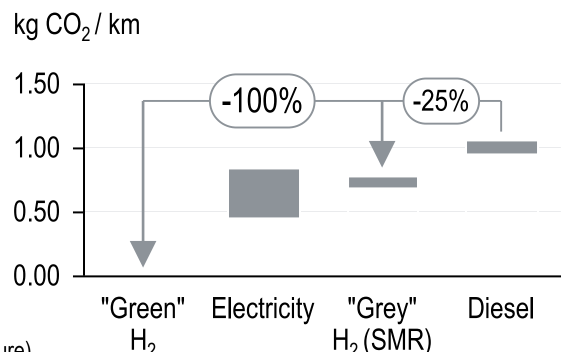
Total Cost of Ownership [EUR/km], annualised at 2017 prices



Environmental

> Zero tailpipe emissions of CO_2, pollutants (NO_X , SO_x) and fine dust particles, saving ~100 kg NO_X per bus a year (in this example)

> Well-to-wheel CO_2 emissions depend on fuel source (source of H_2, electricity mix, etc.) and vehicle efficiency, green H_2 or 100% green electricity would reduce well-to-wheel CO_2 emissions to zero



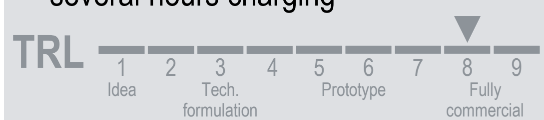
Technical/operational

> Fuel cell electric buses (full FC powertrain and FC range extender) are entering the commercial phase with large scale demonstration projects under way; besides, add. OEMs will launch vehicles in the short/medium run

> FC electric buses currently with availabilities of ~85% (longer down times), expected to reach ~95% in the medium run

> Range of FCH buses 250-450 km; (comparable to diesel buses), BE buses reaching 150-200 km max. guaranteed range

> Refuelling times of ~7-15 min per bus; comparable to diesel vs. BE bus several hours charging



1) The "POTENTIAL" scenario requires a number of FCE-related and other factors to fall in place in the medium/long run (please see previous slide)

Source: FCH2 JU, Roland Berger

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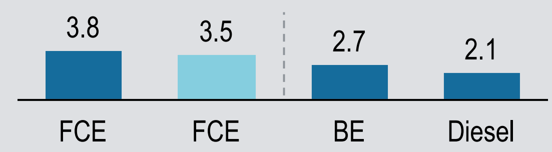
Impact of TCO drivers varies, opening up several leverage points for reduction of hydrogen TCO compared to diesel & electric TCO

Determinants of the TCO[1] – INDICATIVE

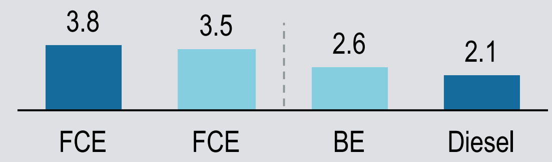
Key sensitivities considered (selection) …

… estimated impact on TCO [EUR/km]

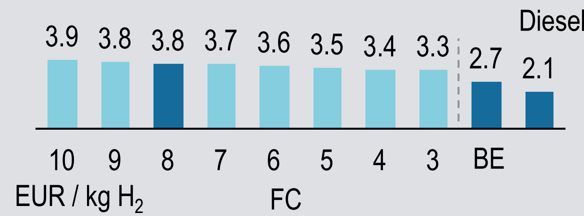
1 **Bus purchasing price:** reducing the bus purchasing price by 20% would lead to a reduction of the TCO of ~EUR 30 ct per km; total purchase price reductions to ca. EUR 400k per bus have been established by European studies ("POTENTIAL" scenario)



2 **Infrastructure costs:** setting attributable infrastructure investments for FCE buses (as well as electric buses) to zero, results in a potential TCO decrease of ~EUR 30 ct per km for FC buses



3 **Fuel costs:** reducing hydrogen costs to the operator from 10 EUR/kg H_2 to 3 EUR/kg, results in a potential reduction of TCO per km of ~60 ct or ~15-20%



TCO in EUR/km, base case

TCO in EUR/km, adjusted variables

1) Unless otherwise stated, all statements shall be considered *ceteris paribus*, i.e. "all-other-things-equal"

Source: FCH2JU, Roland Berger

Please note the following:

- > *Today's analysis showed one hypothetical example of a multi-dimensional performance comparison between FCE, BE and diesel buses. Real-life projects will differ based on regional circumstances and have to consider a range of additional factors (e.g. specific routes and schedules, individual bus-related requirements, national labour laws, additional cost items such as e.g. insurance and depot-related costs) that this high-level analysis omitted for simplification purposes*
- > *Similarly, the scenarios shown above should be interpreted as potential combinations of key variables that affect the comparative technology performance*
- > *Please note that a number of (industry-based) studies on FCE buses have been published under the auspices of the FCH2 JU over the past years. Please consult them for further reading:*
  - *"New Bus ReFuelling for European Hydrogen Bus Depots", 2017*
  - *"Clean Hydrogen in European Cities (CHIC) – Final Report", 2017*
  - *"Strategies for joint procurement of fuel cell buses", 2017*
  - *"Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe", 2015*
  - *"Urban buses: alternative powertrains for Europe", 2012*

Source: Roland Berger

Please do not hesitate to get in touch with us

Contact information

Carlos Navas
FCH2 JU

Strategy and Market Development Officer

carlos.navas@fch.europa.eu

+32 2 221 81 37

Source: FCH2 JU, Roland Berger