GIANTLEAP

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Evaluation of the achievement of performance target

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

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Scope

This document gives an overview about the achievement of targets described in the project specific proposal.

Overview

BEG
BEG will evaluate whether the project has produced a solution able to satisfy the targets for
2020 set by the FCH2 JU's MAWP (Multi Annual Work Plan) in regards to bus and system cost, availability, consumption
and lifetime, on a basis of 200 units being manufactured.

VDL
VDL will support the estimation of costs for bus and range extender units.

EK
EK will support the estimation of lifetime, also with the help of the prognostic methods developed in the project.

1 Introduction

As observed in the MAWP, almost all critical technological challenges for the implementation of fuel cells in vehicles have been resolved, with the notable exceptions of lifetime and costs. While availability of FC cars has been measured to be 98 %, fuel-cell electric buses (FCEBs) have experienced much lower values: 70 % is the one most often reported across multiple demonstration sites in Europe, Canada and the US. This low availability and the high total costs of ownership (TCO) in comparison to a Diesel bus are the main reason many operators shy away from the technology: for example, BC Transit in Whistler, Canada recently sold their fleet of 20 hydrogen buses and reverted to diesel, citing high maintenance and fuel costs (http://www.cbc.ca/news/canada/british-columbia/bc-transit-s-90m-hydrogen-bus-fleet-to-be-sold-off-converted-to-diesel-1.2861060).

According to the proposal Giantleap aims to reduce total cost of ownership of FCEBs by increasing lifetime and availability by means of advanced control systems, which will measure the state of health of the fuel cells and their ancillaries during operation and ensure the best operating conditions at all times. To convince operators of the credibility of the approach, a demonstration in a relevant environment was carried out in the last year of the project.

The overall objectives of Giantleap range from research in degradation processes, through implementation of novel solutions for diagnostics and prognostics, development of cost effective control strategies to minimize degradation and their validation by means of demonstration in relevant environment. The specific quantitative targets are listed in Table 1.

1.1 FCH2 JU targets 2020

Parameter	State of the art	FCH2 JU 2020	GIANTLEAP	Unit
TRL	3	5–6	6	
Availability	70	95	**98**	%
FC lifetime in bus	12000	2×10 000	2×**12 000**	h
Fuel consumption	9	8	8	kg_{H_2}/100 km
FC bus cost	1250	650	650	k€
FC system cost	4500	500	500	€/kW

Table 1: Expected Targets of the FCH JU in 2020

1.2 TRL achievement and availability

Overview of the specific Readiness levels in the HORIZON 2020 program:

Where a topic description refers to a TRL, the following definitions apply, unless otherwise specified:

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Figure 1: Technology readiness levels (TRL) in HORIZON 2020

The project started at **TRL 3**, “Experimental proof of concept”: research on prognostics on fuel cells is available in the literature, and it is being validated for other applications, such as stationary fuel cells, (for example, in the related FCH JU project Sapphire, in which SINTEF, FESB, UFC and its third parties participate). UFC and its associated third parties in this project have published ground-breaking research on the topic, but its specific application to the automotive sector has yet to be validated in a laboratory.

The goal from the Giantleap project is to enter the **TRL 6**.

The tests with the trailer on public roads show that we have reached **TRL 7** in the project, see:

https://www.youtube.com/watch?v=I0ItJGUJ5ng&feature=youtu.be

Availability:

According to Hua et al. (Thanh Hua, Rajesh Ahluwalia, Leslie Eudy, Gregg Singer, Boris Jermer, Nick Asselin-Miller, Silvia Wessel, Timothy Patterson, and Jason Marcinkoski. “Status of hydrogen fuel cell electric busesworldwide”. In: *Journal of Power Sources* 269 (2014), pp. 975–993.)), with an average of 69 % in the US, about 70 % in the London part of FCH JU CHIC project, and 71 % for the demonstration in Whistler, Canada a parameter in constant need of improvement was the availability of the fuel cell buses. According to the authors the components mostly causing failures/problems on BoP and hybridisation issues rather than on the fuel cells themselves, however. If series components were available, these were used.
The stacks were attached in a system as a range extender to an electric bus from the Dutch manufacturer VDL Bus & Coach, tested in real traffic and exposed to adverse conditions as a result. Even harmful operating states such as insufficient fuel supply, excessively high temperatures and pressures and emergency shutdowns of the system during the development phase have not limited the performance of the fuel cell stacks supplied by ElringKlinger.
Throughout the project, the main components hardly caused any issues. The only key component failing was one of the DC/DC converter A-samples and components actively destroyed by miss-use during component testing. Main source of trouble were small and relatively cheap third party components. Table 2 provides an overview of components that caused issues:

Component	Description of failure	Solution
DC/DC converter	Defective output stage	Repair by manufacturer
Cathode bypass valve	Tends to get stuck when closed to mechanical stop	Close only to electrical stop
CVM unit	Minimum cell voltage is sporadically sent as valid 0V on CAN	Filter values in controller software
FCCU ETK-T2.2	Unwanted hardware resets	Change FCCU hardware
H_2 CAN sensor	H_2 concentration signal on CAN valid 12.7% (0xFF) for very long time during start up	Debounce long enough in FCCU software
Purge valves	Anomaly in purge function, high H_2 concentration in exhaust gas	Replace valves
Main cooling fan	24 V variant PWM signal 15…28 VDC required	Raise LV voltage level to 14.5 V
12 V battery	Battery exhausted, 12 V power supply not sufficient	Battery replaced, calibration corrected, data recording needs to be switched off during longer stand-still
Coolant control valve	Control device half bridge circuit defective	Valve set to 60% and fixed, work-around by calibration
Pressure relief device hydrogen mid pressure	Blow-off causing H_2 leakage	H_2 mid pressure reduced (16.4 bar_a → 15.8 bar_a)
Current sensor	Defective, sensor switching off during operation	Sensor changed, investigation ongoing
Drive recorder	Defective, device not booting	Drive recorder changed, investigation ongoing

Table 2: Overview of the components that caused problems.

1.3 Lifetime and consumption

Lifetime of over 12 000 h of continuous operation have been reported, if also on fuel cells custom built for buses. Since Giantleap chooses the option of using the same stacks as passenger cars, the state of the art for these is more relevant: according to a review by Pucheng Pei and Huicui Chen ("Main factors affecting the lifetime of Proton Exchange Membrane) fuel cells in vehicle applications: A review"), lifetime for these is up to just 3000 h, in contrast to the recorded maximum of 26 300 h for stationary applications. Currently, vendors of fuel-cell systems for buses offer a standard guarantee of 5000 h of operation, which can be extended to 15 000 h for a price.
The Lifetime of over 12000 hours is estimated by prognostics through the FCLab (Universite Franche-Comte) based on the real data transmitted by ElringKlinger.

Remaining useful life (RUL)

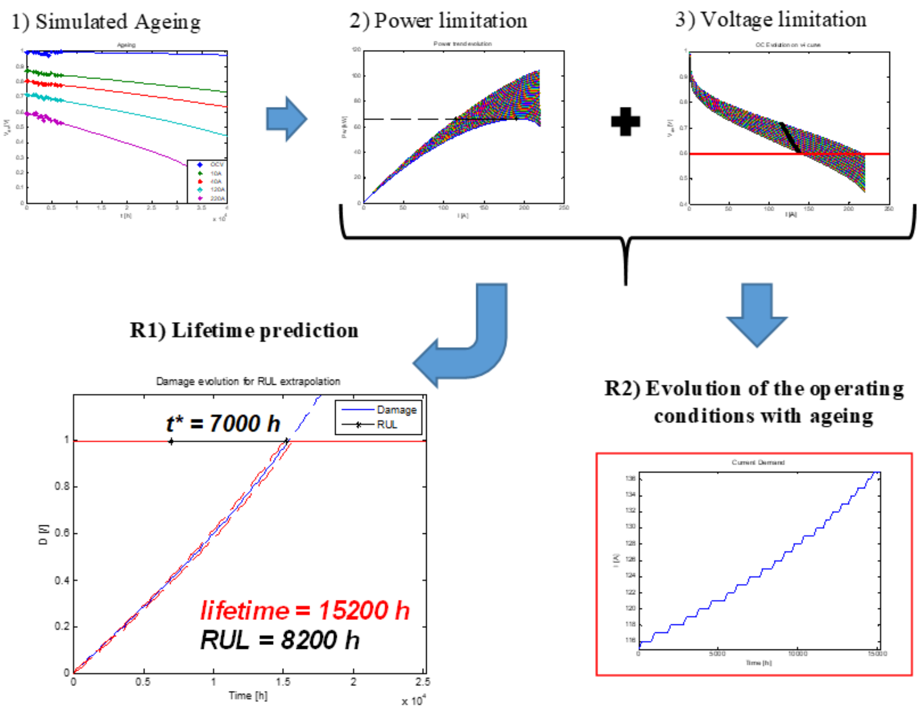


Figure 2: PEMFC RUL and operating conditions evaluation: 1) simulation; 2) power constraint coupled with 3) voltage limitation; R1) RUL extrapolation; R2) change in operating conditions.

The last part of the project aims to develop an algorithm to predict the fuel cell sytem lifetime reliably and efficiently. An ageing model of the fuel cell system has been developed using Matlab/Simulink, which allowed to develop the code for online implementation. At first Fuel cell parameters have been identified to calibrate the model on the used fuel cell. Secondly ageing laws of these parameters have been developed according to the available data and used to predict the fuel cell degradation and therefore estimate the RUL of the fuel cell stack. Due to the lack of the available data in terms of operating hours, an operating point has been simulated for 1000 operating hours, at a current of 136A and a voltage of 285V in order to validate the model. The second part of the work aimed to the online monitoring of the ancillaries to detect critical operating point conditions that can damage the fuel cell stack and reduce its lifetime. Using the available data, air supply device, compressor in terms of flow rate and operating speed, and the cooling system, fan and the pump, their working limits have been identified. These working limits were chosen for the maximum current achieved, according to the available data. The online implementation of the developed algorithm can reliably, efficiently and quickly, estimate the fuel cell life time at each operating hour. The nominal performance is computed using the identified stack parameters and the fuel cell model presented in deliverable 2.2. The critical performance is also computed using the same fuel cell model but using the ageing parameters. The available data is not sufficient, in terms of operational time, to validate the prognosis of the RUL. However, a performance degradation is simulated and could validate the model.

In normal operation for a power demand of 45 kW at 1 operating hour and v(t) = 291V, which represents the voltage at the time of estimating the fuel cell lifetime; the RUL is 14593 h and the EOL is thus 14594 h. The simulated operating point is defined after 1000 operating hours at a current of 136 A and v(t) is set to 285V, the RUL is equal to 11755 hours and the EOL is 12755 h which corresponds to an ageing acceleration of 79.12 %. Indeed the developed algorithm can evaluate, not only the fuel cell lifetime, but also estimate the degradation or recovery acceleration.

The non-linear course of aging over time that FCLab predicts in the models does not have to be reflected in reality. The model progressions have to be readjusted and adjusted with increasing number of data in order to arrive at a more precise statement

Fuel Consumption (kg H2 / km)

Fuel consumption has been found to be about 8 mpgde (miles per gallon of diesel equivalent), or 8.8 kgH2 /100 km, in the US; a very similar value was reported for CHIC London, 9 kgH2 /100 km, whereas a much higher value, 13 kgH2 /100 km, was found in the Canadian demonstration: this deviation was partly seasonal, since the buses used electric heating with power from the fuel cells; even in summer, however, fuel consumption was at the lowest 10 kgH2 /100 km.
During the first measurements there was a defect in the cooling circuit, so the consumption calculations did not give a conclusive picture. The availability of a large buffer battery will make it possible to exploit regenerative braking to the fullest, and increase efficiency; however, the increased weight because of the battery banks may offset this advantage. Giantleap will aim for the 2020 FCH2 JU's objective of 8 kgH2 /100 km.
With a constant power output of 60kW the average consumption was approximately 3,9 kg hydrogen per hour in an empty ride in flat terrain.

2 Costs

2.1 FC Bus cost

Figure 3 shows the expected bus costs in comparison to Diesel Hybrid and conventional Diesel busses:

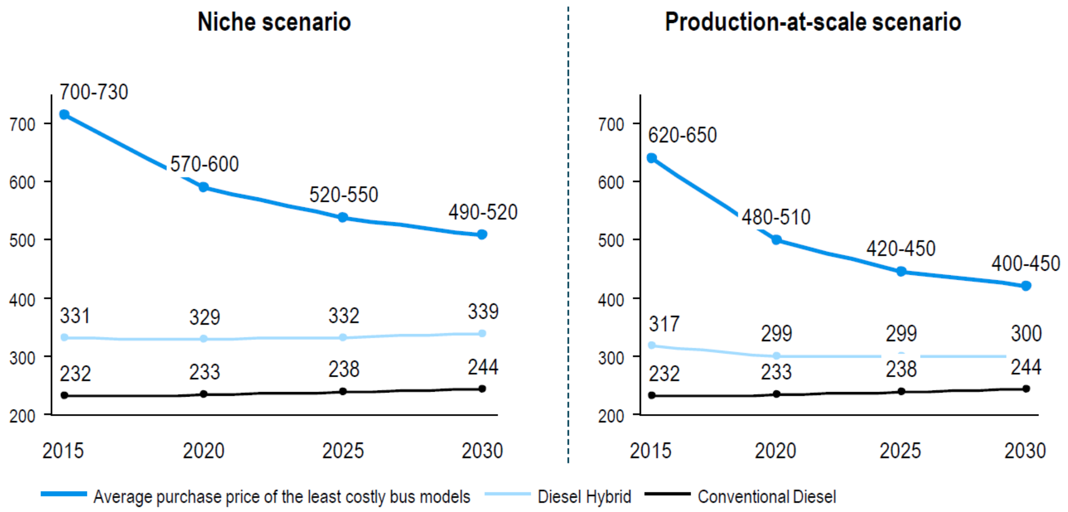


Figure 3: Fuel Cell bus cost. Niche scenario and production-at-scale scenario from fuel cell busses compared to Diesel and Diesel Hybrid busses. (Source: FCH-JU, Roland Berger, Fuel Cell Electric Buses). The expected costs for a fuel cell bus are currently 650.000 €.

2.2 FC system cost

The cost of an 80-kW_{net} automotive polymer electrolyte membrane (PEM) fuel cell system based on next-generation laboratory technology and operating on direct hydrogen is projected to be 50$/$kW_{net}$ when manufactured at a volume of 100,000 units/year and 45$/$kW_{net}$ at a volume of 500,000 units/year. (Source: Department of energy, Hydrogen and Fuel Cells Program Record 2017)

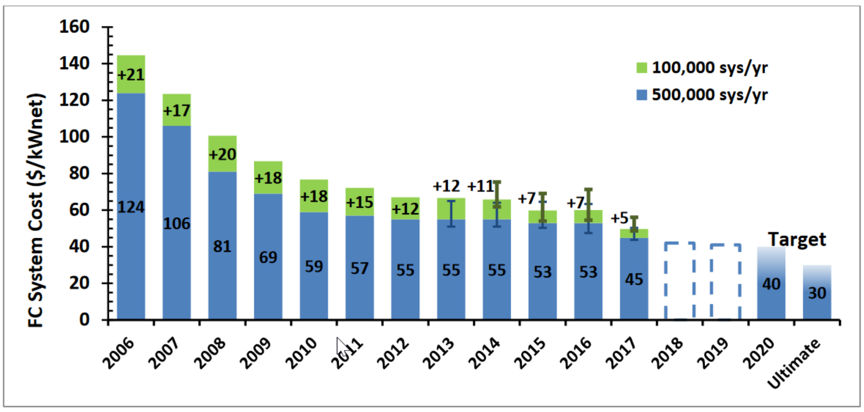
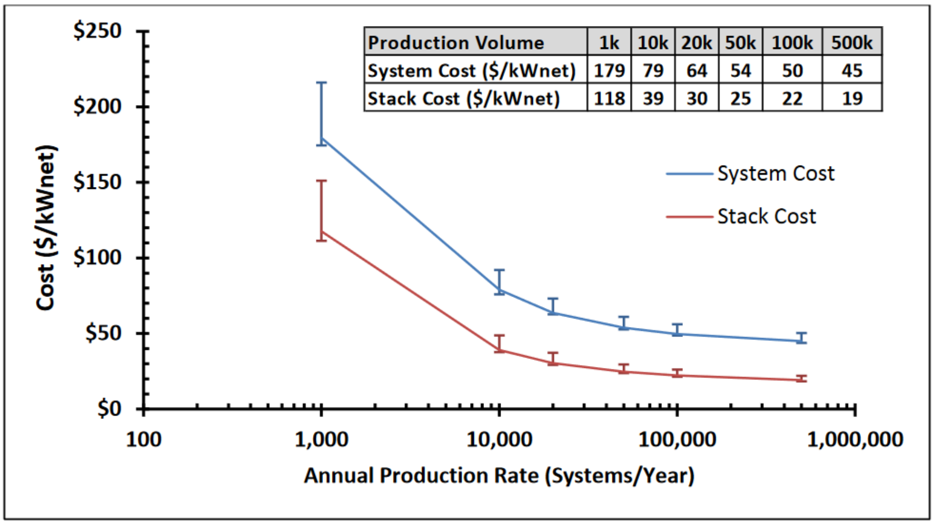


Figure 4: Modelled cost of an 80-kW_{net} PEM fuel cell system based on projection to high-volume manufacturing (100,000 and 500,000 units/year). Source: Department of energy, Hydrogen and Fuel Cells Program Record 2018



Production Volume	1k	10k	20k	50k	100k	500k
System Cost ($/kWnet)	179	79	64	54	50	45
Stack Cost ($/kWnet)	118	39	30	25	22	19

Figure 5: Projected cost of 2017 80-kW$_{net}$ transportation fuel cell stacks and systems at 1,000, 10,000, 20,000, 50,000, 100,000, and 500,000 units/year

The costs for fuel cell system including all Balance of plant components and the tank system is now approximately at 2.100-2.500 €/kW and the hydrogen cost is now 9-11 €/kg.

2.3 Total cost of ownership (TCO)

Total cost of ownership was calculated on a cost per kilometre basis as the sum of purchase, financing, infrastructure and running costs.

Several studies were exploited and were adjusted to the experience to bus manufacturer and operator.

- Conventional buses show a relatively low purchase costs, TCO and high route flexibility, but have the highest GHG (greenhouse gas) emissions, local emissions and noise levels.
- Diesel hybrid buses show slightly higher purchase costs and TCO than conventional buses, but can reduce fuel and GHG emissions by up to ~20 %, with serial hybrids in particular capable of undertaking longer stretches of the route in full electric drive. They also show high driving performance and flexibility.
- Hydrogen fuel cell buses have a high driving performance and a high route flexibility, using filling stations (mostly in depots), comparable to conventional buses. They have higher purchase costs than conventional busses, but also a high potential to reduce GHG emissions (by 75 to 100 percent on a well-to-wheel basis in 2030 depending on the hydrogen production mix).
- Trolley buses can move freely within their network, but flexibility beyond the network is only possible using an auxiliary power unit (APU). They show a high cost for infrastructure and increasing TCO going forward, but high potential to reduce GHG emissions (by 0 to 100 percent on a well-to-wheel basis in 2030 depending on the electricity mix assumed).

- E-buses (opportunity and overnight) show medium to high purchase costs and TCO, but high potential to reduce GHG emissions (by 30 to 100 percent on a well-to-wheel basis in 2030). Their route flexibility is dependent on the charging infrastructure.

The total cost of ownership was calculated on a cost per kilometre basis as the sum of purchase, financing, infrastructure and running costs.
Overall costs for these buses are expected to decrease down to a cost premium of about 11-18% compared to conventional diesel buses on a per kilometer basis in the year 2030. The cost premium is driven by the costs associated with the introduction of a new technology, mainly reflected in a higher FC bus purchase price and thus, higher financing costs.

Future costs strongly depend on the size of the market for FC buses. Hence, two scenarios were developed in order to account for potential variations of the future market size as well as the speed at which fuel cell costs will decrease. The "niche scenario" and the "production-at-scale scenario" portray the variance of potential costs depending on efficiencies and economies of scale achieved with varying market sizes and the related overall technological progress in the framework of the heavy-duty technology pathway. The scenarios reflect the effect that different economies of scale have on cost-down curves and prices. For the niche scenario to materialise, a cumulative number of 1,200-1,800 FC buses needs to be deployed on Europe's roads in total until 2025. For the production-at-scale scenario, a total cumulative volume of 8,000-10,000 FC buses is required until 2025.

The summary of this calculation is that an economical operation of a Hydrogen fleet is feasible in the future and could compete against combustion engine and battery electric buses. The precondition is beside low cost for the fuel cell system and a high average availability the price for hydrogen. To take hydrogen price of about 3 €/kg as a basis shows that the total operational costs are competitive, the following data are not generally valid but are based on a manufacturer's TCO calculations:

Diesel:

0.89 Euro/km total

0.40 Euro/km DSL (45%)

0.00 Euro/km FC (0%)

0.49 Euro/km Vehicle (55%)

All incl. maintenance

H2 now:

2.09 Euro/km total

0.73 Euro/km H2 (35%)

0.67 Euro/km FC (32%)

0.68 Euro/km Vehicle (32%). Vehicle is more expensive and second hand value is 0 Euro.

All incl. maintenance

H2 now:

2.09 Euro/km total

0.73 Euro/km H2 (35%)

0.67 Euro/km FC (32%)

0.68 Euro/km Vehicle (32%). Vehicle is more expensive and second hand value is 0 Euro.

All incl. maintenance

The current TCO calculation is approximately 200% of the TCO of a Diesel bus. With 1/3 of the costs of the fuel cell system and 1/3 Hydrogen costs, the TCO will decrease to 120-125%.

3 Conclusion

In order to meet strict targets set by cities and other regulatory bodies, zero-emission powertrains will very likely be a requirement for parts of the fleet in 2020. Hydrogen fuel cell and electric powertrains reduce local emissions to absolute zero, compared to local (tank-to-wheel) emissions of more than 1 kg CO_2/km for a conventional diesel bus. Diesel hybrids (serial and parallel) also offer a reduction of 15 to 20 % in local emissions, with serial hybrids in particular capable of undertaking longer stretches of the route in full electric drive. Hydrogen fuel cell and other electric powertrains can reduce well-to-wheel GHG emissions by 30 to 100 percent until 2030 compared to Diesel busses. Different powertrains show advantages in different areas of performance. Among the zero local-emission powertrains, the hydrogen fuel cell bus offers the best performance in range, purely electric range and refueling times, at high operational flexibility.

All sources have shown, particularly the TCO calculation of VDL, that the achievement of hydrogen busses will depend highly on the hydrogen price, secondary on the cost of the system.

The cost of Giantleap fuel-cell system was obviously far higher than 500 €/kW due to its nature of being a prototype, but cost projections are encouraging. Lifetime was estimated at higher than the target 12 000 h by means of prognostics, though there was not the physical time nor the budget to test the Giantleap stacks for such a length of time (over 16 months of non-stop testing).

The summary of the TCO calculation is that an economical operation of a Hydrogen fleet is feasible in the future and could compete against combustion engine and battery electric buses. The pre- condition is beside low cost for the fuel cell system and a high average availability the price for hydrogen. To take hydrogen price of about 3 €/kg as a basis shows that the total operational costs are competitive.

The forecast costs for a fuel cell system along with the costs of a fuel cell bus could not be achieved in the project. However, the developments in terms of quantity increases allow the conclusion that the DoE target of 650.000 € can be achieved with a corresponding quantity. The price of a system can be significantly reduced, particularly by using automotive components produced in series production.

Figure/Table Overview