CHIC

# CLEAN HYDROGEN IN EUROPEAN CITIES

2010 - 2016


## FUEL CELL ELECTRIC BUSES: A PROVEN ZERO-EMISSION SOLUTION

## KEY FACTS, RESULTS, RECOMMENDATIONS


FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

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# CHIC PROJECT PARTNERS

IN COLLABORATION WITH

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NOTE: ALL FIGURES IN THIS DOCUMENT ARE AS OF JUNE 2016

# FOREWORDS

The drive to improve air quality in our cities and mitigate the impacts of climate change continues to be a high priority for our city leaders. The CHIC project has brought together a number of cities, transport operators and suppliers who are committed to demonstrating that fuel cell buses can help deliver these improvements alongside other emerging technologies.

With the support of the European Union the CHIC project has clearly demonstrated the role clean fuel cell electric buses have in making our cities better places to live.

The positive results of this project, following the success of previous fuel cell bus projects, have clearly demonstrated from a transport operator perspective that this technology is a practical form of propulsion to replace the standard diesel bus in our cities.

The project has also clearly shown that hydrogen can be produced efficiently and with minimal carbon emissions when renewable and other low carbon energy sources are utilised. The future for fuel cell buses is assured with many cities now planning and moving towards larger scale deployment.
This is a real testament to the benefits the CHIC project has delivered.

I would like to thank all the CHIC partners for their hard work which has made this project such a success.

**MIKE WESTON**
**CHIC Steering Committee Chairman**
**Transport for London**

Transport is at the heart of our society, enabling people and goods to move about flexibly, quickly and at reasonable cost across Europe. At the same time, it is a sector which is responsible for one third of Europe's greenhouse gas emissions, and the main cause of air and noise pollution in cities. For these reasons, transport and mobility are essential components of the European transition towards a sustainable, low-carbon economy.

It is therefore a logical step that the European Commission has recently adopted a Communication on *A European Strategy for Low-Emission Mobility* (COM(2016) 501 Final), which sets out priority areas for the decarbonisation of the transport sector. Moreover, the European Commission voices frequently its support for electric vehicles.

I strongly believe that, by combining emission-free and silent electric transport with the short refuelling time of diesel buses, fuel cell buses can be an integral part of this Strategy. But fuel cell buses are more than just another building block in the reduction of emissions and the creation of a more liveable urban environment: as a widely-used means of transport, they are ideal ambassadors towards the general public for introducing hydrogen in our society. In addition, their development brings together public and industrial partners.

The green production of hydrogen from renewable sources creates a link between the energy and the transport sectors, allowing a system-oriented and smart approach for cities to manage their environment. This systemic approach has already been demonstrated in earlier projects, but I am particularly impressed with the amount of experience, progress and support that has been gathered during the past six years. Thanks to the CHIC project, fuel cell buses are now firmly in the spotlight, building confidence for operators across Europe. I am delighted to see that a steadily increasing number of cities and regions are now becoming convinced that hydrogen is offering a real, reliable and affordable alternative to existing mobility options.

I would like to congratulate the CHIC project partners for their achievements, and for the role they have played in taking fuel cell buses this crucial step closer to maturity. I very much hope that, thanks to your hard work, millions of European citizens will soon have a chance to embrace a new, environmentally-friendly technology that is also a real pleasure to use.

**JAN-ROBERT SMITS, DIRECTOR-GENERAL**
**Directorate General Research and Innovation, European Commission**

# CHIC AT A GLANCE

The Clean Hydrogen in European Cities project (CHIC) was a flagship zero emission bus project that deployed a fleet of fuel cell electric buses and hydrogen refuelling stations in cities across Europe and at one site in Canada. The project started in 2010 and ended in December 2016.

The project successfully demonstrated that fuel cell buses can offer a functional solution for cities to decarbonise their public transport fleets, improve their air quality and lower their noise levels. The buses can operate with the same flexibility as a diesel bus without compromising the productivity of public transport.

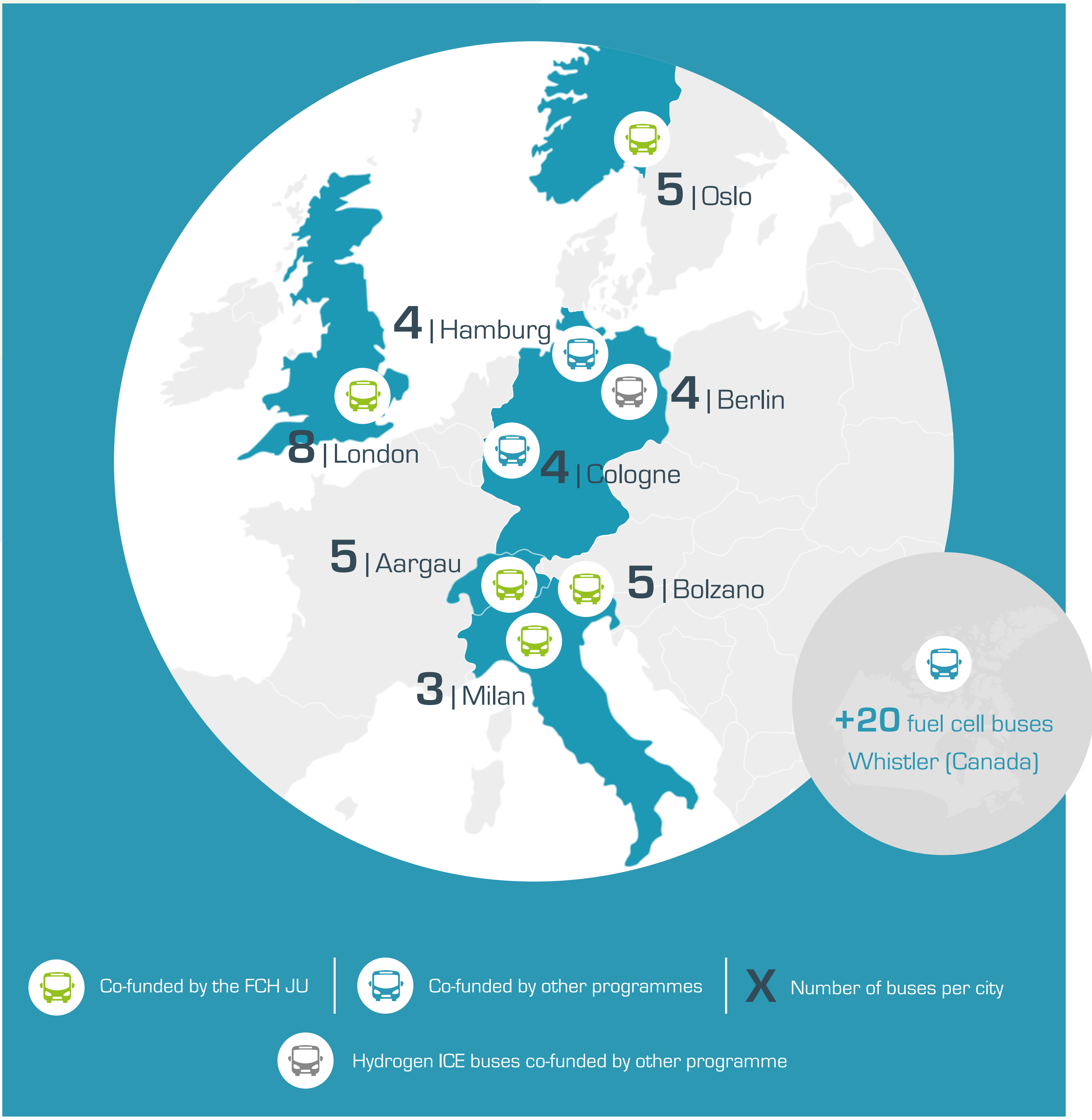
The total project budget was €81.8 million, of which €25.88 million was co-funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU). 26 fuel cell electric buses receiving FCH JU co-funding operated in the canton of Aargau (CH – 5 buses), in Bolzano (IT – 5 buses), London (UK – 8 buses), Milan (IT – 3 buses) and Oslo (NO – 5 buses). Cologne (DE – 4 buses) and Hamburg (DE – 4 buses) operated 8 further fuel cell buses through separately funded programs. In Whistler (CA), 20 fuel cell buses were deployed between 2010 (Winter Olympics Games) and March 2014. In Berlin (DE), 4 hydrogen internal combustion engine (ICE) buses operated between 2006 and December 2014.

Throughout the project lifetime, 54 fuel cell buses were demonstrated in total. The diversity of climate and city sizes allowed the testing of the vehicles under different conditions.

Photography ©RVK

**The CHIC project has demonstrated that fuel cell buses can offer:**

- An operating range similar to that of a diesel bus (>350 km)
- Short refuelling times at hydrogen refuelling stations (<10 min)
- High fuel efficiency with a consumption of 9 kg of hydrogen/100 km for 12 m buses (equivalent to 30 litres of diesel) – 26% more efficient than an equivalent diesel bus (40.9 l of diesel/100 km on average [a])
- $CO_2$ emissions reduced by 85% compared to diesel buses along the bus life cycle when the hydrogen fuel is produced from renewable energy sources; within CHIC 6,800 tonnes of $CO_2$ equivalent saved [b]
- Use of over 4.3 million litres diesel avoided
- Survey results show that CHIC regional stakeholders, bus drivers and passengers support the technology and a move to zero emission public transport




## What is the FCH JU?

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) is a public private partnership supporting research, technological development and demonstration activities in fuel cell and hydrogen energy technologies in Europe. Its aim is to accelerate the market introduction of these technologies, so realising their potential as an instrument in achieving a low carbon energy system.

The partnership is formed by the European Commission (Directorate General Research and Innovation), industry (represented by Hydrogen Europe) and research (represented by N.ERGHY.) [1]

# FUEL CELL BUS TECHNOLOGY

## WHAT ARE FUEL CELL BUSES?

Fuel cell buses are a type of electric bus. They share many components with battery electric buses, such as electric motors and associated power electronics. However, rather than storing energy in large batteries, fuel cell buses use hydrogen as fuel. The fuel cells consume hydrogen and oxygen to generate electricity through an electro-chemical process, producing only water and heat as by-products, which then powers the electric motors.

Hydrogen offers a much higher energy density than electrical storage systems (batteries and super capacitors), meaning fuel cell buses can comfortably operate for an entire day of service without refuelling.

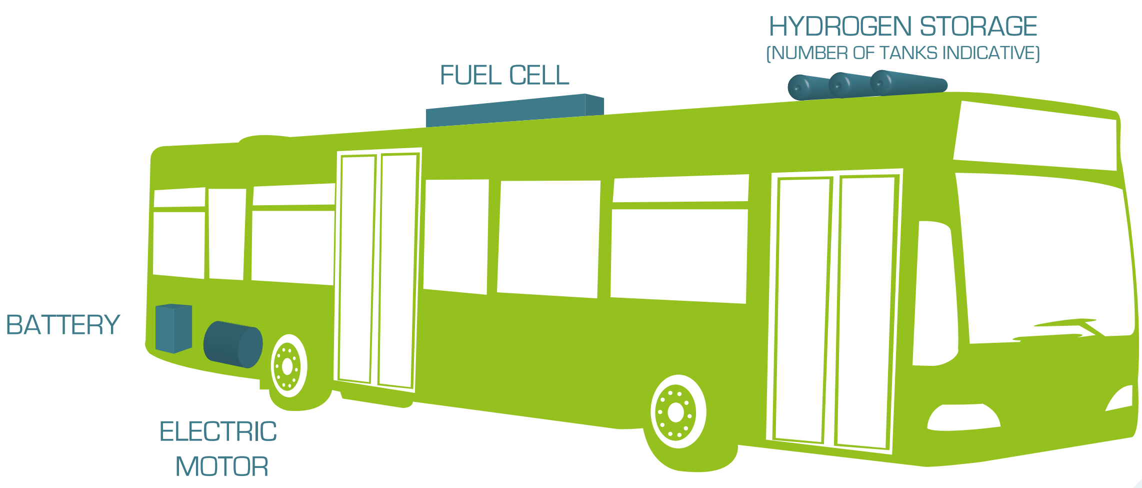
Modern fuel cell electric buses generally incorporate a small battery or super capacitor as a part of the drivetrain, which improve the performance of the fuel cell and the overall energy efficiency of the bus, for example by boosting acceleration and allowing recuperation of braking energy.

Apart from these differences, the bus structure and the other non-electric components are the same as in conventional buses.

*"I particularly enjoy driving a fuel cell bus because of the smooth ride without the noises and vibrations you have in a diesel bus. You feel more relaxed after your shift and in addition you know that you have done something good for the environment."*

***Sylvia Sendlhofer,***
*bus driver at RVK, Cologne*

## MAIN FUEL CELL BUS COMPONENTS



## BENEFITS OF USING FUEL CELL BUSES

Fuel cell buses have the potential to be a drop-in replacement for diesel buses, with a long driving range, route flexibility and short refuelling times. They offer a local zero emission solution, with no pollution at the tailpipe as the buses emit nothing but water vapour, and can help reduce $CO_2$ emissions when the hydrogen is produced from a low carbon source (see "environmental analysis results" section). Additionally, they offer enhanced comfort, reduced noise and vibrations levels and can provide a solution to ambitious policy targets set for transport decarbonisation and clean air.

## CHIC BUSES KEY SPECIFICATIONS

Within CHIC, fuel cell buses from five manufacturers were trialled. The table below shows their key specifications.

| Bus manufacturer | APTS | EvoBus Mercedes-Benz | New Flyer | Van Hool | Wrightbus |
|---|---|---|---|---|---|
| Operated in CHIC city and number of buses | Cologne (2) | Aargau (5)<br>Bolzano (5)<br>Hamburg (4)<br>Milan (3) | Whistler (20) | Cologne (2)<br>Oslo (5) | London (8) |
| Overall length (m) | 18.5 | 12 | 12.5 | 13.2 | 11.9 |
| Passenger capacity | 96 | 76 | 60 | 101 / 75 | 49 |
| Net weight (tonne) | 20.59 | 13.20 | 15.42 | 15.70 / 16.07 | 10.35 - 11.35 |
| Drive power (kW) | 240 | 240 | 170 | 170 | 134 |
| Fuel cell system power (kW) | 150 | 120 | 150 | 150 | 75 |
| Hydrogen storage capacity (kg and in kWh) | 40 (1,333) | 35 (1,167) | 56 (1,866) | 40/35 (1,333) | 31 (1,023) |
| Electricity storage type | NiMH battery + super capacitors | Li-Ion battery | Li-Ion battery | Li-Ion battery | Super capacitors |
| Electricity storage power (kW) | 200 | 250 | n/a | 90 (max 120) / 100 | 105 |
| Electricity storage capacity (kWh) | 26 (battery) + 2 (super capacitors) | 26.9 | 47 | 24 / 17.4 | 20 |

## ADAPTATION OF THE BUS DEPOT

Bus maintenance facilities were adapted to accommodate the fuel cell buses. Specifically, hydrogen sensors, lighting and ventilation adapted for use in hazardous locations, along with emergency venting, were installed in the workshops and (indoor) parking spaces. Platforms to allow rooftop working (e.g. mobile working platform) were built.

## TRAINING

A specialised operator training programme was required to optimise deployment conditions for the fuel cell buses. Dedicated initial and regular "refresher" courses were held for bus drivers, maintenance staff/technicians and first responders. For bus drivers, the training included explanation of the technology, emergency measures, procedures to follow in case of failure and hydrogen refuelling. Courses for technicians focussed on enhancing their understanding of the hybrid diagnostics systems, and of the hybrid, high voltage and gas systems. First responder training focussed on risk assessment and handling hazardous materials.

**Interested?** (see page 48)

- Analysis of investments in workshops for fuel cell buses and hydrogen refuelling stations

# INFRASTRUCTURE TECHNOLOGY

## HYDROGEN PRODUCTION

**1.** Hydrogen from conventional sources: Most hydrogen used in industry today is produced from a process known as steam reforming. When natural gas (methane) is used as the feedstock, it is referred to as steam methane reforming (SMR). Alternatively, oil, coal and Liquefied Petroleum Gas (LPG) can be employed.

**2.** Hydrogen from renewable sources: Hydrogen is produced by using electricity to separate water into hydrogen and oxygen. This process is called water electrolysis. "Green hydrogen" can be made through this process when the electricity is generated from renewable sources. The term "green" highlights that this hydrogen is produced with very low emissions of greenhouse gases e.g. $CO_2$.

**3.** By-product hydrogen: This is hydrogen originating from the chemical industry as a by-product, such as during chlor-alkali electrolysis.

In addition, other production methods are being developed such as biological, waste, solar heat or photoelectrochemical.

| CHIC city | Hydrogen infrastucture manufacturer | Hydrogen sources and supply pathways |
|---|---|---|
| Aargau | Air Liquide | On-site production from renewable sources + regular trailer delivery from by-product source |
| Bolzano | Linde | On-site production from renewable sources |
| London | Air Products | Trailer delivery of gaseous hydrogen from SMR |
| Milan | Linde | On-site production with a mix of electricity (from the grid, from a local combined heat and power plant and photovoltaics plant) (+ trailer backup delivery) |
| Oslo | Air Liquide | On-site production from renewable sources |
| Berlin | Linde | Trailer delivery of gaseous hydrogen from SMR |
| Cologne | Air Products | Trailer delivery of gaseous hydrogen from by-product source (nearby chemical plant) |
| Hamburg | Linde | On-site production from renewable sources + regular trailer delivery from by-product source |
| Whistler | Air Liquide | Trailer delivery of liquid hydrogen from hydro-electric power in Quebec, refuelled in gaseous form |


Photography ©PostAuto

## HYDROGEN SUPPLY PATHWAYS IN CHIC

As shown in the schematic, there are two main approaches for hydrogen supply:

1. On-site production of hydrogen involves installing a hydrogen generation unit as part of the refuelling station, with on-site compression.

2. Delivered hydrogen involves trailer transport of either compressed hydrogen or liquid hydrogen to be evaporated at the refuelling station. Depending on the delivery pressure, an on-site compressor may not be required.

## LOCATION OF THE HYDROGEN REFUELLING STATIONS IN CHIC

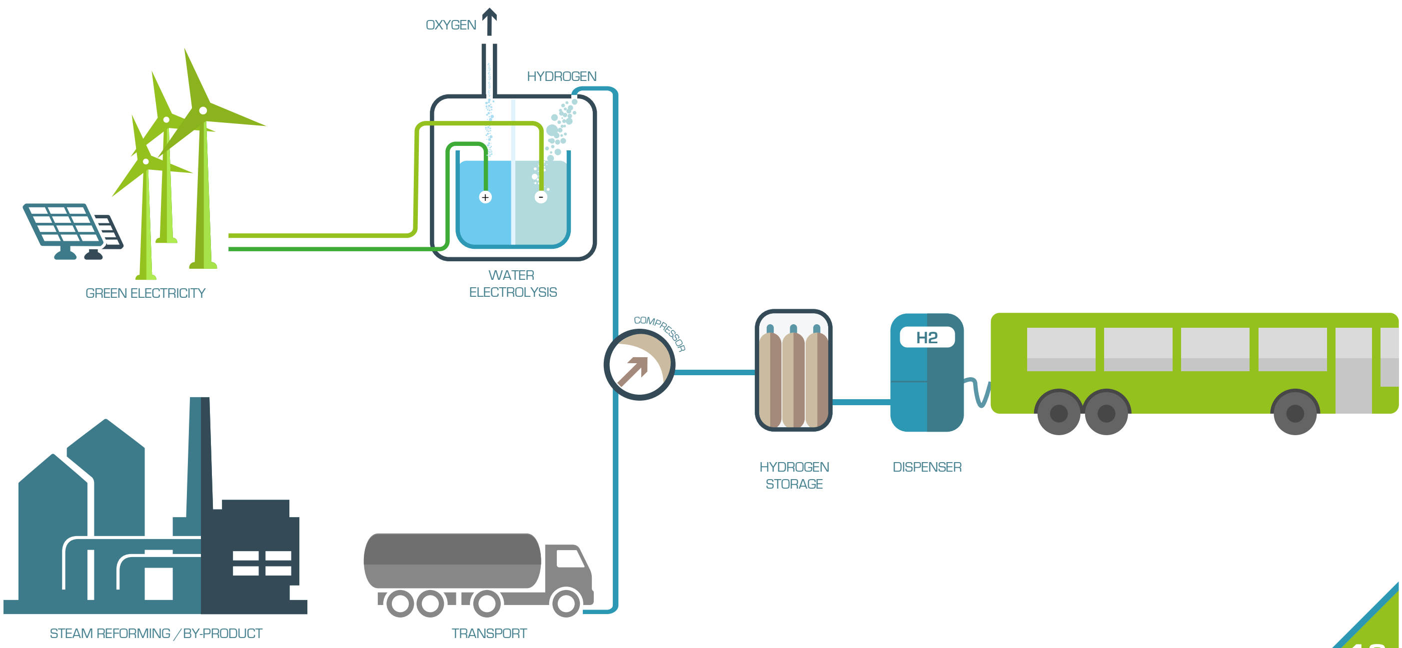
Most of the hydrogen refuelling stations in the CHIC project were located either at bus depots or close by. Some refuelling stations were open to the public (such as in Hamburg) and could be used by other vehicles, e.g. fuel cell cars.

## REFUELLING A FUEL CELL BUS

At the refuelling station, hydrogen is compressed (unless delivered at sufficiently high pressure), stored, and dispensed on demand to the buses. Dispensing requires a pressure differential between the station storage and the vehicle tank. The equipment (e.g. gas-tight nozzles and receptacles) is comparable to that used for the refuelling of natural gas. It takes less than 10 minutes on average to refuel a bus after a full day of service.

Since hydrogen can be produced in several ways, every region can produce its own fuel, based on its specific resources and circumstances, potentially providing benefits for the environment and the local economy.

## HYDROGEN SUPPLY PATHWAYS IN CHIC



# AARGAU

The canton of Aargau, located in the North of Switzerland, is one of the country's most densely populated areas, and has adopted an ambitious energy strategy to reduce local emissions. To meet these targets, Aargau is taking part in a number of different projects, including the deployment of fuel cell buses and diesel hybrid vehicles. PostBus will also be testing two electric buses in the areas of Berne and Obwalden from winter 2016.


Photography ©PostAuto

***Daniel Landolf,***
*CEO PostBus Switzerland*

*"PostBus is very upbeat about the project. The fuel cell Postbuses are popular among passengers and drivers alike, attracting attention for their quiet and smooth ride."*


Photography ©PostAuto

**5** BUSES (12 M)

**1,230,691** KM
SINCE 12/2011

**18-20** HOURS/DAY

**7.9** KG $H_2$/**100** KM

HYDROGEN PRODUCED ON-SITE
FROM RENEWABLE SOURCES
+ TRAILER DELIVERY
(BY-PRODUCT HYDROGEN)

**467,663**
LITRES DIESEL REPLACED

THE CANTON OF AARGAU,
THE SWISS POST, IBB HOLDING AG,
THE PAUL SCHERRER INSTITUTE
AND EMPA

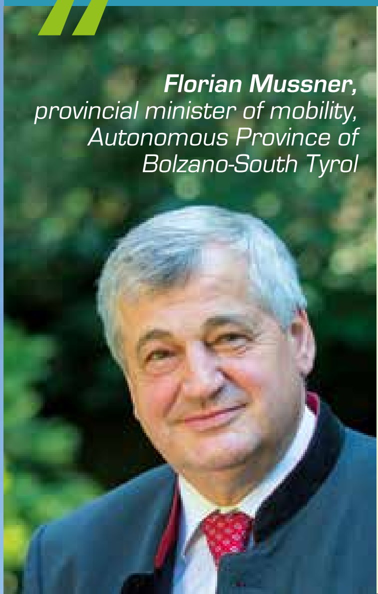
## NEXT STEPS

The fuel cell Postbuses will gradually be replaced from the beginning of 2017. The end of the fuel cell bus project in Aargau does not mean that PostBus is definitively departing from hydrogen-based technology. PostBus's long term goal is to become fossil free and fuel cell technology remains an option for future fleets. PostBus will continue to closely monitor developments in the field.


Photography ©PostAuto

# BOLZANO

The Autonomous Province of Bolzano - South Tyrol is taking action in the fight for climate protection. With the Climate Plan "Energy South Tyrol 2050" drawn up in 2011, a series of activities have been defined for different key areas to reduce annual $CO_2$ emissions below 1.5 tons per capita by 2050. South Tyrol has the ambitious aim of taking a leading role and positioning itself as a model region for sustainable alpine mobility by 2030.



***Florian Mussner,***
*provincial minister of mobility, Autonomous Province of Bolzano-South Tyrol*

*"The Autonomous Province of Bolzano, South Tyrol will reduce its $CO_2$ emissions in the transport sector by implementing various measures. This includes the further extension of public transport over the whole province, fostering the reduction of individual transport use, the increase of intermodality, the long term substitution of fossil fuels by renewables, and the expansion of electromobility in both private and public transport."*


Photography ©STA


Photography ©STA

## NEXT STEPS

With the introduction of the first five fuel cell buses on the city routes of the bus operator SASA in 2013, the Autonomous Province of Bolzano-South Tyrol gave a strong political signal. The aim in the coming years will be to deploy further emission free buses (both hydrogen powered fuel cell buses and battery electric buses) in city and suburban public transport, as well as to build the associated infrastructure for refuelling/recharging these vehicles.

Photography ©STA

**5** BUSES (12 M)

**481,454** KM
SINCE 11/2013

UP TO **12** HOURS/DAY
**6** DAYS A WEEK

**8.6** KG $H_2$/**100** KM

HYDROGEN PRODUCED BY ELECTROLYSIS AND REFUELLED AT THE $H_2$-CENTRE SOUTH TYROL

**208,277**
LITRES DIESEL REPLACED

STA, SASA AND IIT

# LONDON

London has been pioneering the development of clean bus technology to tackle the city's challenging poor air quality issues, which contribute to premature death and respiratory illnesses. By 2019 the central London area is expected to become an Ultra-Low Emission Zone (ULEZ). All double decker buses operating in the zone must be Euro VI standard hybrids, and all single decker buses operating in the ULEZ must be zero emission at tailpipe models.

Outside the central area, around 4,000 Euro IV and Euro V buses will be retrofitted to reduce tailpipe NOx and particulate matter by up to 95%. This will raise them to the latest Euro VI standard. On top of these extensive measures, the Mayor of London proposes that only diesel hybrid or zero emission double decker buses join the fleet from 2018.


"

***Valerie Shawcross,***
*London Deputy Mayor for Transport*

Photography ©Tower Transit


Photography ©Tower Transit

*“Cleaning up the toxic air is London’s biggest environmental challenge and hydrogen technology plays a key role in our vision for a low carbon city. With help from this project, London was one of the first cities to use hydrogen fuel cell buses in its fleet. We are now working with the industry to build on this success going forward.”*

## NEXT STEPS

Two additional fuel cell buses will join the fleet in 2017 as part of the European project 3Emotion [2]. London is expected to expand the fuel cell bus fleet further in the coming years if external funding can be tapped into.

**8** BUSES (11.9 M)

**16-18** HOURS/DAY

TRAILER DELIVERY
OF GASEOUS HYDROGEN

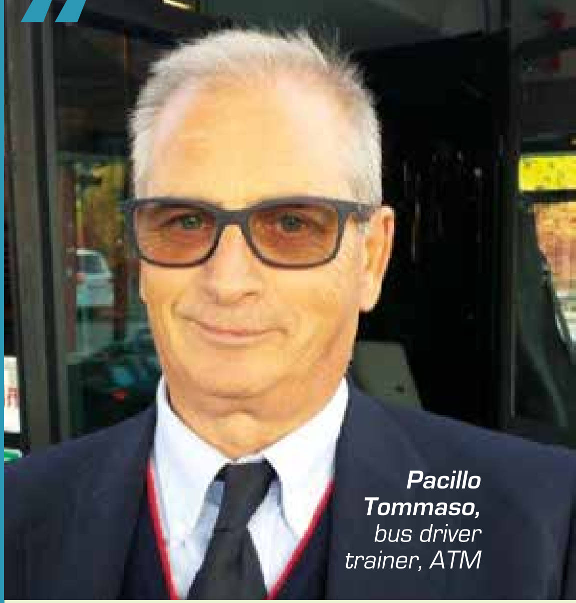
**1,298,565** KM
SINCE 01/2011

**9.7** KG $H_2$/**100** KM

**480,469**
LITRES DIESEL REPLACED

TRANSPORT FOR LONDON, TOWER TRANSIT, UK DEPARTMENT OF ENERGY AND CLIMATE CHANGE (DECC), AIR PRODUCTS

# MILAN



**Pacillo Tommaso,** *bus driver trainer, ATM*

The city of Milan is looking at ways to improve its poor air quality as, particularly in winter, it affects citizens' health and their mobility needs, with cars being regularly banned from the city. In 2012 Milan launched the Congestion Charge area (Area C) in the historic centre of the city. To enter Area C a ticket must be purchased, although certain high emission vehicles are banned completely, and low emission vehicles are exempt from the charge. Milan's bus operator, Azienda Trasporti Milanesi (ATM), is looking for clean technologies offering the right compromise between costs and operational results. Along with fuel cell buses, ATM is considering the potential offered by hybrid and electric buses.

*"Fuel cell buses are great vehicles to drive, offering comfort with no noise or vibrations. Some of the initial issues were solved in collaboration with the bus manufacturer and now the level of reliability is high. The drivers love these buses for their visibility and maneuverability. It has been very easy to learn how to drive fuel cell buses and also to teach drivers how to use them. Impressed by passengers' enthusiasm, drivers always give particular attention in service and are happy to answer questions."*


Photography ©ATM

3 BUSES (12 M)

UP TO 17 HOURS/DAY

ONSITE AT THE BUS DEPOT,
POWERED BY A MIX OF ELECTRICITY
(FROM GRID, CHP, SOLAR ENERGY)
+ TRAILER DELIVERY AS BACKUP

178,396 KM
SINCE 10/2013

10.3 KG $H_2$/100 KM

100,259
LITRES DIESEL REPLACED

ATM, LOMBARDY REGION,
CITY OF MILAN

## NEXT STEPS

After CHIC, ATM will, in collaboration with the bus manufacturer and infrastructure provider, continue passenger service with fuel cell buses for another couple of years, and test other clean technologies.




Photography ©ATM

# OSLO / AKERSHUS

Photography ©Ruter - Moxness/CatchLight Fotostudio

The environmental targets in Oslo and in the surrounding region of Akershus are very ambitious. In June 2016, Oslo announced it would reduce the city's carbon emissions 50% by 2020 and 95% by 2030, while Akershus has a target of 50% reduction by 2030.

A regional hydrogen strategy for 2014-2025 has been adopted which aims to make hydrogen widely available in the transport sector by ramping up the number of hydrogen refuelling stations.

Ruter, the public transport authority in the region, is working to ensure that all public transport in Oslo and Akershus runs on only renewable energy by the end of 2020.

**Bernt Reitan Jenssen,**
*CEO, Ruter*

*"For Ruter to succeed in our ambitious mission, it is essential to test new technology. Participation in the forward-leaning CHIC project has provided us with valuable experience in testing fuel cell buses in operation. This is important knowledge in our further efforts to accelerate the commercialization and deployment of zero emission solutions in public transport."*

Fuel cell bus at the hydrogen refuelling station

Photography ©Ruter - Moxness/CatchLight Fotostudio

## NEXT STEPS

Fuel cell buses are part of the hydrogen strategy of the region and of Ruter's Fossil Free 2020 plan.

5 BUSES (13.2 M)

546,223 KM
SINCE 04/2013

UP TO 17 HOURS/DAY

13.2 KG $H_2$/100 KM

HYDROGEN PRODUCED ON-SITE AT THE BUS DEPOT FROM RENEWABLE SOURCES

273,112
LITRES DIESEL REPLACED

RUTER, CITY OF OSLO, AKERSHUS COUNTY, TRANSNOVA, THE NORWEGIAN RESEARCH COUNCIL

# BERLIN


Photography ©TOTAL/Bernd Lammel

***Guillaume Larroque***
*Director of Service Stations, Total Deutschland*

*"We've been investing in research and development on hydrogen mobility since 2002. Initially our efforts centered on defining common standards for tank technology together with our partners. As a leading player in the network expansion, Total alone operates nine of Germany's 22 public hydrogen refuelling stations! With regard to fuel cell buses, we do believe they could play an important role in reducing emissions especially in major cities like Berlin. They would also help to increase capacity use of our existing stations. In Berlin, we use 100% green hydrogen from a windfarm and, together with partners, we are able to produce green energy at our dedicated facility in Schönefeld."*

Berlin's Mobility Programme 2016 ("Mobilitätsprogramm") includes key measures that aim to support increased use of public transport and uptake of electro-mobility from renewable energy sources, as well as reduce noise and local air pollution produced by transport. The operation of hydrogen Internal Combustion Engine buses began during the 2006 FIFA World Cup and ended in December 2014. The buses deployed were the same as those deployed in a previous EU funded hydrogen bus project, HyFLEET:CUTE. Additional alternative technologies have since been trialled, with four battery electric buses currently in operation.


Photography ©TOTAL/Bernd Lammel

## NEXT STEPS

On 30 August 2016, the first mayor of Berlin, Mr Müller, and the first mayor of Hamburg, Mr Scholz, signed a joint Letter of Intent to adopt zero emission buses, giving a strong signal to the industry that there is demand for such alternative vehicles. The Letter of Intent foresees that the two cities will procure up to 200 zero emission buses per year from 2020.

**4** BUSES (12 M)

**898,477** KM
SINCE 06/2006

$H_2$

TRAILER DELIVERY OF GASEOUS HYDROGEN

**22.8** KG $H_2$/**100** KM

BERLINER VERKEHRSBETRIEBE,
CLEAN ENERGY PARTNERSHIP,
TOTAL DEUTSCHLAND

**377,360**
LITRES DIESEL REPLACED

# COLOGNE


Photography ©RVK

In 2013 the state of North Rhine-Westphalia passed a climate protection law that sets a target to cut greenhouse gas emissions in the region by at least 25%, compared to 1990 levels, by 2020. One of the key elements in achieving this goal is the reduction of road traffic emissions. Through the project "Zero Emission/ Null Emission", Regionalverkehr Köln GmbH (RVK), the public transport operator in the region of Cologne, has set an ambitious target to replace its entire diesel bus fleet with alternative powertrains. From 2030 onwards, only zero emission buses will be procured by RVK, and in the meantime a significant fleet of emission free buses and corresponding infrastructure will be built up.

**_Carsten Bußjaeger,_**
*Operations Director, RVK*

*"From a regional public transport operator's perspective, if you are looking for zero emission solutions, fuel cell buses are the best alternative, given their short refuelling time and most importantly their range and flexibility. Furthermore fuel cell buses offer the same passenger capacity as diesel buses. With the same or similar characteristics as conventional buses we don't need to change or adjust our operating processes when introducing fuel cell buses to our fleet. On top of that, they come with the major advantage of emitting locally no harmful emissions unlike conventional buses."*


Photography ©RVK

## NEXT STEPS

Fuel cell electric buses are part of the hydrogen strategy of the region and there are plans to expand the fleet, with 30 additional vehicles and two additional refuelling stations in the region of Cologne. A large share of the fleet will be replaced with fuel cell buses and more depots will be equipped with hydrogen refuelling stations by 2030.

- **2** BUSES (18.5 M)
- **2** BUSES (13.2 M)

- **109,790** KM SINCE 09/2011
- **122,656** KM SINCE 05/2014

UP TO **12-16** HOURS/DAY

- **16.5** KG $H_2$/**100** KM
- **12.5** KG $H_2$/**100** KM

TRAILER DELIVERY OF GASEOUS HYDROGEN BY-PRODUCT SOURCED NEARBY (CHEMICAL PLANT)

- **48,813**
- **54,533**

LITRES DIESEL REPLACED

REGIONALVERKEHR KÖLN GMBH (RVK), HYCOLOGNE – WASSERSTOFF REGION RHEINLAND, STADTWERKE HÜRTH, STADTWERKE BRÜHL, STATE OF NORTH RHINE-WESTPHALIA

# HAMBURG


Photography ©CEP

Hamburg, the second largest city in Germany, is a role model for sustainability and climate protection. The city's target to reduce $CO_2$ emissions by 80% in 2050 (compared to 1990 baseline) is very ambitious. Fuel cell buses and other emission-free buses have the potential to eliminate airborne pollutant emissions from public transport, so from 2020 onwards, only emission-free buses are to be purchased by HOCHBAHN.

***Ulrike Riedel,***
*Board Member of HOCHBAHN*

*"The growing amount of traffic in cities and the corresponding pollution and noise emissions present an enormous challenge for all of us. Using public transport is in itself an option to contribute to climate protection. However, HOCHBAHN's objective is to further improve their services to protect the climate and to improve air quality. Therefore, we already operate fuel cell buses in regular line service since 2003."*


Photography ©HOCHBAHN

## NEXT STEPS

In Hamburg, as part of Europe's first bus innovation line 109, HOCHBAHN currently operates fuel cell and other alternative technology buses, with an increasing amount of electric buses set to come into service from 2017 onwards.

**4** BUSES (12 M)

DOUBLE SHIFT SERVICE UP TO
**16** HOURS/DAY

**80%** PRODUCED ON-SITE AT THE HYDROGEN REFUELLING STATION FROM RENEWABLE SOURCES;
**20%** DELIVERED BY TRAILER (BY-PRODUCT HYDROGEN)

**457,712** KM
SINCE 04/2012

**8** KG $H_2$/**100** KM

**171,651**
LITRES DIESEL REPLACED

HOCHBAHN
hySOLUTIONS
VATTENFALL




Photography ©CEP

# WHISTLER

Whistler is a mountain resort community in the Province of British Columbia (B.C.), Canada. BC Transit is the Provincial Crown Agency charged with coordinating the delivery of public transport in the region, and has been involved in fuel cell bus deployment for over a decade. Their fleet of 20 fuel cell buses was introduced during the 2010 Winter Olympic Games to support B.C's initiative to reduce greenhouse gases.

The bus fleet became the largest demonstration of this zero-emission technology in the world. The five-year demonstration project was completed on March 31, 2014.

Two reports on the performance of the buses were released by the US National Renewable Energy Laboratory (NREL) in collaboration with BC Transit for the California Air Resources Board [3].

**Juan Carlos Gomez,**
*P. Eng. General Manager, Whistler Transit Ltd*

*"Whistler Transit Ltd., a division of Pacific Western Transportation, is honored to have been the entity responsible for the operation and maintenance of the largest fuel cell bus fleet in the world. Due to the innovation and technology of these buses, our technicians were thrilled, eager and excited about the whole project. Operating the fleet did come with some challenges, but the technical support from our partners and suppliers, strong teamwork, commitment and leadership helped us persevere. The results of this project were amazing, having a zero emission heavy duty vehicle, which can carry up to 60 passengers, can perform well in adverse weather conditions."*

## NEXT STEPS

BC Transit's 2030 Corporate Strategic Plan includes increasing the company's environmental, social and economic accountability. BC Transit resolves to continue to test and implement vehicles with alternative propulsion systems that are less reliant on fossil fuels.


Photography ©BC Transit


Photography ©BC Transit

**20** BUSES (12.5 M)

UP TO **22** HOURS/DAY

LIQUID HYDROGEN GENERATED FROM HYDRO-ELECTRIC POWER IN QUEBEC, DELIVERED TO THE BUSES IN GASEOUS FORM

GOVERNMENT OF CANADA, PROVINCE OF BRITISH COLUMBIA, BC TRANSIT, RESORT MUNICIPALITY OF WHISTLER, CANADIAN HYDROGEN FUEL CELL ASSOCIATION

OVER **4,005,000** KM SINCE 12/2009

**15.67** KG $H_2$/**100** KM

**2,202,750** LITRES DIESEL REPLACED

# BUS OPERATION

The operation of the CHIC fuel cell buses has been highly successful, with the buses meeting the demanding daily operational requirements of public transport without compromise. This, combined with the step change generational improvement in performance, bodes well for the technology into the future.

Photography ©Tower Transit

## THE 54 FUEL CELL BUSES HAVE:

- **Travelled over 9 million kilometres – equivalent to travelling around the globe 233 times!**
- **Operated for about 500,000 hours on the fuel cell system, with some of the individual fuel cell stacks already having logged over 20,000 operating hours and still operating.**
- **Demonstrated a daily duty up to 20 hours and over 350 km driving range.**
- **Achieved a high fuel efficiency with a consumption as low as 9 kg hydrogen / 100 km for 12 m buses (equivalent to 30 litres of diesel) – 26% more efficient than an equivalent diesel bus (40.91 l of diesel/100 km on average).** [a]
- **$CO_2$ emissions reduced by 85% compared to diesel buses along the bus life cycle when the hydrogen fuel is produced from renewable energy sources; saved 6,800 tonnes of $CO_2$ equivalent.** [b]

## MAIN ACHIEVEMENTS

### New generation technology leading to improved efficiency

All fuel cell buses operated in CHIC belonged to a newer generation than previous bus models. The key improvements were:

- Hybridisation of the fuel cell drivetrain, with the integration of batteries/super capacitors allowing the bus to buffer peak loads, boost acceleration and allow energy recovery from braking.
- Hybrid systems allowed smaller and cheaper fuel cell systems, offering extended lifetimes and better fuel efficiency, leading to the use of fewer storage tanks while maintaining the range.

### A full-time operation in the making

- Operators have been able to plan to have fuel cell buses provide daily transit services that usually have been provided by a diesel or a Compressed Natural Gas (CNG) bus.
- However, as is the case for all innovative technologies, one cannot expect a fuel cell bus to be 100% reliable on day one. All city partners had to face a teething period where bus availability was lower than expected due to component failures and long spare parts delivery times.
- Bus availability steadily improved, as issues with some of the components and controls on these new bus generation were ironed out and maintenance technicians learned to maintain the vehicles.
- By the end of the project the buses were close to meeting the 85% availability project target across the fleet – with some buses reaching a 90% availability level.
- The bus operators agreed that there is no technological reason why fuel cell buses cannot meet the level of availability expected for diesel buses. Instead issues with availability have primarily derived from immature supply chains, diagnosis of problems requires experts that are in short supply and there are currently too few trained maintenance technicians on depots to carry out repairs.
- These issues will be resolved with increased scale in the supply chain and thus there is no obvious technical issue preventing a move to the next stage of larger scale commercialisation of the technology.

## New maintenance concepts

Another step change in CHIC was the move to in-house maintenance of the fuel cell buses. While most previous fuel cell bus fleets had been maintained by dedicated technicians from the bus manufacturers, bus operator staff conducted much of the CHIC bus maintenance: an important step forward in bringing fuel cell technology into the normal commercial operational environment of bus operators.

> *"Repairing and maintaining these vehicles, to me, was like working on a giant computer […]. As we were the only fuel cell bus operator in the country at the time, it was a big learning curve […]. Being a part of the solution gave me the feeling that I was working towards something that could have a positive impact on the environment, and future generations to come."*
>
> ***Ross Lewin,***
> *Tower Transit Mechanical / Electrical Apprentice, London*


Photography ©STA

# NEXT STEPS/RECOMMENDATIONS

## Reducing technology costs

Whilst a 12 m a fuel cell bus cost well over €1 million at the project start, this is expected to come down to €650,000 or even below for orders placed in 2017 [4]. Further cost reductions in total servicing cost are required for commercialisation. This is expected to be achieved through a combination of scale (primarily) and further technology development.

The FCH JU's fuel cell bus commercialisation study [5] concluded that a volume of 300-400 fuel cell buses would be a sufficient pre-condition to speed up commercialisation. Hence a pan-European effort has begun, with a view to unlocking the market potential of fuel cell buses by bringing down the costs through joint procurement of large fuel cell bus fleets across Europe. The expectation is that these orders will stimulate bus manufacturers to invest in production of larger and therefore cheaper fuel cell bus fleets. (see section "closing the gap to commercialisation").

## Increasing availability

Operational availability needs to meet or exceed that of a diesel bus. This has been partly solved by resolving the teething issues of the new drivetrains within CHIC. This will be further improved in next generation demonstration projects currently underway, where the increased scale in the supply chain will reduce waiting times for parts and ensure more trained specialists are available to diagnose and fix problems. These improvements to create a more mature and robust supply chain will be an essential part of commercialising the technology.

Photography ©RVK

## Strategies for a full 10-15 year life for fuel cell buses

The longevity of the fuel cell bus components has been demonstrated during the trial. Indeed, some of the fuel cells which were expected to last for 6,000 hours are still running after 20,000 hours. However, for a fully commercial product, fuel cell bus suppliers must develop strategies for the full 10-15 year working life of a bus. This will involve even longer life fuel cell stacks and/or low cost programs for fuel cell replacements.

## People are key – don't underestimate training

Sufficient time and financial resources should be allocated for training and refresher courses for bus drivers, as well as training for depot managers, first responders etc. It is important to start training as early as practical, although having buses available increases participant levels of interest and understanding. Providing those bus drivers and staff who will have contact with passengers with a good knowledge of the technology and its broader environmental and community benefits helps to increase public understanding and acceptance. Sharing training resources from other cities was highly beneficial in CHIC and a repository where all upcoming "fuel cell bus" cities can pool training information would be beneficial.

***Billy Hadley,***
*Tower Transit driver trainer, London*

Photography ©Tower Transit

*"Because of the different characteristics the fuel cell bus has from a diesel bus, it was important that drivers had a basic understanding of how hydrogen and the engineering/electrical components combine in order for this bus to be used in service. Training for this vehicle takes one day. All selected drivers are given classroom training with an emphasis on safety and vehicle handling. Drivers are also given a tour of the refuelling compound and the specially built workshops where Tower Transit's highly trained engineers are available to answer any "more technical" questions. Classroom training is usually managed in a group session [...]."*

## A collaborative approach and strong project management

Given their complexity, fuel cell bus deployment trials require strong planning (including a detailed funding strategy) and project management. Given the number and diversity of partners involved, collaboration at an early stage is key to make the project a success. Establishing a "delivery forum" where all partners involved in the project (operators, infrastructure providers, bus suppliers, funders, planners etc.) can meet and update each other on progress should be an early priority when developing these projects.

## Policies driving clean air regulations

Industry is improving the technology and availability of both fuel cell and battery electric zero emission buses, while costs are decreasing. Local authorities and national regulators will play a key role in introducing these technologies by mandating zero emission public transport in certain zones (e.g. London's Ultra Low emission Zone). Based on the results of the CHIC project, decision-makers can start to feel secure that the technology is ready to allow regulation in favour of these technologies.

*"I am happy and somewhat proud that this innovative technology was implemented here in my town [...]. It is good for the environment and a very pleasant ride – similar to a tram in regards to the noise and judder."*

***Passenger***
*while riding a fuel cell bus in Hürth, near Cologne*

**Interested?** (see page 48)

- Guidelines for delivering fuel cell bus projects
- Public executive summary of the report on bus operation
- Report collecting the experience with respect to certification of the buses and hydrogen refuelling infrastructure

# INFRASTRUCTURE OPERATION

Photography ©Tower Transit

## THE HYDROGEN REFUELLING STATIONS IN CHIC:

- Were highly reliable – with an average availability of 97% across all sites.
- Allowed fuel cell buses to be refuelled in less than 10 minutes after a full day in service.
- Were well integrated into busy bus depots.
- Matched expectations, with a refuelling capacity of over 200 kg/day, easily capable of fuelling current fleets of fuel cell buses.
- More than 1.2 million kg hydrogen refuelled .
- Close to 62,000 fillings.
- About 17 kg dispensed per filling on average at the European sites and 25 kg in the Canadian site.
- Use of more than 4.3 million litres of diesel avoided.

## MAIN ACHIEVEMENTS

### High availability of the refuelling stations

On average across the project, the availability achieved by stations was 97%, a number achieving more than 99% and none falling short of 94%[c]. This is by far better than in previous trials.

More than half of all downtime hours were caused by issues with hydrogen compressors. At all sites where station availability fell below 97% it was because of a hydrogen compressor problem. Downtime was also partially caused by immature supply chains and resulting long lead times for spare parts, as was also encountered on the bus side.

For the time being, this issue can be resolved or at least mitigated by installing a spare unit in parallel (redundancy), or alternatively through high-pressure hydrogen delivery from an external source.

### A short refuelling time

A high refuelling speed will be very important for large hydrogen bus stations where many buses need to refuel in a short overnight window. CHIC usually achieved refuelling in less than 10 minutes, typically 6 to 8 minutes for the average dispensed amount of hydrogen (17 kg), representing a significant improvement compared to the previous generation of hydrogen refuelling stations for buses.[6]

# NEXT STEPS/ RECOMMENDATIONS

### Towards hydrogen refuelling stations for complete bus depots

Today's stations have demonstrated their capability to reliably supply current fuel cell bus fleets with hydrogen fuel. The challenge is to develop stations suitable for refuelling a complete depot of fuel cell buses, i.e. 100+ vehicles every day. The question of what requirements such stations will have to meet was debated among the CHIC partners. Whilst there was an agreement on qualitative criteria, it turned out that the quantitative expectations associated with some of these criteria were not universal. These expectations depend on the size of the individual depot and on how the routine of preparing the buses for the next day of service is organised. In particular:

- Apart for a generally high availability, the station has to be operative by 100% every day during a dedicated refuelling window (4 to 12 hours, depending on the local circumstances).
- If buses are cleaned during refuelling, refuelling time is not critical so long as it is shorter than the cleaning time. Up to 10 minutes may be acceptable. When refuelling and cleaning are consecutive work items, the requirements on filling time are usually more demanding. 5 minutes or faster were quoted.

### Scaling up: making the refuelling of 100's of buses a reality

Bus operators are unlikely to convert a depot to hydrogen within a short period, such as a year. Such a process will primarily be based on the end-of-life schedule of existing diesel vehicles. Future stations therefore need to be scalable (modular and flexible) in line with fleet growth, to avoid a huge initial investment followed by underutilisation for a long time.

Significant challenges still lie ahead on the way to large-scale, fully commercial refuelling infrastructure for buses. These challenges are well understood and are being tackled. A dedicated project, New-BusFuel [7], looks at engineering solutions for depots integrating larger fuel cell bus fleets (50 to 250 buses) in 12 locations across Europe, with results expected for spring 2017.

### People, people, people!

With respect to staff requirements in day-to-day service, operators point out that enthusiastic and trained staff are still key to ensuring a high level of availability. Future stations need to place less demands on staff. In particular, unsupervised refuelling must always be possible.

### Enhancing collaboration

The interaction with the various parties throughout the trial, in particular during its early stages, was of key importance. Recommendations in this respect include:

- Hold regular progress meetings with all parties involved, both within the organisation and with local partners.
- Keep the neighbourhood, the general public, decision makers etc. well informed.[8]
- Involve the relevant permitting authorities from the beginning and develop a collaborative working relationship. An inclusive approach at the outset pays major dividends.
- Early work with local first responders (fire brigade and police) to ensure they are aware of the project and receive the information and training they need to be comfortable with the installation.

Comprehensive lessons and recommendations that resulted from planning, procurement, obtaining approvals, and operation of the hydrogen stations in the CHIC project were collected and compiled.

> *"We have been trained to do the refuelling of fuel cell buses. Refuelling is fast and safe. [...]"*
>
> ***Antonio Cosentino,***
> *bus operator, ATM, Milan*

### Harmonising standards at European level

Some of the cities encountered delays due to lengthy permitting procedures for their hydrogen refuelling infrastructure. This underlines the need for specific documents which support both the operator, who has to obtain approvals, and the authorities considering granting them. This could lead to a mandatory EU description of safety requirements on/around hydrogen infrastructure, such as a recognised European standard. Some CHIC partners even favoured the set-up of a European Directive.

However, the prevailing experience is that individual local authorities follow their own procedures within an overarching framework. Therefore, even an EU Directive would not necessarily solve all major infrastructure licensing issues, since such a document cannot substitute individual and organisational experiences on regional level.

The project has gathered best practices that will be helpful for fuel cell bus deployments in other cities. Additionally, further Europe-wide harmonisation of regulations, codes and standards (RCS) are ongoing. Key stakeholders in the sector work on a common framework to simplify procedures and thereby reduce costs.

**Interested?** [see page 48]

- Recommendations for hydrogen infrastructure in subsequent projects
- Guidelines for delivering fuel cell bus projects
- Public executive summary of the report on infrastructure operation
- Report collecting the experience with respect to certification of the buses and hydrogen refuelling infrastructure

# SOCIAL STUDY RESULTS

## PEOPLE AND FUEL CELL BUS TECHNOLOGY

### Understanding influencing factors in fuel cell bus acceptance

Before CHIC, research on social acceptance of fuel cell & hydrogen technologies in transport had focussed on public acceptance and revealed a generally positive attitude amongst the general public. In contrast to some other contemporary innovations e.g. nanotechnology, hydrogen applications appeared to not unduly concern people. However, stakeholders responsible for planning, implementing and operating hydrogen applications have generally not been the focus of social acceptance studies, nor has there been engagement with people "sceptical" about the potential of hydrogen in transport.

The CHIC approach aimed to extend the existing knowledge about the state of technology acceptance by identifying drivers to acceptance, shedding light on the concerns of different stakeholders such as environmental groups, industry, civil servants and decision-makers, and providing the necessary background information to understand the acceptance process rather than measuring it.

The CHIC qualitative research approach was based upon the understanding that acceptance is a process, dependent on several influencing factors and changing over time. In total 185 face-to-face, one-hour interviews in five of the CHIC regions (Bolzano, Hamburg, Cologne/Huerth, Oslo, Aargau/Brugg) were conducted between August 2011 and March 2013.

### The importance of added value

An important finding of the acceptance study was that changing a running system and switching to a new technology when competitive and reliable alternatives are in place will require more than "just" environmental benefit and energy efficiency – it requires a greater added-value to the early adopters (region and/or organization). The social acceptance needed in the transition phase of a new technology is a highly supportive one: people will either have to actively use it, adapt their behaviour, pay additional costs or take the risk of investing into this new technology. Possible motivation factors to make these changes are manifold:

- People want the product.
- People want the image the product provides.
- People are "externally motivated" to use the product.

The analysis of expectations and experiences of bus drivers, stakeholders, and the general public revealed a high support of the idea to green transport and of the technology potential on the one hand, and a set of regional challenges to be tackled to increase acceptance in demonstration projects, whenever technology is more expensive and less reliable in daily use than expected and required by the regional stakeholders and the public. In addition, it was revealed that so long as the concrete regional or personal benefits remained unclear in the project environment and amongst the actors responsible for supporting the implementation process, "value for money" was questioned.

"Value for money" may be a promising concept to increase motivation and acceptance of higher costs or the need to change behaviour, as interviewees in the CHIC research stated. It is not always the absolute cost that seems to be relevant to the acceptance process, but the perceived added value that offsets the additional cost.

For the transition to the new technology, it would be helpful to find added value other than that related to the technology concept. For example, improved bus services related to fuel cell buses (connections, fast lanes), more comfortable or appealing design of the buses (including seating) and other improvements will help increase the acceptance of higher costs.

To sum up, framing the cost discussion of the new technology in terms of "value for money" proved to be a key argument in favour of fuel cell buses, on top of the arguments related to the environmental benefits.

Photography ©STA

# ENGAGING WITH HYDROGEN SCEPTICS

> *"At the end of the day for us, it is all about where hydrogen will come from."*
> ***Environmental NGO***

Two rounds of interviews were conducted with 50+ individuals within organisations external to the hydrogen world in Europe and in North America, representing governments (elected and civil servants), industry, lobby and peak groups (in particular environmental NGOs) and research organisations. They were thought in most cases to be sceptical of hydrogen in transport.

Subsequently a round table was held at which a sub group of the interviewees discussed key issues and concerns raised frequently in the initial interviews with members of the CHIC consortium along with some influential hydrogen experts. In general, interviewees believed that hydrogen would have an application in future transport because hydrogen powered fuel cells had technological and environmental advantages.

> *"If hydrogen is to be an efficient energy vector for transport it needs to find its niche."*
> ***Researcher***

Discussions over a two year period between "sceptics" and CHIC partners came to some general agreements, specifically:

- Hydrogen production must be sustainable and based on renewable energies.
- Hydrogen transport business cases must be credible and focus on those areas where the technology has advantages.
- Policy development should include the role of hydrogen within the broader energy system.
- Supportive government policy will continue to be a most significant influence in the drive to commercialise fuel cell vehicles.
- The costs of hydrogen production and acquiring the vehicles must be significantly reduced.

> *"We should also be aware of the WOW factor of all of this.*
> *We are living in a time when we can produce buses that don't pollute."*
> ***Comment by participant in "Sceptics" Roundtable***

**Interested?** [see page 48]

- Study on the influencing factors for fuel cell and hydrogen technologies in public transport
- Issues of concerns for external stakeholders and critics and pathways to their resolution

# ENVIRONMENTAL ANALYSIS RESULTS

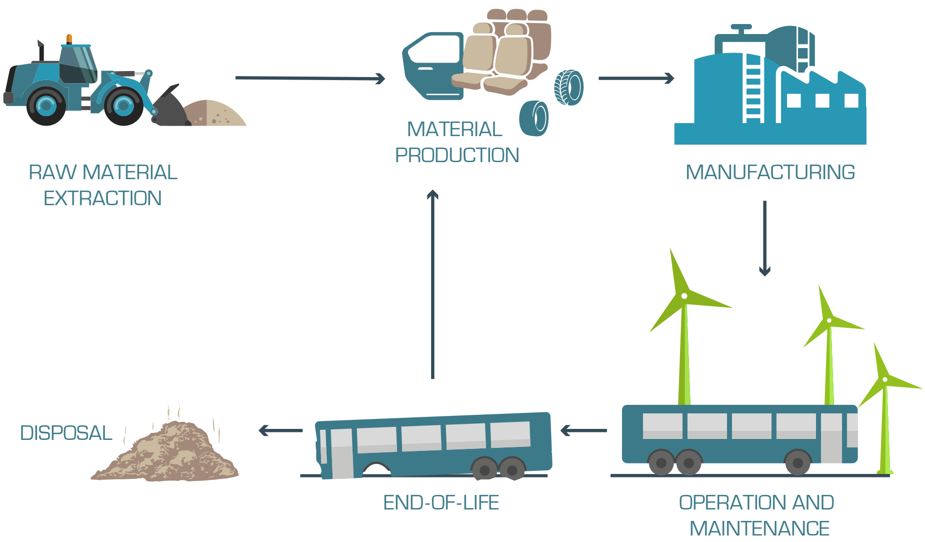
## LOCALLY EMISSION FREE

Fuel cell buses have a great advantage in comparison to diesel buses: they are emission free while driving, except for water vapour. Even state of the art diesel buses (Euro VI emission standard) release NOx and particulate emissions.
For example, a 12 m bus emits 0.45 g/km NOx and 6 mg/km of particulate matter (PM) on average [9]. Additionally, the combustion of one litre of diesel produces 2.67 kg $CO_2$. All of these emissions are avoided entirely through a move to fuel cell buses.

## LIFE CYCLE ASSESSMENT

To understand the full environmental impact of the application of fuel cell buses, further investigations on the environmental impacts of fuel cell buses within CHIC were quantified with a Life Cycle Assessment (LCA) study, considering not only the local lack of emissions from fuel cell buses on the road, but all phases of their life cycle, from raw material extraction, manufacturing of the buses, operation including the production of hydrogen, and maintenance of the buses, up to their disposal (see schema below). All data on material flows, energy flows and emissions were collected, aggregated and evaluated.

### LIFE CYCLE PHASES OF A FUEL CELL BUS

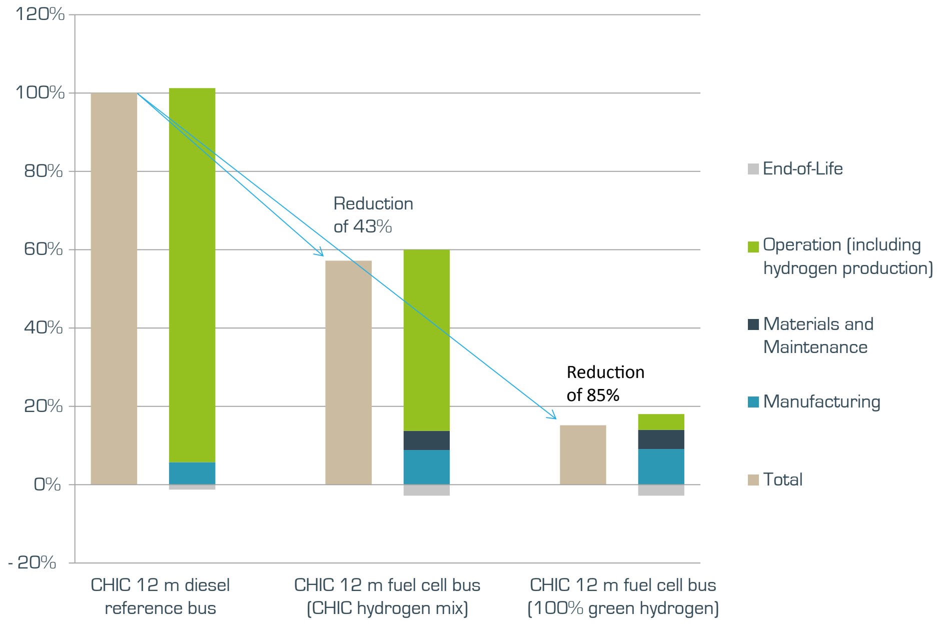



The vehicle profile assumed for the evaluation is the average of all CHIC 12 m fuel cell buses, with a consumption of 9 kg hydrogen/100 km. The hydrogen mix within CHIC consisted of 72% green hydrogen and 28% hydrogen produced from conventional energy sources.

The assessment of a fuel cell bus over its life cycle shows that environmental impacts mainly occur during hydrogen production and bus manufacturing.
The overall impact of fuel cell buses on climate change (Global Warming Potential - GWP - resulting from the emission of $CO_2$ and other greenhouse gases) was studied in detail, considering two hydrogen supply routes: the CHIC hydrogen mix and 100% green hydrogen. This was compared to an average CHIC 12 m diesel reference bus, with a diesel consumption of 40.9 l/100 km [a]. The lifetime of the buses was assumed to be 720,000 km [d].

The figure shows that, even when 100% green hydrogen is used and even though fuel cell buses do not emit $CO_2$, a certain GWP impact from the operation of fuel cell buses remains. This is because electricity provision, hydrogen production as well as bus maintenance require facilities, equipment and infrastructure. Their construction, operation and maintenance causes a GHG impact.

## COMPARISON OF GWP IMPACTS - SHARES OF LIFE CYCLE PHASES




**Two main lessons can be drawn with respect to the full life cycle of fuel cell buses:**

- Deploying a CHIC 12 m fuel cell bus using the CHIC hydrogen mix reduces the global warming potential impact by 43% compared with a corresponding state-of-the-art diesel bus.
- Deploying a CHIC 12 m fuel cell bus using 100% green hydrogen fuel reduces the global warming potential impact by 85% compared with a corresponding state-of-the-art diesel bus.

## SUSTAINABILITY OF FUEL CELL BUSES

The LCA study was embedded into an even broader assessment of the sustainability of fuel cell buses. The definition of sustainability was interpreted in the following way [e]: "If we use fuel cell buses today, will future generations be able to use them as well, without negatively impacting the environment or their quality of life?"

Fuel cell buses' environmental impact, economic viability and social acceptance were analysed. The outcome is that the buses show a great sustainability advantage compared to diesel buses. No "show stopper" was identified. Using green (low carbon) hydrogen is crucial to succeed in decarbonising public transport.

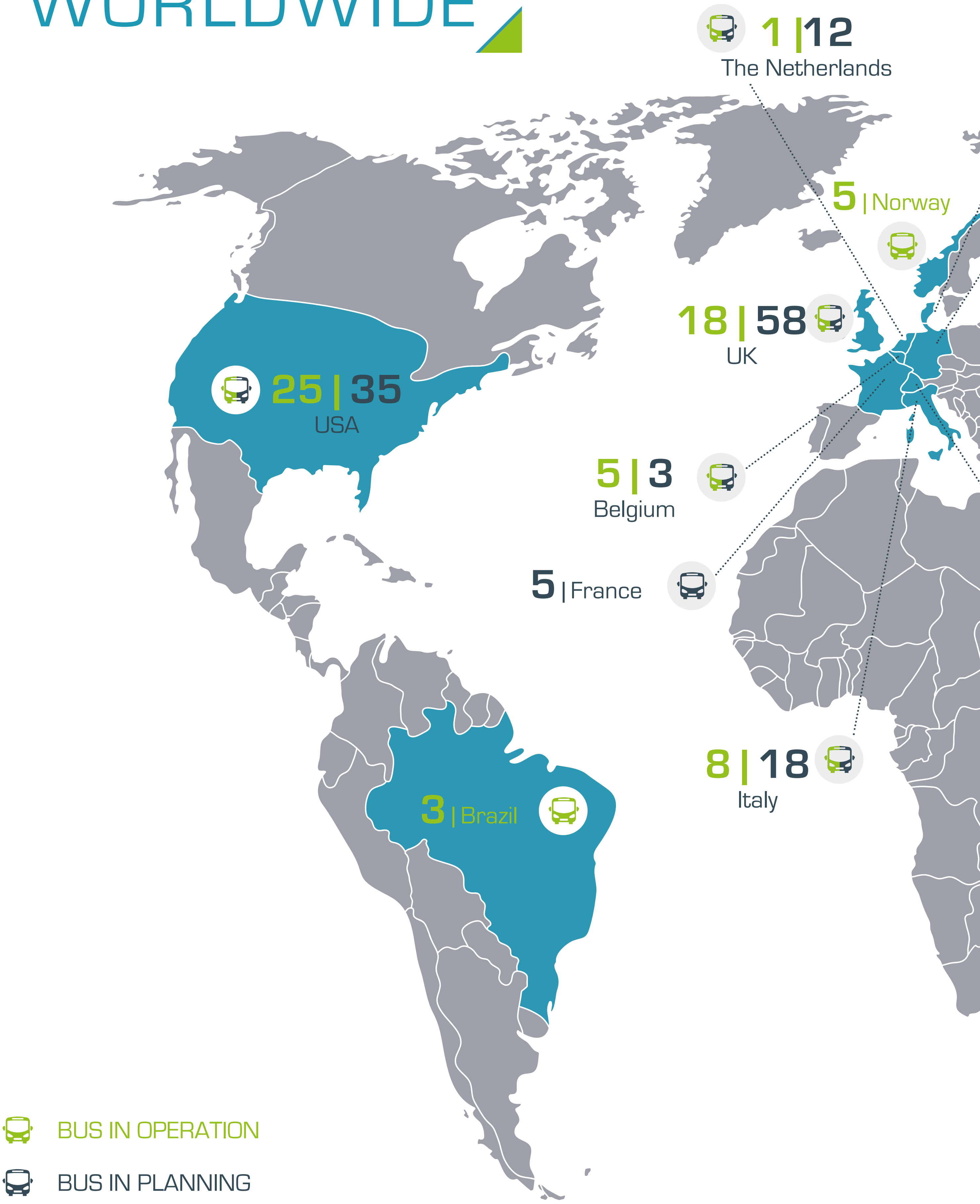
*"Fuel cell buses are even more sustainable if they run on green hydrogen. Green hydrogen should therefore be made a priority in the next fuel cell bus deployments."*

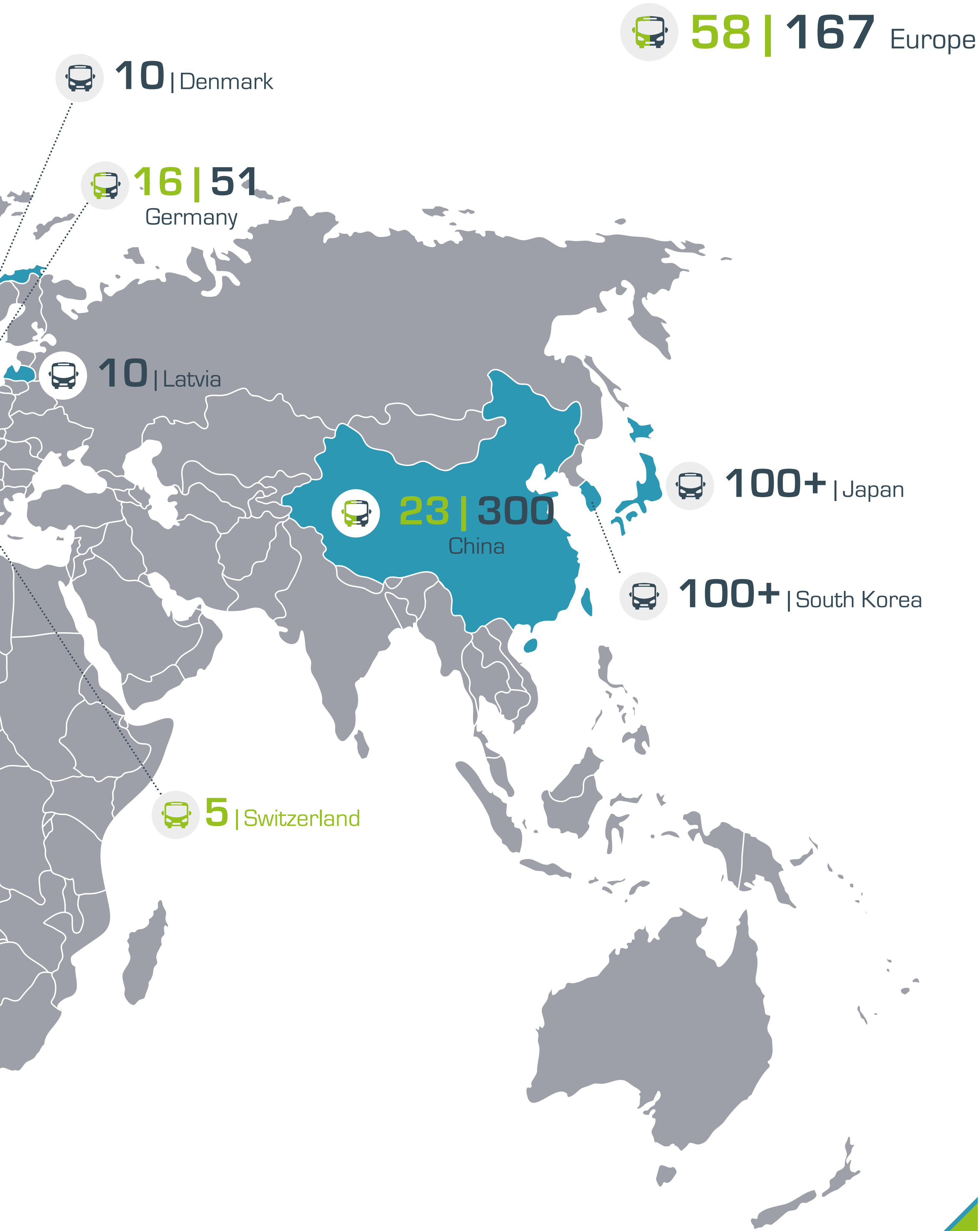
***Comment by the CHIC analysis team***

**Interested?** (see page 48)

Sustainability assessment of fuel cell buses and related infrastructure

# FUEL CELL BUSES WORLDWIDE




58 | 167 Europe
10 | Denmark
16 | 51
Germany
10 | Latvia
23 | 300
China
100+ | Japan
100+ | South Korea
5 | Switzerland

# CLOSING THE GAP TO COMMERCIALISATION

**Fuel cell bus technology is at an early stage of commercialisation. Bridging the gap to full commercialisation will require addressing barriers for both fuel cell bus and refuelling infrastructure technologies.**

A fact-based analysis comparing the long-term potential of multiple powertrains for buses [10] concluded that at production volumes of 1,500 units per year, and assuming a widespread roll-out of fuel cell electric cars, fuel cell buses can be commercially competitive, particularly on environmentally sensitive routes where diesel vehicles are prohibited. Furthermore, many public transport operators consider the technical advantages of fuel cell buses to be superior to other ultra low emission buses (e.g. zero tailpipe emissions, equivalent range and refuelling time to a conventional diesel bus). Before a move to widespread commercialisation can occur, the technical issues identified by the CHIC project must be resolved (discussed above). Additionally, there are specific commercial challenges (discussed below).

## FUEL CELL BUS TECHNOLOGY COST

Fuel cell bus operational performance has improved significantly since first demonstration in the early 2000s, as proven by trials like CHIC.

The most significant barrier to increased uptake of fuel cell buses is vehicle capital cost. A key reason for high capital costs is that fuel cell buses are currently batch produced, with a number of components made by hand in batch production. Diesel buses are manufactured in continuous production, which is a far more optimised and efficient process. As such, it is widely accepted that the next step to bring down fuel cell bus capital costs will be to optimise manufacturing processes by benefiting from economies of scale and standardisation. Bus manufacturers can only achieve this with large orders (i.e. 50-100 of buses as opposed to recent orders of 5-10 buses).

A pan-European consortium, formed as part of the FCH JU's fuel cell bus commercialisation study [5], has been engaged in regular dialogue with industry and formed clusters of bus operators from different regions/countries. The clusters have been established to agree on a common bus specification and enable joint procurement of fuel cell buses. To-date, across all five European clusters, first board level approval has been reached for up to 600 new fuel cell buses, and a successful application for funding has already been made which will support deployment of the first 140 buses. This first wave of large-scale joint procurement aims to reduce fuel cell bus capital costs by 25% versus the current state-of-the-art (i.e. from today's €850,000€ per 12 m bus to below €650,000) [4].

Ultimately the sector will need to go further than this level, with improvements in technology, as well as increased volumes from fuel cell buses and other fuel cell vehicles (e.g. passenger cars) allowing a fuel cell bus price below €400,000.

Photography ©HOCHBAHN

## SUPPORTING INFRASTRUCTURE

Industry has made excellent progress in recent years to improve infrastructure performance. For example, all stations deployed across Europe for CHIC refuelled buses within 10 minutes on average, and availability has improved significantly, with stations being in service on average 97% of the time.

The next generation of fuel cell bus fleets will likely include a higher number of vehicles per depot and will require refuelling solutions with higher capacity than exist today. As the fleet of buses increases, the reliability of the refuelling stations must also rise to effectively guarantee 100% available hydrogen. As mentioned in the "infrastructure operation" section, a large pan-European project called NewBusFuel [7] is working to understand the technical challenges of designing higher capacity stations in order to support fuel cell bus commercialisation. Partners in the NewBusFuel project are working to resolve the knowledge gap on how to refuel large amounts of hydrogen (>1,000 kg/day) whilst maintaining high performance expectations and ensuring sufficient flexibility to cope with incremental procurements, i.e. demand ramp-up.

A useful metric for bus operators to compare hydrogen and diesel infrastructure costs is the average hydrogen cost (€/kg), which incorporates all capital and operating costs. For cost parity with diesel, a hydrogen fuel price of €5-6/kg is widely accepted as the target for industry, as this is the level which allows parity with diesel costs for today's buses. As larger refuelling facilities are designed, industry will benefit from economies of scale. Hydrogen supply partners will also need to access low cost sources of primary energy to ensure cheap enough hydrogen to achieve these price levels.

Photography ©Air Products

## OVERALL BUSINESS CASE

Improving the overall fuel cell bus business case for operators is fundamental to achieving their full commercialisation. For example, for infrastructure, a number of partnerships are investigating the potential for flexible electrolysers to supply demand whilst also providing balancing services to constrained power networks, in order to benefit from additional revenue streams. Furthermore, opportunities exist to optimise net electricity costs by operating electrolysers during off-peak hours or by developing in-house electricity trading capabilities to benefit from spot price variations. These new business streams need to be understood and considered to maintain competitiveness whilst zero emission buses become increasingly relevant.

To support the second wave of large-scale activities, a number of innovative financial instruments could back bus operator's business plans. For example, establishing a novel debt mechanism to enable lease financing for zero emission buses and infrastructure would assist operators spread high capital cost payments over time. Furthermore, exploring mechanisms would reduce risk burdened by bus manufacturers to help minimise high mark-up on zero emission technologies.

**Interested?** (see page 48)

- Strategies for joint procurement of fuel cell buses
- Fuel Cell Electric Buses – Potential for sustainable Public Transport in Europe
- Urban buses: Alternative Powertrains for Europe

# CHIC CONCLUSIONS

**The CHIC project is the culmination of over 15 years of efforts around the world to bring fuel cell bus technology to the point that it is ready to be deployed as a solution to the challenges cities are facing in eliminating air pollution from their streets and in reducing their contribution to climate change. The project has succeeded in this task. CHIC has proved that fuel cell buses can offer a driving experience which passengers prefer over conventional buses. The buses achieve this with an operational flexibility which allows bus operators to use the buses as a like for like replacement for diesel on even the most challenging city routes. This has all been achieved with material reductions in $CO_2$ emissions and the complete elimination of harmful bus emissions from urban streets.**

This has not been achieved without challenges. The CHIC project has identified areas which the fuel cell bus sector will need to work on to allow it scale up. These include:

- Bus availability – over the 6 years of the CHIC project, availability of buses improved, as specific components were upgraded and maintenance technicians learned how to keep the buses operational. Availability issues in the final years of the project were mainly related to the immaturity of the maintenance supply chain. Developing a more mature supply chain will require larger scale bus deployments, to allow investments across the supply chain.

- The costs of procuring and maintaining fuel cell buses needs to fall further – during the CHIC project, the capital cost of a fuel cell bus fell by over 50%. Further cost reductions will be required to achieve a mass market breakthrough. These are expected to come from economies of scale through increased volume of demand and through technology improvements (particularly through crossover from the automotive sector).

- Hydrogen stations at scale – CHIC has demonstrated hydrogen stations able to reliably fuel buses. Larger hydrogen station designs will be needed for larger bus fleets. These will need to demonstrate essentially 100% reliability of supply (through equipment redundancy) and a lower hydrogen cost to those in CHIC.

- Bus efficiency –The fuel economy of the buses more than doubled between the first fuel cell bus trials (2003-2008) and CHIC. There is still room for improvement and optimised hybrid fuel cell drivetrains for buses can help ensure an attractive financial proposition for the buses.

- Importance of green hydrogen – social science research suggested, that for hydrogen to be fully accepted by society, a clear and viable path to fully sustainable hydrogen needs to be articulated by the industry as an essential part of any new fuel cell bus deployment.

A lasting legacy of the CHIC project will be that it has catalysed a substantially increased awareness and interest in fuel cell buses. As a result, projects across Europe are already preparing larger scale deployments of 100+ buses in the coming years. These promise to resolve many of the scale related challenges above and will ensure the fuel cell bus continues its progress to becoming the best choice for cities looking to eliminate public transport emissions in their cities. [11]

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### Explanations

[a] 40.9 l diesel/100 km is the average fuel consumption of 12 m European diesel reference buses as reported by the CHIC cities.

[b] The $CO_2$ calculation was done on a well-to-wheel basis; it includes bus manufacturing, hydrogen production and supply, bus operation and maintenance, and the end-of-life phase of bus and infrastructure (see section "Environmental analysis results" on page 38). To draw the comparison with diesel buses, the following figures were used: average diesel consumption 40.9 l/100 km (see explanation [a]); average mileage of an urban bus over its lifetime 720,000 km (see explanation [d])

[c] The availability of the hydrogen refuelling stations was calculated as the ratio of the number of hours that the station was in operation and the total number of hours (24 hours, 7 days a week).

[d] A bus lifetime of 720,000 km corresponds to 60,000 km/year over 12 years. Source: Faltenbacher, M. (2006) Modell zur ökologisch-technischen Lebenszyklusanalyse von Nahverkehrsbussystemen. Dissertation, Universität Stuttgart

[e] The definition of sustainability generally recognised by the scientific community is: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

**http://chic-project.eu/info-centre/publications**

# ABBREVIATIONS AND DISCLAIMER

## ABBREVIATIONS

**CHP:** Combined Heat and Power
**CNG:** Compressed Natural Gas
**$CO_2$:** Carbon dioxide
**FCH JU:** Fuel Cells and Hydrogen Joint Undertaking
**GWP:** Global Warming Potential
**$H_2$:** Hydrogen
**ICE:** Internal Combustion Engine
**LCA:** Life Cycle Assessment
**LPG:** Liquefied Petroleum Gas
**NGO:** Non-Governmental Organisation
**RCS:** Regulations, Codes and Standards
**SMR:** Steam Methane Reforming
**ULEZ:** Ultra Low Emission Zone

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