Urban buses: alternative powertrains for Europe




A fact-based analysis of the role of diesel hybrid, hydrogen fuel cell, trolley and battery electric powertrains

The following companies and organisations participated in this study:

Bus manufacturers	EvoBus, Hess, Iveco, MAN, Solaris, Van Hool, VDL/APTS
Bus operators	BVG (Berlin), Bogestra (Bochum), GVB (Amsterdam), HOCHBAHN (Hamburg), RET (Rotterdam), Ruter (Oslo), RVK (Cologne), MIVB/STIB (Brussels), SWS (Solingen), Transport for London, TMB (Barcelona), VRR (Gelsenkirchen)
Infrastructure providers	Air Liquide, Air Products, Ballast Nedam, Hydrogenics, H2 Logic, Linde, Shell
Technology providers	ABB, BAE Systems, Ballard, Bombardier, Enerdel, Hydrogenics, NuCellSys, Proton Motor, Siemens, ŠKODA ELECTRIC, UTC Power, Voith, Vossloh Kiepe, ZF
Organisations and associations	European Fuel Cells and Hydrogen Joint Undertaking, NOW GmbH, Element Energy, Fuel Cell and Hydrogen Network NRW, HyER (Hydrogen, fuel cells and electro-mobility in European Regions), HyCologne — Wasserstoff Region Rheinland

This study was financially supported by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), a unique public-private partnership supporting the research, development and demonstration (RD&D) of fuel cell and hydrogen energy technologies in Europe. Its aim: to accelerate the market introduction of these technologies in order to realise their significant potential within a low-carbon energy system.

FCH JU believes it is essential to understand how fuel cells and hydrogen technologies compare to other technologies. It has therefore supported this neutral and fact-based comparison of alternative powertrains for urban buses.

For more information on this study, or the next steps, please contact the FCH JU: fch-ju@fch.europa.eu or www.fch-ju.eu.

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McKinsey & Company, the management consultancy, provided analytical support to the study. Any recommendations or positions taken in this report are the responsibility of the authors, not of McKinsey & Company.

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Executive summary

Alternative powertrains for urban buses are necessary to reduce GHG emissions and improve air quality

The European Union (EU) is committed to significantly reducing its greenhouse gas (GHG) emissions – by at least 80 percent[1] by 2050. However, in order to meet this target, emissions in the road transport sector may need to be cut by as much as 95 percent[2]. With urban mobility set to double by 2025[3], increasing the share of public transport (currently just 8 percent[4] of all transport) and fuel efficiency will play a key role, but are not expected to be enough. Further emissions reductions are therefore necessary if the EU is to meet its current – and future – climate targets.

With the development of alternative powertrains that reduce local emissions to zero, urban buses can now contribute to decarbonising road transport while addressing the critical issue of air pollution. Indeed, a number of cities are already focused on cleaner public transport (see Exhibit 2), while many bus operators are renewing their fleet or deploying low-emission powertrains.

While these zero local-emission buses offer different advantages – depending on local conditions and operator requirements – all have more efficient energy conversion than conventional buses and offer substantial reductions in well-to-wheel GHG emissions and pollutants which degrade air quality. They are also virtually silent, reducing noise pollution significantly.

A fact-based analysis based on proprietary industry data

In order to study the potential advantages and outlook for zero local-emission buses, a group of companies and government organisations participated in a study on the various powertrain technologies available for urban buses in Europe from 2012 to 2030. The aim: to provide a fact-based and objective evaluation of their sustainability, performance and economics (on a well-to-wheel basis), based on proprietary industry data. Focusing on the standard 12-metre bus and articulated bus segment of ~10,000 buses[5], this is currently representative of ~65 percent of the European urban bus market and responsible for a comparable share of GHG and local emissions.

Eight powertrain concepts and their respective energy sources were analysed, representing the most common archetypes for these bus segments (see Exhibit 4 for a detailed description):

- Four internal combustion-based concepts: diesel, CNG, diesel parallel hybrid and diesel serial hybrid. It is assumed that fuels will contain an increasing share of biofuels over time, according to targets given in the directive 2009/28/EC.
- Four zero local-emission concepts: hydrogen fuel cell, trolley, opportunity e-bus and overnight e-bus.

The results show the outcome of two possible rollout scenarios:

1. The bus industry leads in the development of zero local-emission powertrains, without taking into account “cross-industry” effects from developments in the car industry.
2. Zero local-emission powertrains in the passenger car and bus industries develop in parallel, with considerable “cross-industry” effects due to synergies between car and bus technologies.

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1 From 1990 levels
2 McKinsey Global GHG Abatement Cost Curve; International Energy Agency World Energy Outlook 2009; US Environmental Protection Agency; European Environment Agency (EEA)
3 From 2005 levels: International Association of Public Transport (UITP)
4 TREMOD IFEU institute, Heidelberg
5 Annual new registrations

Alternative powertrains offer a range of advantages

Alternative powertrains for urban buses differ in terms of advantages:

- Hydrogen fuel cell buses have a long driving range, are flexible in their route and use filling stations (mostly in depots), comparable to conventional buses.

- Trolley buses can move freely within the network of overhead lines and are well proven in operation, but require substantial investments in infrastructure (overhead network).

- Opportunity e-buses are electric buses that aim to minimise the weight of the battery by recharging en route at passenger stopping points. They are promising in terms of projected costs and require a network of recharging points.

- Overnight e-buses are electric buses that carry the weight of battery required to drive the entire route without recharging. They are flexible in their route, but over the next 10 years are not expected to meet average daily range requirements nor carry a sufficient number of passengers due to the weight of the batteries.

- Diesel hybrid buses have been used for a number of years, relying on fossil fuels for long-distance driving using existing diesel infrastructure. However, hybrids reduce fuel and GHG emissions, and serial hybrids in particular are capable of undertaking certain stretches of the route in fully electric drive.

Zero local-emission buses differ in terms of technological maturity

While it is possible that technological breakthroughs could provide step changes in current pathways to sustainable mobility, the focus of the study is on technologies that are proven in R&D today and therefore considered capable of commercial deployment within the time frame of the study.

However, there are differences in the technological maturity of the powertrains considered in this study that need to be taken into account when assessing the results: trolley buses have been in operation for decades, while hydrogen fuel cell buses have been used in test fleets since the late 1990s, with the latest fuel cell technology in operation for a number of years, including hydrogen fuel cell hybrids.

Electric buses using the latest battery and charging technology, on the other hand, are currently being trialled throughout Europe. This means that while data for the hydrogen fuel cell bus are based on real-life operations, data for opportunity and overnight e-buses are based on projections (Exhibit 1).

Results

Please see Chapter 2 for a detailed description of the key assumptions underlying the results.

Offering a similar performance to conventional buses, alternative powertrains can significantly reduce local and GHG emissions for a limited price premium until 2030

Zero local-emission buses can significantly reduce GHG emissions until 2030 at a price premium of EUR 0.3 to 1.0/kg CO_2e[6] compared to conventional diesel buses (based on the two rollout scenarios described above). However, between 2012 and 2030, the total cost of ownership (TCO) of conventional and alternative powertrains converges, with a 2030 TCO gap of 10 to 12 percent and 17 to 26 percent for standard opportunity e-buses and hydrogen fuel cell buses respectively. For articulated buses, the 2030 TCO gap compared to diesel is expected to be 11 to 19 percent for the hydrogen fuel cell bus and 22 percent for the trolley bus. GHG abatement costs for urban buses are also lower than for passenger cars in terms of passenger km.

6 CO_2 equivalent; a term used to indicate the impact of other greenhouse gases (e.g. 1 ton of methane is equivalent to the effect of 25 tons of CO_2)

Exhibit 1

ALTERNATIVE POWERTRAINS DIFFER IN TERMS OF TECHNOLOGICAL MATURITY

Facts as of 2012 for Western Europe (12-m and 18-m buses)

	Diesel/CNG/ trolley	Diesel hybrids[1]	Hydrogen fuel cell bus	Opportunity e-bus	Overnight e-bus[3]
Number of buses deployed	*Diesel, CNG and trolley buses are considered fully mature as they have been in use for >50 years and cover >95% of the current market (for 12-m and 18-m buses)*	>1,000	>30	0[3]	0[4]
Number of Km driven		>>10,000,000	>1,000,000 (>5,000,000)[2]	0[3]	0[4]
Recharging/ refuelling procedures completed		*Same as diesel*	>500	0[3]	0[4]
Number of years in operation		~2-3 years	~2 years	▪ No operation yet for 12-m/18-m buses ▪ ~2 years for 8-m overnight e-buses	
Supply industry/ adjacent industries		▪ Battery ▪ Electric drives	▪ Fuel cell in automotive ▪ H_2 supply ▪ Battery, electric drives	▪ Infrastructure ▪ Battery ▪ Electric drives	▪ Infrastructure ▪ Battery ▪ Electric drives

Data on all **powertrains** to be **treated with appropriate caution** as

- Data on **hydrogen fuel cell** buses are **based on real-life operations** (12-m or 18-m buses) in **small-scale fleets** with a **time frame** of a **few years**
- Data on **electric buses** (opportunity and overnight e-buses) are based on **Clean Team data** for the **core components, diesel serial hybrid Clean Team data** for **other components** and **expert estimates** for the **remaining parts** as no information from actual operation of 12-m or 18-m buses was available
- Data on **hybrids** are based on a **few years of experience** only despite **large number of buses**

1 Latest-generation serial hybrid and parallel hybrid 2 Both for buses without powertrain hybridisation and buses with powertrain hybridisation such as in this report
3 In Turin and Genoa, 31 opportunity e-buses of 8 meter operate since 2002, 16 buses of 8 meter are ordered in Vienna; in Braunschweig and Milton Keynes opportunity charging buses are also ordered; outside Western Europe, opportunity charging e-buses operate in Shanghai (12 meter) and Los Angeles (10 meter)
4 An unknown number of European cities operate or have ordered models, some built by Chinese manufacturers; 3 Optare fast-charging 11 meter buses operate in Coventry
SOURCE: Study analysis

Opportunity e-buses and hydrogen fuel cell buses are the most promising zero local-emission powertrains

In the standard 12-metre bus segment, the opportunity e-bus is the most economical zero local-emission option with a price premium of EUR 0.3/km compared to the conventional diesel bus in 2030 and well-to-wheel GHG emissions close to zero using renewable electricity. The 12-metre hydrogen fuel cell bus has a GHG emissions reduction of up to 75 percent at a price premium of EUR 0.4 to 0.7/km. The hydrogen fuel cell bus requires hydrogen filling stations to be installed at the bus depots, whereas the opportunity e-bus requires charging points along the route and/or at the first and the final stops.

In the articulated bus segment, the hydrogen fuel cell bus is the most economical zero local-emission option with a well-to-wheel GHG emissions reduction of up to 75 percent at a price premium of EUR 0.3 to 0.6/km, compared to the conventional diesel bus. It uses the same filling stations as the standard hydrogen fuel cell bus. (The concept of an articulated opportunity e-bus has yet to be proven in tests and pilots, and is therefore not included in this study.)

The price premium for alternative powertrains could be significantly reduced or eliminated

The results described above are based on conservative assumptions, as outlined in Annex 2. However, there is considerable potential for further cost reductions due to the following factors:

- The development of cheaper, alternative methods of hydrogen production, e.g. steam methane reforming (SMR) with natural gas and CO_2 capture and storage (CCS), or novel technologies such as electrolysers based on proton exchange membranes

- A higher oil price due to limited resources

- A higher tax on diesel in some Member States; a CO_2 tax is also not included in the base case
- Lower costs for the fuel cell stack and battery, as assumed in other studies within the car industry[7].

Under these conditions, the hydrogen fuel cell bus and opportunity e-bus have the potential to reach TCO parity with the conventional diesel bus even sooner than 2030.

The role of taxation and oil prices

In the same way that there is a potential upside to cost reductions for alternative powertrains between 2012 and 2030, there are also potential risks:

- Directive 2003/96/EC aims to tax hydrogen and electricity as conventional fossil fuels which would have a highly detrimental effect on zero local-emission buses.
- There are scenarios which favour a lower oil price than that used in this study. In a world where increased use of natural gas reduces the demand for oil, the price could fall back to USD 90/bbl or less, which would improve the TCO for conventional diesel buses and diesel hybrids.

Diesel hybrid options could provide cost-effective solutions in the short term

With high-driving performance and high flexibility, diesel hybrid options (serial and parallel) could provide a bridging technology towards zero local-emission powertrains at almost zero cost penalty ~EUR 0.1 to 0.5/kg CO_2e for the standard 12-metre bus and the same (or lower) cost penalty for the articulated bus. In this transitional period, serial hybrids in particular could provide zero-emission driving capability for longer distances and allow a partial reduction of GHG emissions of up to ~20 percent compared to conventional buses. As importantly, they would allow the buildup of critical competence on the electrification of drivetrains required for both e-buses and hydrogen fuel cell buses.

Recommendations

NB: For certain recommendations, the relevant group is indicated in italics between square brackets at the start of the paragraph.

The deployment of zero local-emission buses in European cities is not only necessary to achieve EU climate targets, but addresses the critical issue of air pollution. Where an infrastructure of overhead lines is present, trolley buses will continue to be a zero local-emission option for public transport; for all other cities, both hydrogen fuel cell buses and opportunity e-buses are promising.

Diesel hybrid buses reduce both local and GHG emissions, but there is a limit to the reductions achievable (~20 percent). However, since many elements of their powertrains are similar to those of zero local-emission buses, diesel hybrids offer an attractive bridging technology for the medium term while enabling zero local-emission technologies to reach critical volumes.

Europe requires the gradual deployment of zero local-emission buses – as of today

Zero local-emission powertrains can be available at a lower TCO than conventional diesel buses even before 2030, as shown in Chapter 4 ("Upside potential"). However, both hydrogen fuel cell buses and opportunity e-buses face potential market failure issues that are inherent to any new technology. This

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7 For example: "A portfolio of powertrains for Europe: a fact-based analysis – the role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles": www.fch-ju.eu/sites/default/files/documents/Power_trains_for_Europe.pdf

means that proactive measures are needed to accelerate market introduction beyond "early mover" cities and regions in order to achieve the necessary economies of scale.

It is therefore essential that policymakers and bus operators, manufacturers and component providers synchronise their efforts in order to commence large-scale deployment within the next decade:

[Public authorities as funding agencies] Continuing the momentum initiated by pilot projects is key to achieving aggregate numbers, which in turn will drive down the costs of major components. While several funding schemes are currently in place at an EU and national level, the majority end in 2015 or 2016. It is therefore imperative to set up further follow-up programmes comprising a number of local projects and focusing on the transition to a commercial market over the next 5 to 10 years. Policymakers and other sponsors should consider different financial structures (e.g. subsidies, project bonds, partnerships, low-cost financing) to support these pilots and the subsequent (pre-)commercialisation phase.

[Public authorities and bus operators] For powertrains that are already at or near the point of commercialisation, gradual fleet procurement needs to be initiated as of today. Indeed, with a lifetime of 12 years or longer, buses that are purchased this year will remain part of the fleet until at least 2024. An aspirational change in the bus fleet by 2020 must therefore be initiated in the immediate future. Sustained periodic purchases are also key to the commercial success of bus manufacturers and component suppliers. Finally, the case for commencing the procurement of zero local-emission buses is even more pronounced in those cities or regions where local conditions are favourable, e.g. there is a cheap supply of hydrogen as a by-product; hydrogen is used as medium to balance renewable electricity; there is sheddable electricity during the night; or where hydrogen fuel cell deployment can be combined with investment in CCS.

A gradual but steady move to zero local-emission powertrains will allow the development of industry experience and expertise in key areas such as operation and maintenance. It will also generate a clearer view on which technologies are best suited to specific scenarios and local needs, and in turn help accelerate their development.

The deployment of zero local-emission buses in European cities should be further accelerated

[Bus manufacturers and component providers] On the supply side, bus manufacturers, component suppliers and infrastructure providers need to develop concrete and detailed masterplans, indicating the technical and commercial viability of their products over time. This will enable the market to make longer-term commitments that are essential to increasing the learning rates of zero local-emission powertrains.

In order to achieve further cost reductions, manufacturers of buses and bus components need to collaborate on innovation and standardisation by sharing experiences gained in pilots and early deployment in the form of benchmarks or other quantitative metrics. Learnings from regions outside Europe should also be proactively exchanged, with insights and results incorporated into plans for the European market. Since a large element of the drivetrain technology for a hydrogen fuel cell bus and an opportunity e-bus is similar, efforts should be made to share experiences, benchmark across both powertrains and codevelop components.

[Public authorities as regulators] In order to achieve a stable investment climate for zero local-emission powertrains, a change in the legal framework on a European or national level is necessary. Potential legislative changes are already being developed in a number of areas (see Chapters 4 and 5), but greater clarity is required on future alternative fuel taxation, carbon taxes, air quality legislation and other issues in order to sustain stable, long-term investments.

Next steps

The European Fuel Cells and Hydrogen Joint Undertaking (FCH JU) invites public authorities, transport operators, bus manufacturers, component providers and other interested organisations to partner with in the next phase of the study. The aim of this phase is to detail the roadmap towards the implementation of hydrogen fuel cell technology in urban transport in Europe. This would ideally focus on a select number of interested cities and/or regions from which insights would lead to recommendations on a pan-European level. Interested parties are invited to contact the FCH JU at fch-ju@fch.europa.eu or www.fch-ju.eu.

1 Objective and scope of study

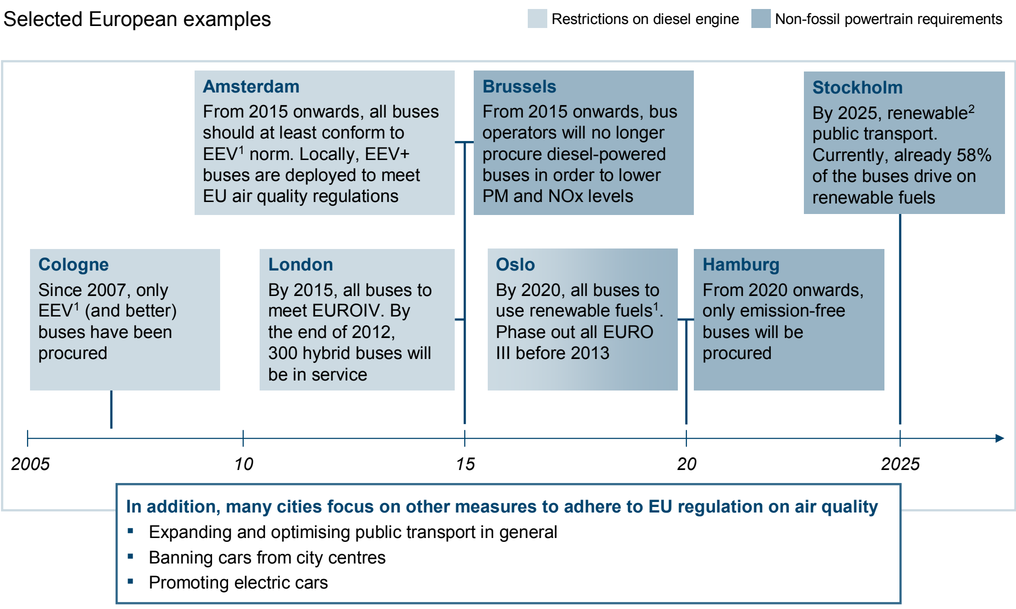
Alternative powertrains for urban buses reduce GHG emissions and improve air quality

The EU is committed to significantly reducing its GHG emissions – by at least 80 percent[8] by 2050. However, in order to meet this target, emissions in the road transport sector may need to be cut by as much as 95 percent[9]. With urban mobility set to double by 2025[10], increasing the share of public transport (currently just 8 percent[11] of all transport) and fuel efficiency will play a key role, but are not expected to be enough. Further emissions reductions are therefore necessary if the EU is to meet its current – and future – climate targets.

With the development of alternative powertrains that reduce local emissions to zero, urban buses can now contribute to decarbonising road transport while addressing the critical issue of air pollution. Indeed, a number of cities are already focused on cleaner public transport (Exhibit 2), while many bus operators are renewing their fleet or deploying low-emission powertrains.

Exhibit 2

POST 2015, MANY EUROPEAN CITIES ARE FOCUSED ON ALTERNATIVE POWERTRAINS



1 EEV: Enhanced Environmentally friendly Vehicle is a EURO norm in-between EUROV and EUROVI
2 Incl. biofuels

SOURCE: Local city municipal websites; 2001/81/EC

A fact-based analysis based on proprietary industry data

A group of companies and government organisations therefore undertook a study on the various powertrain technologies available for urban buses in Europe from 2012 to 2030. The aim: to provide a fact-based and objective evaluation of their sustainability, performance and economics, on a well-to-wheel basis.

The fact base used in this study is the result of the collaboration of more than 40 parties from the urban bus industry: bus manufacturers, operators, infrastructure providers, technology providers and several associated partners, all providing proprietary industry data and expert knowledge.

8 From 1990 levels
9 McKinsey Global GHG Abatement Cost Curve; International Energy Agency World Energy Outlook 2009; US Environmental Protection Agency; European Environment Agency (EEA)
10 From 2005 levels: International Association of Public Transport (UITP)
11 TREMOD IFEU institute, Heidelberg

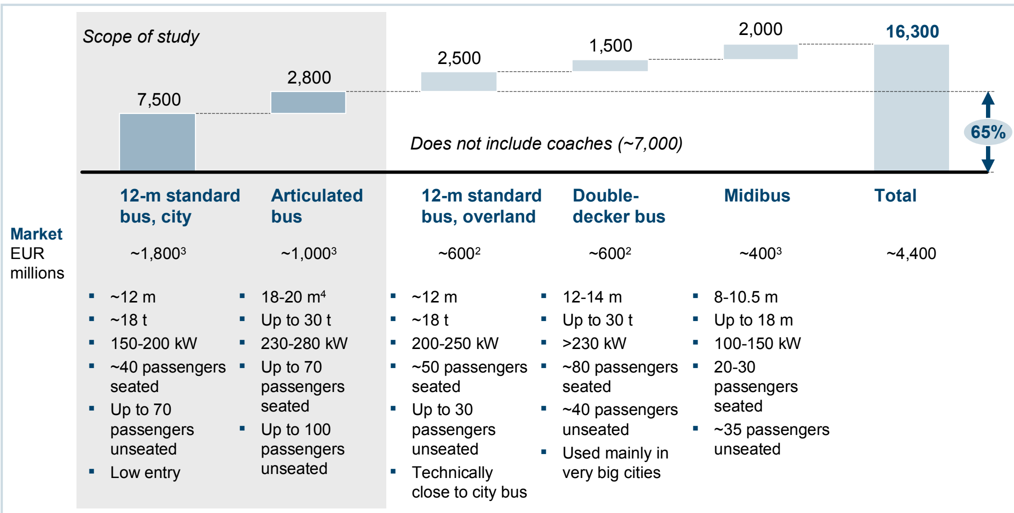
Covering the sustainability, performance and economics of urban buses in Europe, 2012 to 2030

The study focuses on the standard[12] and articulated bus segment covering ~10,000 buses[13], which is currently representative of ~65 percent of the European urban bus market and responsible for a comparable share of GHG and local emissions (Exhibit 3).

Exhibit 3

THE STUDY FOCUSES ON THE STANDARD AND ARTICULATED BUS SEGMENT, REPRESENTATIVE OF ~65% OF THE EUROPEAN URBAN BUS MARKET

European urban bus market segments[1], Western Europe, 2010
Number of annual registrations



1 Split based on 2010 registrations for UK, France, Italy, Spain; total number of registrations in Europe via extrapolation based on population size (Europe vs. UK, France, Italy, Spain together); coaches not taken into account
2 Based on the estimated numbers above and estimated average prices
3 Figures for midibus, standard bus and articulated bus based on estimations by study participants
4 Can be more for, e.g., double-articulated buses

SOURCE: Truck & Bus Builder Reports Ltd.; SMMT; AAA; UNRAE; IEA; VDV; OEM publications; study analysis

Eight powertrain concepts and their respective energy sources were analysed, representing the most common archetypes for these bus segments (Exhibit 4):

- Four internal combustion-based concepts: diesel, CNG, diesel parallel hybrid and diesel serial hybrid.
- Four zero local-emission concepts: hydrogen fuel cell, trolley, opportunity e-bus and overnight e-bus.
- Fuels being used in the combustion-based concepts contain an increasing share of biofuels over time, in accordance with targets given in the directive 2009/28/EC.

12 12-metre size
13 Annual new registrations

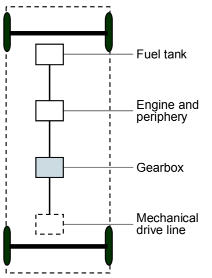
Exhibit 4

THE STUDY FOCUSES ON A PORTFOLIO OF POWERTRAINS: DIESEL, CNG, PARALLEL HYBRID, SERIAL HYBRID, HYDROGEN FUEL CELL, TROLLEY, OPPORTUNITY E-BUS AND OVERNIGHT E-BUS

ICE powertrain | Transmission | Electric powertrain | Battery or supercaps | Fuel cell powertrain

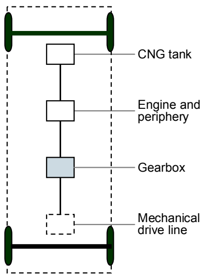
Diesel, CNG and diesel hybrids are powertrains in scope which rely partly on a conventional engine

Diesel powertrain



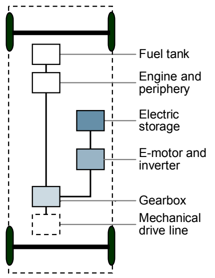
- **Conventional** diesel combustion engine
- **No dependence** on electric infrastructure
- **High fuel consumption** and exhaust emissions
- **High range** typically >300 km

CNG powertrain



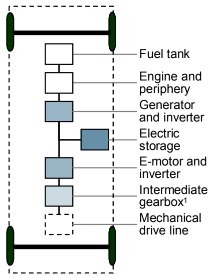
- **Conventional** CNG combustion engine
- **No dependence** on electric infrastructure
- **High fuel consumption** and exhaust emissions
- **High range** typically >300 km

Parallel hybrid powertrain



- **Parallel** hybrid configuration of electric and ICE drive
- **Conventional engine is primary mover** of the vehicle with support from small electric motor
- **Energy storage recharged** by recuperation of braking energy
- Fully electric driving for **smaller distances** (<2 km)

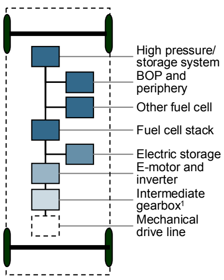
Serial hybrid powertrain



- **Serial** hybrid configuration of dominating electric system
- **Conventional engine & e-generator unit** produces full driving power
- **Energy storage recharged** by recuperation of braking energy
- Fully electric driving for **smaller distances** (<10 km), larger range possible depending on capacity of battery

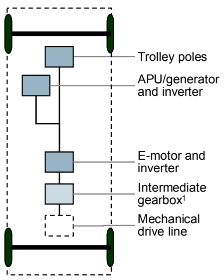
Hydrogen fuel cell, trolley and two e-buses are powertrains in scope with zero local emissions

Hydrogen fuel cell hybrid powertrain



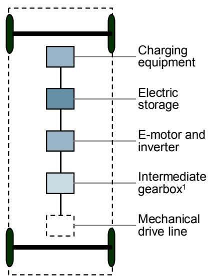
- **Serial hybrid** configuration of fuel cell system and electric drive
- **Battery recharged** by recuperation (capacity typically ~20kWh)
- Hydrogen tank pressure typically 350 or 700 bar
- **Medium/high range** (typically 200 - 250 km)

Trolley powertrain



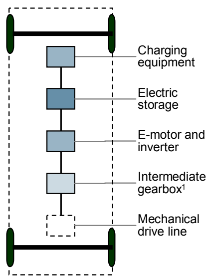
- **Purely electric** drive
- Conventional auxiliary power unit **(APU)** to cover short distances without overhead wiring – short free range
- Electric energy taken **from the overhead wiring** while driving

Opportunity-charging powertrain



- **Purely electric** drive
- Medium battery capacity (typically ~40-60kWh), Li-ion technology
- **Short free range** (typically <100 km)
- Only charging of battery **from the grid** while stationary at intermediate stops (e.g., through an overhead catenary system)

Overnight-charging powertrain



- **Purely electric** drive
- Large battery capacity (typically >200kWh), Li-ion technology
- **Medium free range** (typically 100 - 200 km)
- Only charging of battery **from the grid** while stationary at the depot

1 Intermediate gearbox optional depending on drivetrain architecture

SOURCE: Study participants

The study analyses all concepts from a well-to-wheel perspective, which means that it includes GHG emissions from all stages of the value chain (Exhibit 5). As the hydrogen supply chain for road transport is still in the development stage, detailed cost figures and efficiencies were collected from the relevant parties in order to obtain reliable data for the required hydrogen infrastructure. For fully mature supply chains such as diesel and electricity, external data sources were used.

Exhibit 5

FOCUS OF THE STUDY IS ON BUS AND INFRASTRUCTURE COSTS; FOR HYDROGEN FUEL CELL, THE OVERALL SUPPLY CHAIN IS CONSIDERED.

Based on external source | Based on Clean Team data

Powertrain concept	Fuel production costs	Fuel distribution costs	Fuel dispensing/ charging costs	Bus costs
Diesel	Refining	EU mix	Filling station	All production costs
CNG	Processing	EU mix	Filling station	All production costs
Diesel parallel hybrid	Refining	EU mix	Filling station	All production costs
Diesel serial hybrid	Refining	EU mix	Filling station	All production costs
Hydrogen fuel cell	10 production methods	3 distribution methods	Filling station	All production costs
Trolley	EU electricity generation mix[1]	EU mix	Overhead wiring	All production costs
Opportunity e-bus	EU electricity generation mix[1]	EU mix	Charging points	All production costs
Overnight e-bus	EU electricity generation mix[1]	EU mix	Charging points	All production costs

1 Premium of EUR 50/MWh added for fully renewable electricity

SOURCE: Study analysis

Zero local-emission buses differ in terms of technological maturity

While it is possible that technological breakthroughs could provide step changes in current pathways to sustainable mobility, the **focus of the study is on technologies that are proven in R&D today** and therefore considered capable of commercial deployment within the time frame of the study.

However, there are differences in the technological maturity of the powertrains considered in this study that need to be taken into account when assessing the results: trolley buses have been in operation for decades, while hydrogen fuel cell buses have been used in test fleets since the late 1990s, with the latest fuel cell technology in operation for a number of years, including hydrogen fuel cell hybrids.

Electric buses using the latest battery and charging technology, on the other hand, are currently being trialled throughout Europe. This means that while data for the hydrogen fuel cell bus are based on reallife operations, data for opportunity and overnight e-buses are based on projections (Exhibit 6).

Exhibit 6

HYDROGEN FUEL CELL BUS DATA ARE BASED ON REAL-LIFE OPERATIONS, DATA ON ELECTRIC BUSES ON PROJECTIONS

Facts as of 2012 for Western Europe (12-m and 18-m buses)

	Diesel/CNG/ trolley	Diesel hybrids[1]	Hydrogen fuel cell bus	Opportunity e-bus	Overnight e-bus[3]
Number of buses deployed	*Diesel, CNG and trolley buses are considered fully mature as they have been in use for >50 years and cover >95% of the current market (for 12-m and 18-m buses)*	>1,000	>30	0[3]	0[4]
Number of Km driven		>>10,000,000	>1,000,000 (>5,000,000)[2]	0[3]	0[4]
Recharging/ refuelling procedures completed		*Same as diesel*	>500	0[3]	0[4]
Number of years in operation		~2-3 years	~2 years	▪ No operation yet for 12-m/18-m buses ▪ ~2 years for 8-m overnight e-buses	
Supply industry/ adjacent industries		▪ Battery ▪ Electric drives	▪ Fuel cell in automotive ▪ H_2 supply ▪ Battery, electric drives	▪ Infrastructure ▪ Battery ▪ Electric drives	▪ Infrastructure ▪ Battery ▪ Electric drives

Data on all **powertrains** to be **treated with appropriate caution** as

- Data on **hydrogen fuel cell** buses are **based on real-life operations** (12-m or 18-m buses) in **small-scale fleets** with a **time frame** of a **few years**
- Data on **electric buses** (opportunity and overnight e-buses) are based on **Clean Team data** for the **core components, diesel serial hybrid Clean Team data** for **other components** and **expert estimates** for the **remaining parts** as no information from actual operation of 12-m or 18-m buses was available
- Data on **hybrids** are based on a **few years of experience** only despite **large number of buses**

1 Latest-generation serial hybrid and parallel hybrid 2 Both for busses without powertrain hybridisation and buses with powertrain hybridisation such as in this report
3 In Turin and Genoa, 31 opportunity e-buses of 8 meter operate since 2002, 16 buses of 8 meter are ordered in Vienna; in Braunschweig and Milton Keynes opportunity charging buses are also ordered; outside Western Europe, opportunity charging e-buses operate in Shanghai (12 meter) and Los Angeles (10 meter)
4 An unknown number of European cities operate or have ordered models, some built by Chinese manufacturers; 3 Optare fast-charging 11 meter buses operate in Coventry
SOURCE: Study analysis

2 Methodology

The collection and sanitisation of over 5,000 data points

The results of the study are based on proprietary industry data. To enable the collection of this confidential data, a clean team was installed:

- The clean team collected, challenged and sanitised more than 5,000 data points. The resulting aggregated data was signed off by all group members and used as the basis for the study.

- Expert interviews and industry workshops were conducted for the few data points for which an insufficient number of proprietary data were submitted in order to enable the evaluation of new technologies which have only been produced and used by a limited number of players to date. (These data points are outlined in Annex 2).

A holistic comparison of conventional and alternative powertrains, on a well-to-wheel basis

In order to make a holistic comparison, the evaluation of the powertrains focused on three key criteria: sustainability, performance and total cost of ownership:

- Sustainability is reflected by GHG and local emissions (NOx, PM, noise) as well as energy efficiency. GHG emissions are based on a well-to-wheel perspective: not only were local, tank-to-wheel emissions considered, but also the fuel-specific, GHG footprint of production, distribution and dispensing. Local emissions of the different powertrain technologies were based on the EURO norm certification (i.e. EURO V and EURO VI); energy efficiency was assessed over the complete value chain of the different fuel and powertrain combinations.

- Performance was assessed based on acceleration, zero-emission driving capability, range and refuelling time; free range/route flexibility was also evaluated.

- Total cost of ownership was calculated on a cost per kilometre basis as the sum of purchase, financing, infrastructure and running costs. An emission penalty according to EC Directive 2009/33 was also added (Exhibit 7).

Key assumptions

Recognising the uncertainty within the input parameters, which originates from projecting developments of novel powertrain technologies and local conditions into the future, and from forecasting data in general, production scenarios were developed:

- Different **scenarios** were developed to simulate different **bus production volume levels,** especially impacting batteries and fuel cell systems:

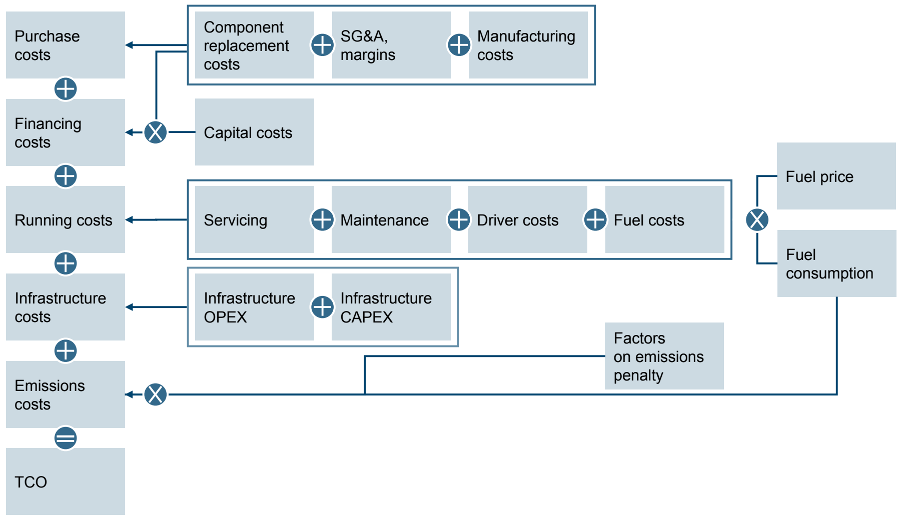
  — *Niche scenario:* no major breakthrough occurs; only up to 120 buses per powertrain per manufacturer are produced each year from 2020 to 2030

  — *Production-at-scale scenario:* diesel hybrids, hydrogen fuel cell buses and/or e-buses capture a significant market share, resulting in production volumes of 1,500 buses per powertrain per manufacturer each year from 2020 to 2030

  — *Cross-industry scenario:* as the alternative powertrain market takes off for cars and other applications, more than 100,000 fuel cell systems and batteries for the automotive sector are produced each year from 2020, resulting in additional economies of scale for urban buses.

Exhibit 7

TOTAL COST OF OWNERSHIP COMPRISES PURCHASE, FINANCING, RUNNING, INFRASTRUCTURE AND EMISSION COSTS



SOURCE: Study analysis

- **The price premium for alternative powertrains versus conventional buses could be further reduced or eliminated before 2030:** key factors such as a higher oil price, lower battery costs and lower fuel cell costs could increase the competiveness of alternative powertrains (see Chapter 4). These factors simulate local conditions that strongly impact the TCO (e.g. hydrogen and electricity prices), resulting in a range of input values.

- **Potential limitations** to a large-scale rollout of zero local-emission powertrains include a lower oil price, or taxations on alternative fuel sources such as hydrogen (see Chapter 5).

Macroeconomics, reference buses, reference routes and productivity requirements were aligned and agreed upfront:

- All prices and costs in this study are in real 2011 terms, i.e. excluding inflation.

- Sunk costs and local subsidies were not taken into account.

- Costs for permits and adaptations to the bus depot, depending on the respective powertrain (e.g. equipment to detect leakages for CNG) have not been taken into account.

- A neutral macroeconomic source was used

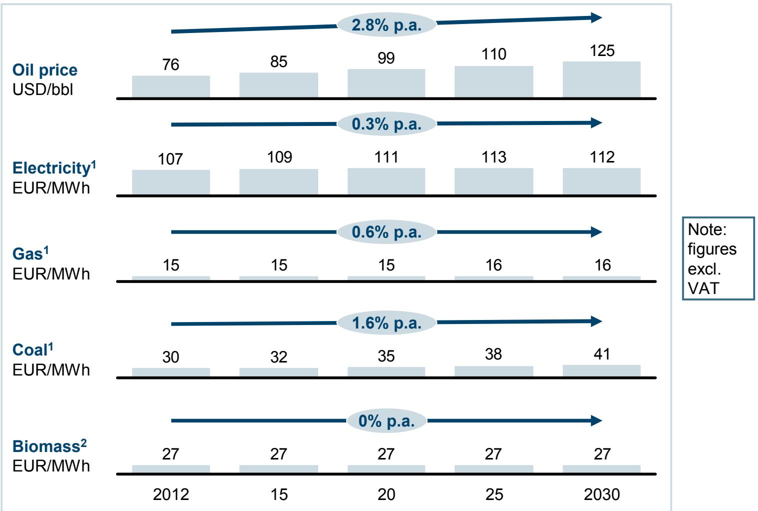
  — Enerdata's Recovery scenario[14] was selected as the macroeconomic source for the base case (Exhibit 8). It is widely used by industry and governments, and provides a consistent set of basic assumptions, simulating the interdependencies between oil price, GDP growth, feedstock prices and other macroeconomics. **The Recovery scenario does not include extreme developments** in any direction (economic, political, environmental) and has comparable oil price forecasts to other well-known sources such as the International Energy Agency (IEA) and Energy Information Administration.

14 Please refer to Exhibit 27 for the breakdown in electricity generation of this scenario

Exhibit 8

A REFERENCE MACROECONOMIC SCENARIO (ENERDATA RECOVERY SCENARIO) WAS SELECTED WITH CONSERVATIVE PRICE DEVELOPMENTS

European average energy prices, 2011 real terms



1 Based on weighted industrial average prices (excl. VAT) in Belgium, France, Germany, Italy, Netherlands, Spain and UK
2 Based on historical industrial pellet prices in the Netherlands, Germany and Sweden

SOURCE: Enerdata Recovery Scenario 2011; industry analysis

— **European average prices** were used for the purpose of this study (Exhibit 9); country-specific prices may be different, depending on local conditions. Industrial (high-volume) prices were used for coal, gas and electricity. The diesel price is based on a fixed mark-up to the oil price, which was derived from historic data.

- **Taxes were assumed to be constant over time** and based on today's regulations. In the base case, it was therefore assumed that a loss of government tax income from a potential shift from conventional to alternative fuels (e.g. electricity and hydrogen) will not be compensated by taxation of the alternative fuels. No VAT was included as bus operators are in general eligible for VAT refunds. The impact of variable taxes on fossil fuels (i.e. taxes which increase in line with the price of diesel and CNG), is highlighted in Chapter 4.

- **Reference values** were defined for both standard and articulated bus segments (Exhibit 10). All buses in scope have to comply with current safety regulations as defined by the European Union (including crash protection and avoidance, evacuation and rollover protection requirements). They also have similar equipment on board and are similarly insulated, ensuring that energy demand from the auxiliary units is comparable.

- As trolleys and opportunity e-buses depend on infrastructure related to a specific route, a standard line of 8.5 km length and 26 stops was defined; based on this standard line, the infrastructure cost per kilometre was calculated. As no uniformly accepted **reference driving cycles** such as the SORT cycles are available for alternative powertrains, the study used real and empirical data from medium city traffic (comparable to SORT 2) to compare fuel consumption.

- Each bus needed to fulfil the following **productivity requirements:**

  — Operates 320 days per year, 18 hours per day, at -20° to +40°C

— Is refilled/charged overnight, i.e. in less than six hours (less the time required for maintenance and cleaning). The opportunity e-bus requires additional recharging: within six minutes at the start of the line and one minute at the end. It also uses the time for passenger unloading and loading (approximately 20 seconds) at a select number of stops along the route to charge. In order to comply with these requirements and taking a conservative approach for opportunity systems based on current battery limitations, one additional bus and driver were included for every 10 opportunity e-buses in the calculations for 2012 and 2015.

The collected clean team data consisted of three main elements: bus costs, infrastructure costs and hydrogen production/distribution costs – altogether used to calculate the TCO:

- **Bus costs** consisted of all manufacturing and component costs in order to calculate the theoretical selling price of a bus, assuming a fixed margin and overhead rate. This theoretical price assumes that discounts, strategic pricing, amortisation of R&D etc. do not affect prices in the long term. Maintenance costs were also included.

- **Infrastructure costs** related to all additional investments (besides the bus) an operator has to make when deploying a new powertrain:

  — Diesel (including hybrids), CNG and hydrogen fuel cell buses require different types of filling stations. Three reference bus depot sizes were also considered for 35, 85 and 210 buses respectively, representative of depots throughout Europe.

  — Trolley buses require an overhead wiring network (including transformers and high voltage connections).

  — E-buses require charging points within the bus depot; opportunity systems require additional charging points along the routes.

- **Hydrogen production and distribution costs** were collected in order to forecast the cost of hydrogen to the bus operator. 10 different production methods were considered, which may be clustered into the following four groups (Exhibit 11):

  — Gas-based: central steam methane reforming (SMR); with and without CO_2 Capture and Storage (CCS); and on-site SMR without CCS

  — Electricity-based: central and on-site water electrolysis (WE)

  — Coal-based: coal gasification (CG), integrated gasification combined cycle (IGCC), both with and without CCS

  — Biomass-based: biomass gasification (BG)

  — Data was collected for three different distribution methods: distribution by truck with

    □ 250 bar gaseous containers

    □ 500 bar gaseous containers

    □ Liquid containers.

Exhibit 9

BASED ON THE MACROECONOMIC SOURCE, MODERATE FUEL PRICE INCREASES WERE ASSUMED (IN REAL TERMS)

European average industrial prices[1] excl. VAT, 2011 real terms

1 Based on weighted (by population) industrial average prices (excl. retail mark-up) in Belgium, France, Germany, Italy, Netherlands, Spain and UK
2 Diesel price based on fix mark-up on oil price, incl. distribution costs to filling station, no retail mark-up

SOURCE: Enerdata Recovery Scenario 2011; European Commission Oil Bulletin 2012; Platts; Bloomberg; study analysis

Exhibit 10

REFERENCE PARAMETERS FOR STANDARD AND ARTICULATED BUSES WERE DEFINED FOR THE STUDY

Reference vehicle specifics	Standard bus[2]	Articulated bus
Typical number of passengers (seated/standing)[1]	32/68	43/90
Length (m)	11.8-12.2	17.7-18.3
Height (m)	2.9-3.1	2.9-3.1
Width (m)	2.50-2.55	2.50-2.55
Empty weight (t)	11-12	16-18
Curb weight (t)	18-19	28-29
Traction power (kW)	170-220	200-260
Number of doors	2/3	3
Floor type	Low floor	Low floor
Safety requirements	▪ EU standard/ECE standard	
Other specifications	▪ Typical equipment incl. air conditioning and heating ▪ Single-walled windows	

1 Actual capacity dependent on customer requirements
2 Incl. modified version to cover suburban routes

SOURCE: Study analysis

Data collected included the costs of compression or liquefaction required for transportation. Local pipelines were also considered based on expert estimates from industry. Using the cost data for each hydrogen production method, a balanced mix was then developed, reflecting an average European scenario. This scenario was taken as the base case of the study; it does not consider novel technologies, such as water electrolysis using proton exchange membranes (PEM)[15].

Using the sanitised data collected in the clean team, the **hydrogen production mix** was established such that it offered the cheapest option under two boundary conditions:

- The total well-to-wheel GHG emissions reduction of the hydrogen fuel cell bus versus the conventional diesel bus is 50 percent in 2020 and 75 percent in 2030.
- No production method has more than a 25 percent share in the mix. This is done to reflect the variety of production methods that will be used throughout Europe.

Exhibit 12 shows the hydrogen production mix used in this study. Since WE for hydrogen production will only likely be used if electricity comes from a renewable source, a premium of EUR 50/MWh was applied to the electricity price. Analyses show that this premium would be sufficient to fund fully renewable electricity. To be consistent with the WE hydrogen production, the same **renewable electricity** and **price premium** of EUR 50/MWh was applied to the three fully electric powertrains used in this study (trolley, opportunity e-bus and overnight e-bus).

The share of central WE is zero in the base case as it is estimated to be more expensive than distributed WE when accounting for distribution costs. The use of large WE stations operating, in particular, during peak energy availability (e.g. strong wind in a wind farm) in order to store energy within large hydrogen storage facilities is currently being investigated. This offers the potential to reduce costs, but cannot be fully evaluated today and was therefore not included in the study.

15 PEM water electrolysis is an efficient hydrogen production method in areas where there is a high volume of volatile wind or other renewable sources.

Exhibit 11

DATA FOR 10 DIFFERENT HYDROGEN PRODUCTION METHODS WERE COLLECTED BY THE CLEAN TEAM

Technology	Process	Governing reaction[1]	Methods
SMR Steam methane reforming	Methane → → H_2 Steam → → CO_2	$CH_4 + 2H_2O \rightarrow 4H_2$ with CO_2	▪ On-site SMR ▪ Central SMR ▪ Central SMR with CCS
WE Water electrolysis	Water → → H_2 Electricity → → O_2	$2H_2O \rightarrow 2H_2$ with O_2	▪ On-site WE ▪ Central WE
CG/(IGCC) Coal gasification/ internal gasification combined cycle	Coal → → H_2 Steam → → CO_2	$C + 2H_2O \rightarrow CO_2$ with $2H_2$	▪ CG ▪ CG with CCS ▪ IGCC ▪ IGCC with CCS
BG Biomass gasification	Biomass → → H_2 Steam → → CO_2	$C_xH_yO_z + H_2O \rightarrow CO_2$ with H_2	▪ BG

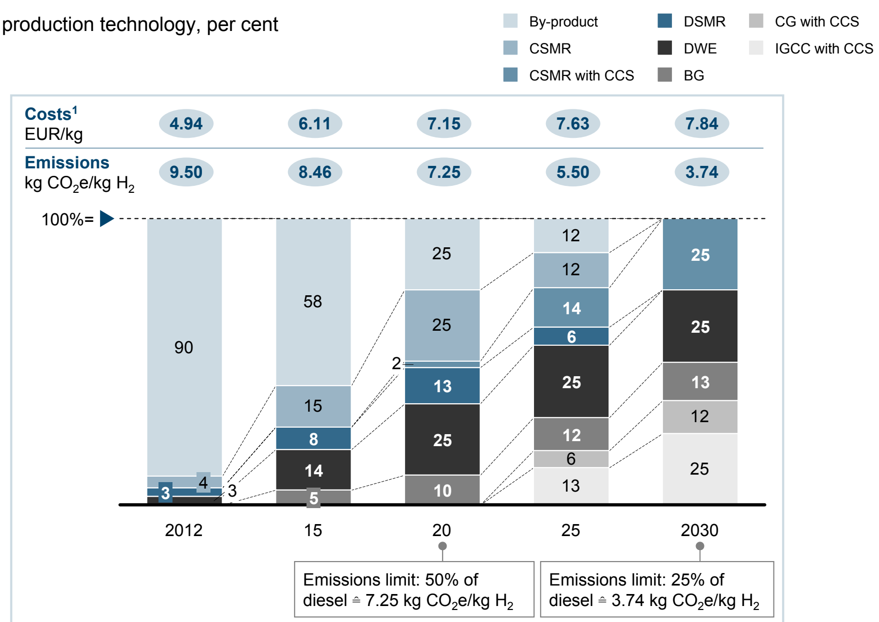
1 Simplified reaction

SOURCE: Study analysis

Exhibit 12

OVERVIEW OF THE HYDROGEN PRODUCTION MIX USED IN THIS STUDY, SHOWING THE RAMP UP TO 2030

Share per production technology, per cent



1 Incl. margins and distribution costs for gaseous truck (500 bar)

SOURCE: Study analysis

3 Results

Overview

If not stated otherwise, the results presented in this chapter show the outcome of two possible rollout scenarios: the "production-at-scale" scenario and the "cross-industry" scenario (see Annex 2).

a) Alternative powertrains differ in terms of flexibility and price premium

While all alternative powertrains have a more efficient energy conversion and reduce GHG, local and noise emissions significantly, they offer different levels of flexibility and require different amounts of price premium, compared to conventional powertrains (Exhibit 13).

- *Conventional buses* show a relatively low purchase cost, TCO and high route flexibility, but have the highest GHG 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 percent, 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 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[16], 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.

b) Opportunity e-buses and hydrogen fuel cell buses are the most promising zero local-emission powertrains

In the *12-metre bus segment,* the opportunity e-bus is the most economical zero local-emission option with a price premium of EUR 0.3/km compared to the conventional diesel bus in 2030 and well-to-wheel GHG emissions close to zero when using renewable electricity. The standard hydrogen fuel cell bus has a GHG emissions reduction of 75 percent at a price premium of EUR 0.4 to 0.7/km. The hydrogen fuel cell bus requires hydrogen filling stations to be installed at the bus depots, whereas the opportunity e-bus requires charging points along the route and/or at the first and final stops.

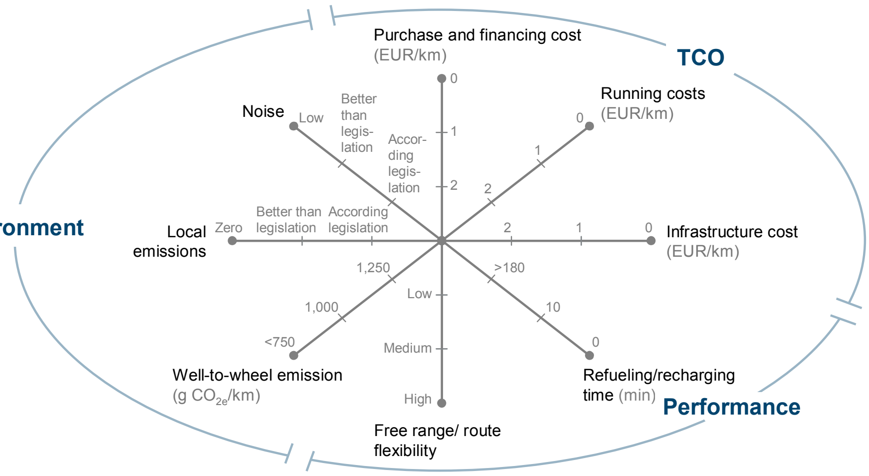
In the articulated bus segment, the hydrogen fuel cell bus is the most economical, zero local-emission option with a GHG emissions reduction of 75 percent at a price premium of EUR 0.3 to 0.6/km, compared to the conventional diesel bus in 2030. It uses the same filling stations as the standard hydrogen fuel cell bus. (The concept of an articulated opportunity e-bus has yet to be proven in tests and pilots, and is therefore not included in this study.)

16 Trolley is the only zero local-emission powertrain expected to increase in TCO over time due to anticipated major technological improvements, combined with increasing wages and electricity prices.

Exhibit 13
AN OVERALL EVALUATION OF INDIVIDUAL POWERTRAINS

STANDARD BUS | 2030
PRODUCTION AT SCALE SCENARIO

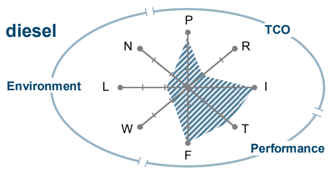
Powertrain evaluation grid – legend



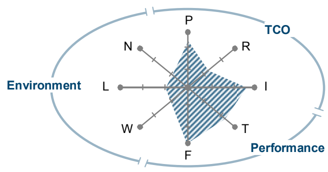
Better evaluation

Ability of conventional powertrains to meet key criteria on sustainability, performance, and TCO

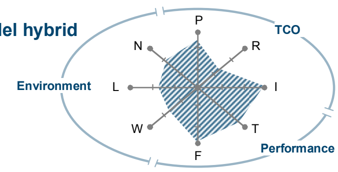
A Conventional diesel



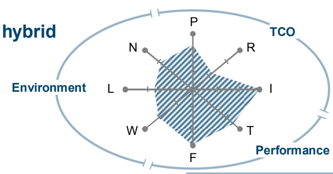
B CNG



C Diesel parallel hybrid

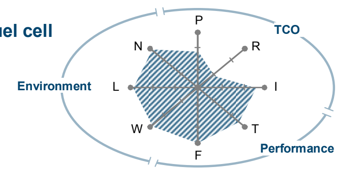


D Diesel serial hybrid

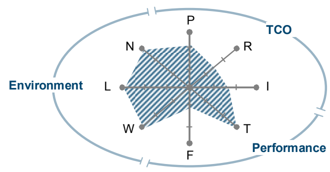


Ability of zero local emission powertrains to meet key criteria on sustainability, performance, and TCO

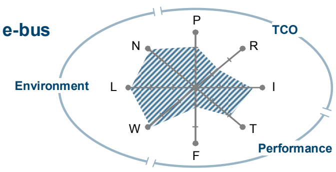
E Hydrogen fuel cell



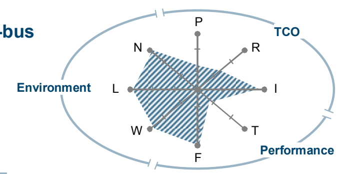
F Trolley



G Opportunity e-bus



H Overnight e-bus



By 2030, all powertrains will be able to achieve the required daily range (250km)

SOURCE: Study analysis

c) Diesel hybrid options could provide cost-effective solutions in the short term

With high driving performance and high flexibility, diesel hybrid options (serial and parallel)could provide a bridging technology towards powertrains with zero local emissions at almost zero cost penalty (EUR 0.1/km). In this transitional period, serial hybrids in particular could provide zero-emission driving capability for longer distances and allow a partial reduction of GHG emissions of up to 20 percent compared to conventional buses. As importantly, they would allow the build-up of critical competence on the electrification of drive-trains required for both e-buses and hydrogen fuel cell buses.

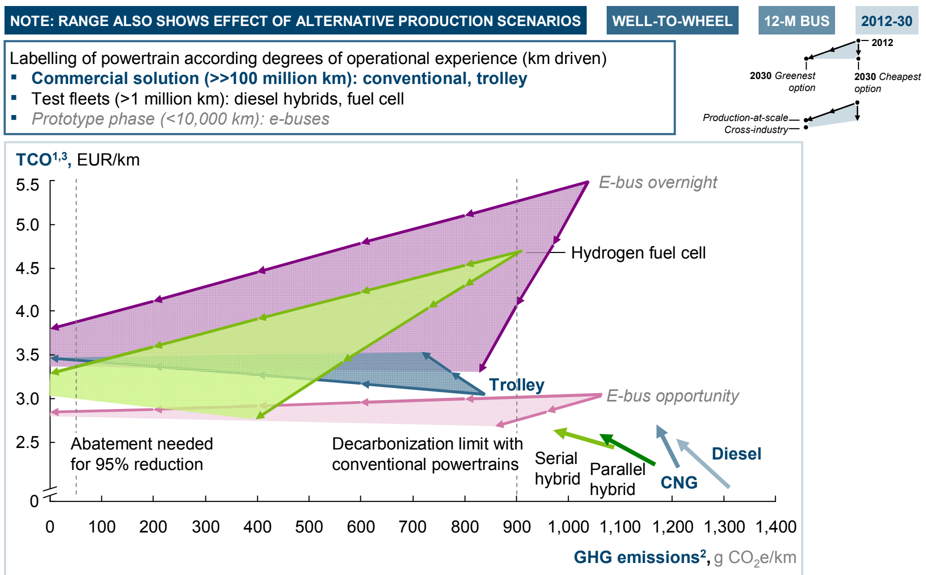
Alternative powertrains can reduce local and GHG emissions significantly

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_2e/km for a conventional diesel bus. Diesel hybrids (serial and parallel) also offer a reduction of 15 to 20 percent 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 at a price premium of EUR 0.3 to 1.0/kg CO_2e for a standard bus (Exhibit 16).

Exhibit 14

CO_2e/TCO (EUR/KM) COMPARISON OF STANDARD BUS POWERTRAINS



1 TCO for a 12-m bus incl. purchase; running and financing costs based on 60,000 km annual mileage and 12 years bus lifetime
2 Total CO_2e emissions per bus per km for different fuel types from well-to-wheel
3 Electricity costs for e-bus and water electrolysis part of hydrogen production based on renewable electricity price with a premium of EUR 50/MWh over normal electricity

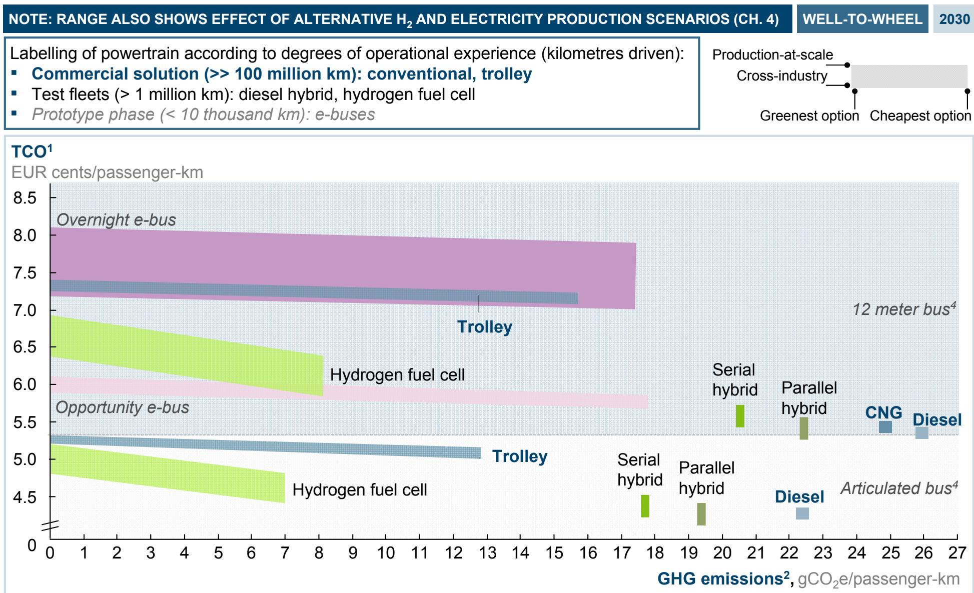
SOURCE: Study analysis

- Exhibit 14 shows the trajectory the powertrains will follow from 2012 to 2030. The range is formed by the two production volume scenarios ("production-at-scale" and "cross-industry") and by alternative electricity and hydrogen production scenarios which are clarified in Chapter 4.

- The well-to-wheel GHG footprint of hydrogen fuel cell and electric powertrains decreases by ~20 percent between 2012 and 2030 due to the change in the electricity and hydrogen production mix and end-to-end efficiency.
- Diesel hybrids are expected to have ~15 to 20 percent fewer GHG emissions on a well-to-wheel basis, but still emit ~1 kg CO_2e/km. They offer the opportunity to partially reduce the GHG footprint of the bus fleet at little additional cost, using the same infrastructure.
- The values shown in Exhibit 15 are for 2030 only. As in Exhibit 14, the range is formed by the two production volume scenarios and by alternative electricity and hydrogen production scenarios which are clarified in Chapter 4.

Exhibit 15

GHG/TCO COMPARISON IN 2030 FOR STANDARD AND ARTICULATED BUSES



1 Total cost of ownership for a bus, including purchase, running and financing costs based on 60,000 km annual mileage and 12 years' bus lifetime 2 Total CO2e emissions per bus per km for different fuel types from well-to-wheel 3 For greenest option, electricity cost for e-bus and water electrolysis hydrogen production based on renewable electricity price with a premium of EUR50/MWh over normal electricity
4 Passenger loading 47 per standard bus, 73 per articulated bus as per UITP definition

SOURCE: Study analysis

Calculating the cost of GHG abatement

In order to estimate the cost of the GHG abatement potential (Exhibit 16), the TCO and emissions of alternative powertrains were compared with those of diesel by dividing the difference in GHG emissions. The result is the cost of GHG abatement, measured in EUR per kg CO_2e. Where the abatement cost is negative, the respective powertrain reduces TCO and emissions compared to diesel.

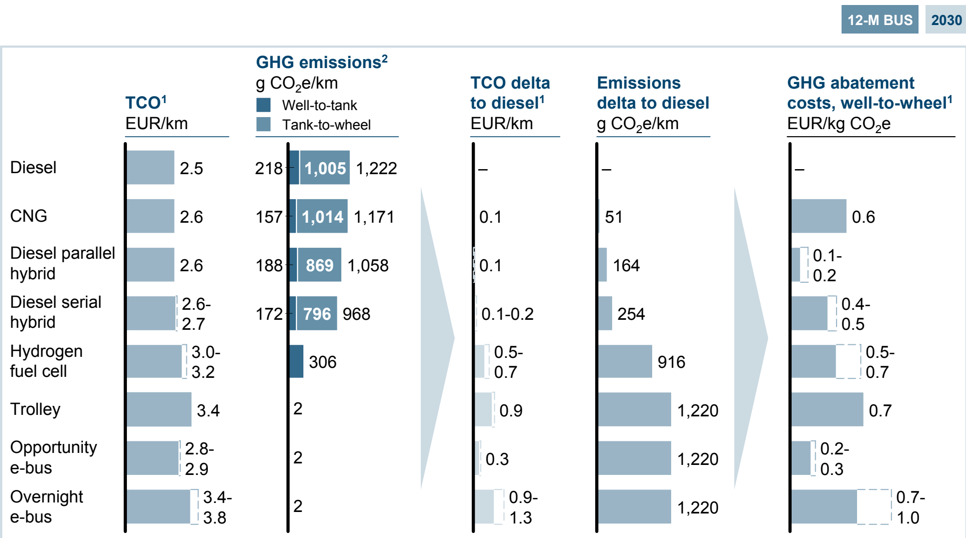
METHODOLOGY

$$CO_2e \text{ abatement}: \frac{TCO_{alternative} - TCO_{conventional}}{CO_2e_{conventional} - CO_2e_{alternative}} \left[\frac{\frac{EUR}{km}}{\frac{kg\ CO_2e}{km}}\right] = \left[\frac{EUR}{kg\ CO_2e}\right]$$

The cost of abatement on a well-to-wheel perspective considers emissions along the entire pathway of the fuel (e.g. for diesel: refining, distribution in trucks, refilling and fuel combustion); the cost of abatement on a tank-to-wheel perspective, on the other hand, only considers emissions during driving (i.e. zero for fuel cell, trolley and e-buses).

Exhibit 16

GHG ABATEMENT COSTS OF INDIVIDUAL POWERTRAINS



With an even more renewable hydrogen production mix, further upside can be achieved (see Chapter 4)

1 Lower numbers correspond to “cross-industry” scenario, higher numbers to “production-at-scale” scenario
2 Using balanced mix scenario for H_2 production and fully renewable electricity

SOURCE: Study analysis

- The cost of GHG abatement for zero local-emission powertrains ranges from EUR 0.3 to 1.0/kg CO_2e with the opportunity e-bus showing the lowest cost and overnight e-bus the highest cost. Hydrogen fuel cell and trolley range between the two e-bus concepts showing EUR 0.5 to 0.7/kg CO_2e and EUR 0.7/kg CO_2e, respectively. As mentioned above, the GHG footprint of hydrogen and electricity – and therefore the abatement potential – depend strongly on the assumed production concept of the individual energy source.

- The cost of GHG abatement for articulated buses with a zero local-emission powertrain versus diesel ranges from EUR 0.3 to 0.5/kg CO_2e (hydrogen fuel cell) to EUR 0.4/kg CO_2e (trolley).

- GHG abatement costs could be higher or lower depending on factors influencing the upside potential or potential limitations, as highlighted in Chapters 4 and 5.

Diesel hybrids could provide cost-effective solutions in the short term

Diesel hybrids (serial and parallel) could provide a bridging technology to zero local-emission powertrains at almost zero cost penalty (EUR 0.1 to 0.5/kg CO_2e). Although they currently show 10 to 15 percent lower GHG emissions than diesel buses, they are expected to reduce their footprint and cut emissions by 15 to 20 percent until 2030.

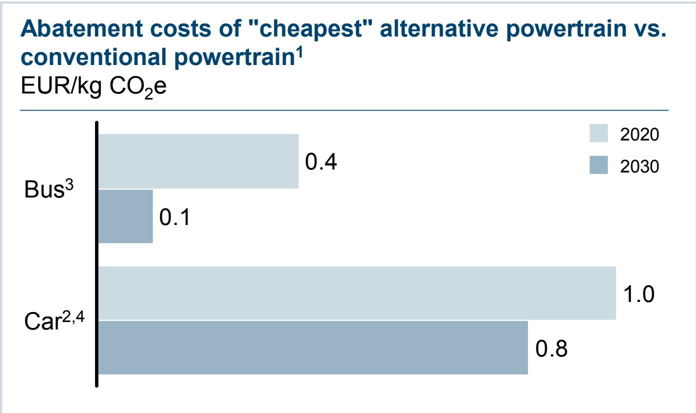
Switching from diesel to a hybrid powertrain comes with only a small surcharge on the overall TCO: although the purchase costs are higher, their lower fuel consumption leads to an overall TCO delta of less than 5 percent compared to diesel in 2030.

Hybrids (especially serial hybrids) also offer the opportunity to undertake short distances in purely electric drive. A precondition is an electrification of the auxiliaries, which is currently not state-of-the art in hybrid powertrains. Given this precondition and a battery capacity of at least 30 kWh, they can drive for ~10 km purely from battery power, with no local emissions. This option is particularly attractive where the route crosses an ancient city centre, where low levels of noise and local emissions are required to reduce local pollution.

Finally, as hydrogen fuel cell and e-buses have a serial hybrid powertrain architecture comparable to diesel serial hybrid, they share many components (except the power source which differs for each powertrain, e.g. diesel engine, fuel cell, battery-charging system). Using any serial drive-train concept, OEMs, operators and components suppliers can therefore gain valuable expertise on key components and apply it to all other serial hybrid powertrains.

Exhibit 17

ALTERNATIVE POWERTRAINS IN URBAN BUSES HAVE LOWER GHG ABATEMENT COSTS THAN ALTERNATIVE POWERTRAINS IN PASSENGER CARS



1 No CO_2 price included in TCO
2 HEV as conventional powertrain, PHEV as cheapest alternative; assuming average passenger car loading factor of 1.2 passengers per car
3 Diesel as conventional powertrain, parallel hybrid as alternative powertrain; assuming 12-m bus with 47 passengers according to UITP definition
4 Compact-class car (C-segment)

SOURCE: Study analysis

- **Alternative powertrains in urban buses can also reduce GHG emissions at lower cost per kg CO_2e compared to alternative powertrains in passenger cars** (Exhibit 17). For example, the cost of GHG abatement is expected to reduce from EUR 0.4/kg CO_2e in 2020 to EUR 0.1/kg CO_2e in 2030 for a diesel parallel hybrid bus, compared to a cost of EUR 1.0/kg CO_2e in 2020 and EUR 0.8/kg CO_2e in 2030 for a plug-in hybrid car.

Alternative powertrains offer a similar performance to conventional powertrains

Different powertrains show advantages in different areas of performance (Exhibit 18). Among the zero local-emission powertrains, the **hydrogen fuel cell bus offers the best performance in range, purely electric range and refuelling times, at high operational flexibility. Trolley performs equally well on driving performance** as long as routes are fully equipped with overhead wiring.

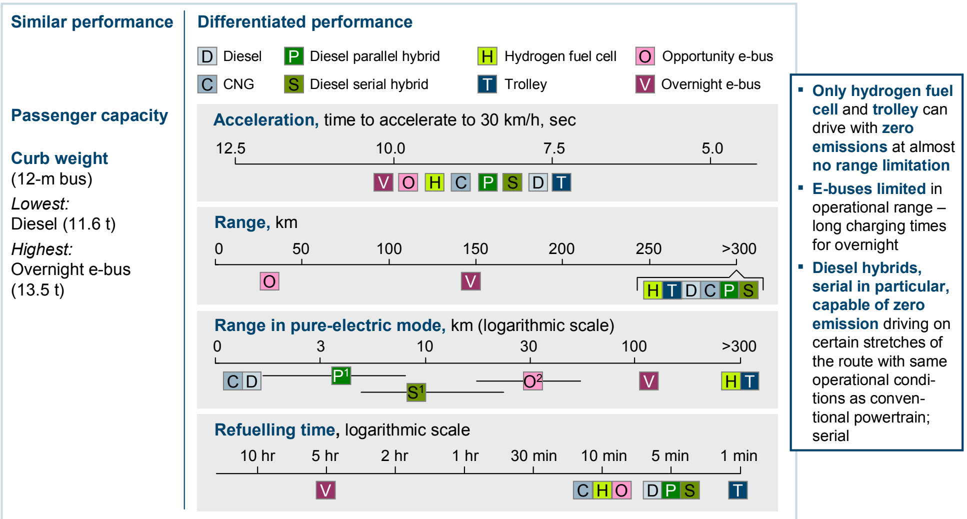
- Conventional buses show good performance on acceleration and range, while requiring only short times for refuelling. They are not able to drive in zero-emissions mode.

- Hybrids show the same performance on acceleration, range and refuelling times. Unlike conventional powertrains, however, they can also undertake short sections of the route in purely electric drive (e.g. through city centres) with zero local emissions and lower noise levels.

Exhibit 18

AN EVALUATION OF DRIVING PERFORMANCE FOR INDIVIDUAL POWERTRAINS

12-M BUS 2030



1 Typical values shown here – pure electric range of hybrid powertrains varies depending on concept of auxiliary units and battery capacity
2 Based on a 60 kWh battery and a consumption (incl. losses from charging) of 2 kWh/km

SOURCE: Study analysis

- The hydrogen fuel cell bus performs equally well as conventional buses and hybrids on all evaluation criteria, with the added facility to drive with zero local emissions continuously for longer distances.
- The trolley bus offers similar performance as conventional buses on acceleration and range; zero-emission driving is virtually unlimited as long as it is connected to its overhead network.
- E-buses also perform well on acceleration and zero local-emission driving range. Opportunity e-buses require charging at the start and end of the line and/or at certain stops. Until 2020, the overnight e-bus requires a longer stop to recharge, which could impact daily operations.
- Conventional, hybrid and hydrogen fuel cell buses can easily change routes, require few intervals and short times for refuelling/recharging – resulting in high flexibility.
- By design, the trolley is bound to the overhead network and does not incorporate refuelling or recharging time in normal operation (except where an APU is used to achieve flexibility).
- The opportunity e-bus has short recharging times, but requires frequent connection to the charging network, whereas the overnight e-bus is flexible during operation, but requires long charging times.

Conventional, hybrid and hydrogen fuel cell buses show high flexibility compared to e-buses (Exhibit 19):

Exhibit 19

AN EVALUATION OF THE FLEXIBILITY OF INDIVIDUAL POWERTRAINS

Conven-tional	*Diesel* *CNG*	+ **Conventionals flexible** in changing routes and detours + **Refilling** needed only after **every 2nd day** + **Refilling times short** (5-10 min)
Parallel hybrid **Serial electric**	*Diesel parallel hybrid* *Diesel serial hybrid*	+ **Hybrids flexible** in changing routes and detours + **Refilling** needed only after **every 2nd day** + **Refilling times short** (~5 min)
	Hydrogen fuel cell	+ **Hydrogen fuel cell flexible** in changing routes and detours + **Refilling** needed **every day** at the end of operations + **Refilling times short** (~10 min)
	Trolley	? **Trolley** in operations **bound to overhead network**, but due to APU **capable of running** short-to-medium distances (~10-50 km) **without the network** + **Refilling needed every few days** – power supply for major part of operations continuously through overhead network + Diesel **refilling times short** (~10 min)
	Opportunity e-bus	– **Opportunity e-bus bound to routes** with charging stations, but can take detours easily and swop routes if charging station network allows ? **Recharging needed multiple times a day** – recharging times short (<10 min) and built into normal operation and dwell times
	Overnight e-bus	+ **Overnight e-bus flexible** in changing routes and detours during the day – **Recharging** needed at the **end of the day** – **recharging times very long** (>3 hr)

SOURCE: Study analysis

Compared to conventional buses, alternative powertrains incur a limited price premium until 2030

Between 2012 and 2030, the TCO of the different powertrains converges[17], with mature zero local-emission powertrain technologies available and a remaining TCO gap of 10 to 12 percent (opportunity e-bus) and 17 to 26 percent (hydrogen fuel cell) compared to conventional buses within the standard bus segment (Exhibit 20). A similar trend is observed in the articulated bus segment.

- Zero local-emission powertrains are expected to have a higher TCO than conventional and hybrid powertrains. This gap is ~50 percent for 2012 when comparing the cheapest conventional powertrain (diesel) with the cheapest zero local-emission powertrain (trolley), until 2030 when this gap is expected to reduce to 10 to 12 percent for standard buses (opportunity e-bus) and 10 to 19 percent for articulated buses (hydrogen fuel cell).

- The TCO of conventional and hybrid powertrains is expected to increase until 2030; this increase is larger for diesel and CNG compared to diesel serial and diesel parallel hybrid. Absolute values for the TCO of a standard bus in 2030 range between EUR 2.5/km (diesel) and EUR 2.6 to 2.7/km (diesel serial hybrid) for standard buses and between EUR 3.2/km (diesel) and EUR 3.1/km (diesel serial hybrid) for articulated buses.

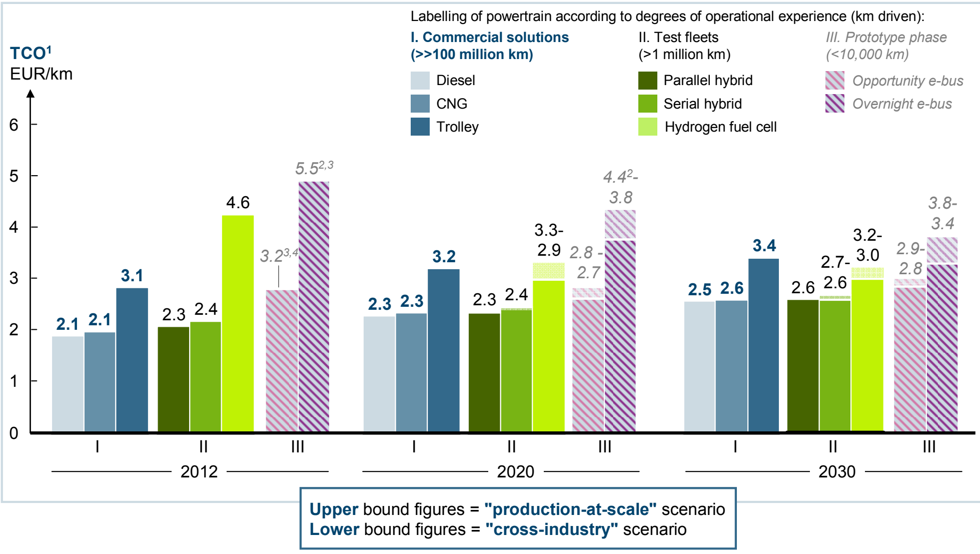
- Hydrogen fuel cell is expected to experience the strongest reduction in TCO from 2012 to 2030. In 2012, it is around twice as high in TCO as a conventional powertrain; this gap reduces to 17 to 26 percent in 2030, making the hydrogen fuel cell economically competitive with the other zero local-emission powertrains. Trolley is the only zero local-emission powertrain expected to increase in TCO over time due to anticipated major technological improvements, combined with increasing wages and electricity prices.

17 In the case of lower production volumes for zero local-emission powertrains (i.e. niche scenario – see Annex 2), the TCO gap to diesel would range between 16 percent (e-bus opportunity) and 41 percent (hydrogen fuel cell) technological improvements, combined with increasing wages and electricity prices.

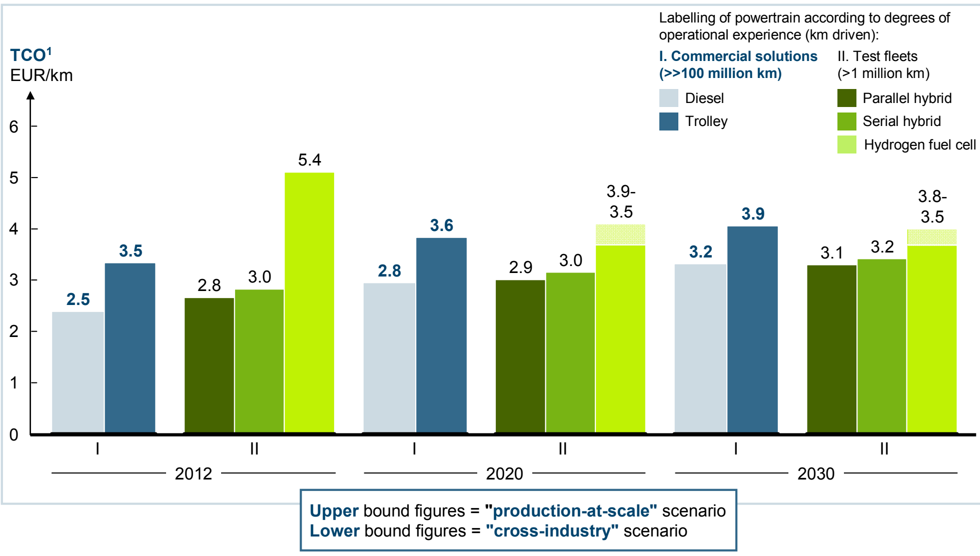
Exhibit 20

A COMPARISON OF TCO FOR INDIVIDUAL POWERTRAINS

12-METER BUS



ARTICULATED BUS



1 Based on 12 years bus lifetime, 60,000 km annual mileage
2 Incl. purchase price of more than 1 bus per daily shift as bus maximum mileage too short for full operational day
3 Theoretical value based on estimations as powertrain not in production yet in 2012
4 Incl. cost for additional bus and driver per fleet of 9 buses to cover charging times at end of route for 2012

SOURCE: Study analysis

4 Upside potential

The results described in Chapter 3 are based on conservative assumptions, as outlined in Annex 1. However, there is considerable potential for further cost reductions in zero local-emission buses in Europe between 2012 and 2030 due to the factors shown in Exhibit 21.

Exhibit 21
FACTORS CONTRIBUTING TO THE UPSIDE POTENTIAL

2030

	Positive external factor	Base case assumption
Costs of fossil fuels	A Crude oil price USD 150/bbl	Crude oil price USD 125/bbl
Taxation on fuel and emissions	B1 Variable taxes	Taxes fixed to 2012 values
	B2 Taxes on CO_2 (EUR 30/t)	No taxes on CO_2
Component costs	C1 Lower fuel cell stack costs: EUR 34/kW	EUR 114/kW
	C2 Lower battery costs: EUR 258/kWh	EUR 459/kW
Hydrogen and electricity production	D1 H_2 from SMR with CCS	H_2 from a balanced mix of major technologies
	D2 H_2 from WE incl. PEM	
	D3 Electricity from EU mix	Electricity from renewable sources

SOURCE: Study analysis

- **Hydrogen production:** alternative methods of hydrogen production could be developed towards 2030. In some countries (e.g. Netherlands), the combination of SMR with natural gas and CCS is a cheaper production method compared to the general mix considered for this study, with ~70 percent GHG emissions reduction. Another promising novel technique is proton exchange membrane (PEM) water electrolysis which is currently being developed, allowing excess electricity from renewable energy sources to be transformed into hydrogen. (Even in stormy weather, windmills could produce hydrogen using this technique.)

- **The cost of fossil fuels:** the 2030 oil price of USD 125 per barrel (in 2011 real terms[18]) used in this study reflects a balanced view of future oil prices. However, in a resource-limited society, an oil price of USD 150 per barrel in 2030 is conceivable.

- **Taxation:** the study assumes a constant tax on diesel. However, in some European countries, this is a variable part of the diesel price, which means that the tax increases at the same rate as the cost. Tax on CO_2 is also not included in the base case, whereas a CO_2 price of EUR 30/tonne in 2030 is referenced in multiple sources and frequently used in companies as an internal target.

- **Component costs:** 2030 costs of the fuel cell stack and battery in this study have been set at EUR 114/kW and EUR 459/kWh respectively, whereas in studies within the car industry projections have been set at EUR 34/kW and EUR 258/kWh respectively.

18 In 2011 dollar equivalent, i.e. without inflation

The price premium for alternative powertrains could be significantly reduced or eliminated

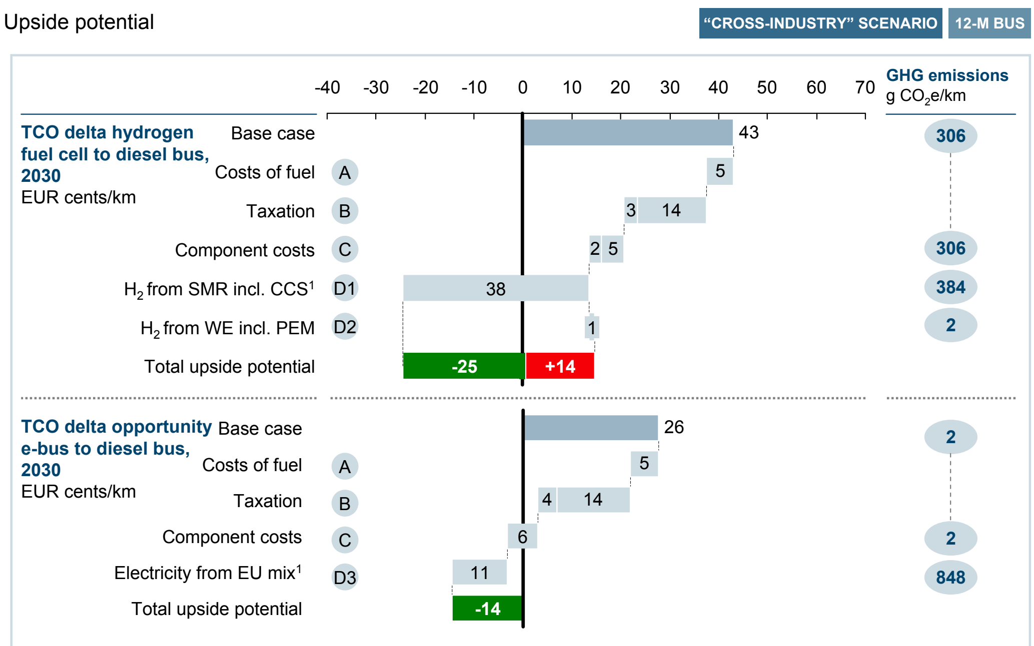
As a result of these factors, it is possible that the price premium of zero local-emission buses vs. conventional diesel buses will not only be reduced, but even eliminated (Exhibit 22). Depending on the local circumstances and the production technology chosen, the TCO gap compared to the diesel bus could turn to EUR -0.25/km (hydrogen fuel cell) and EUR -0.14/km (e-bus opportunity). Factors that strongly influence the gap are taxation on fossil fuels as well as the hydrogen and electricity production method.

Any change in the hydrogen production technology will not only impact the TCO, but also the well-to-wheel GHG footprint of the hydrogen fuel cell bus, e.g. moving to SMR with CCS would increase GHG emissions to 384 g CO_2e/km, whereas moving to WE with PEM technology using renewable electricity would reduce emissions to 2 g CO_2e/km.

The combined TCO and GHG reductions result in a potential scenario in which GHG abatement can be cost negative, i.e. generate profits (Exhibit 23).

Exhibit 22

DEPENDING ON LOCAL FACTORS, THE PRICE PREMIUM FOR THE HYDROGEN FUEL CELL BUS AND OPPORTUNITY E-BUS VS. THE CONVENTIONAL BUS COULD BE SIGNIFICANTLY REDUCED OR ELIMINATED

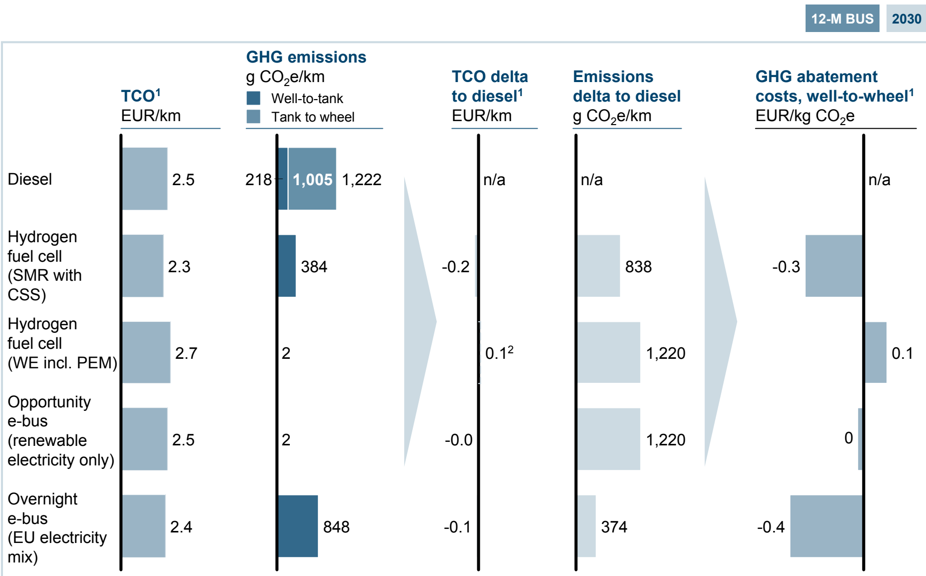


1 Effect already included in ranges shown Exhibit 14

SOURCE: Study analysis

Exhibit 23

UPSIDE POTENTIAL OF GHG ABATEMENT COSTS OF INDIVIDUAL POWERTRAINS



1 Only "cross-industry" scenario shown
2 Numbers do not add up due to rounding

SOURCE: Study analysis

5 Potential limitations

Risks inherent in the evolution of the costs of alternative powertrains

In the same way that there is a potential upside to cost reductions for alternative powertrains between 2012 and 2030, there are also potential risks (Exhibits 24 and 25):

- **Taxation:** Directive 2003/96/EC aims to tax hydrogen and electricity as conventional fossil fuels which would have a highly detrimental effect on zero local-emission buses.
- **Oil price:** there are scenarios which favour a lower oil price than that used in this study. In a world where increased use of natural gas reduces the demand for oil, the price could fall back to EUR 90/bbl or more, which would improve the total cost of ownership for conventional diesel buses and diesel hybrids.
- **Charging infrastructure:** opportunity e-buses are currently being trialled throughout Europe and conclusions as to the amount of infrastructure required are not yet finalised, with the risk that more charging points will be needed than currently anticipated.

In case of a decrease in fossil fuel prices and the taxation of fuels in general, the gap in TCO between the conventional diesel bus and zero-emission powertrains increases by ~EUR 0.2/km. Should additional infrastructure investment for the opportunity e-bus also be required, an extra EUR 0.1/km to the TCO gap would be added (Exhibit 24).

Exhibit 24

POTENTIAL LIMITING FACTORS FOR ZERO LOCAL-EMISSION BUSES

2030

	Negative external factor	Base case assumption
Costs of fossil fuels	E Crude oil price USD 90/bbl	Crude oil price USD 125/bbl
Taxation on fuel and emissions	F Taxation as in Directive 2003/96/EC	
	▪ Diesel: EUR 0.4/l	Diesel: EUR 0.49/l
	▪ CNG: EUR 0.5/kg	CNG: EUR 0.21/kg
	▪ Hydrogen: EUR 1.2/kg	Hydrogen: –
	▪ Electricity: EUR 35/MWh	Electricity: –
Component costs	G Doubling of infrastructure investment for e-bus	

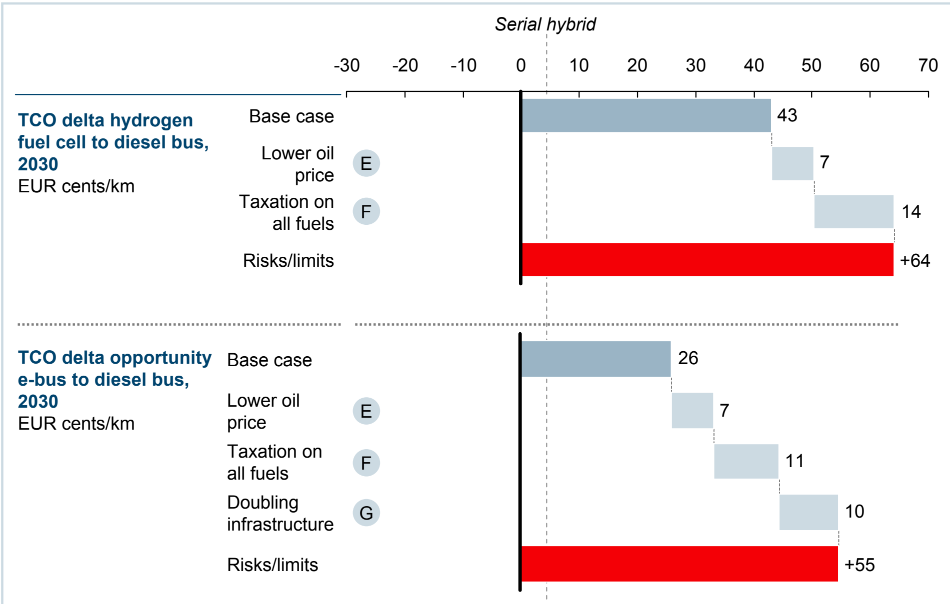
SOURCE: Study analysis

Exhibit 25

POTENTIAL LIMITING FACTORS COULD INCREASE THE PRICE PREMIUM FOR THE HYDROGEN FUEL CELL BUS AND OPPORTUNITY E-BUS VS. THE CONVENTIONAL BUS

Limitations

"CROSS-INDUSTRY" SCENARIO | 12-M BUS



SOURCE: Study analysis

6 Recommendations

N.B. For certain recommendations, the relevant group is indicated in italics between square brackets at the start of the paragraph.

Alternative powertrains for urban buses are necessary to reduce GHG and local emissions

Only through the deployment of hydrogen fuel cell buses, trolley buses, opportunity e-buses and/or overnight e-buses (zero local-emission buses) can the EU reasonably expect to achieve a reduction in road transport emissions of 95 percent by 2050, which is essential to delivering its overall GHG emissions reduction target of at least 80 percent. Furthermore, zero local-emission buses in public transport will play a key role in addressing the critical issue of air pollution in cities.

Where an infrastructure of overhead lines is present, trolley buses will continue to be a zero local-emission option for public transport. For all other cities, both hydrogen fuel cell buses and opportunity e-buses are promising alternative powertrains with zero local emissions. However, both powertrains face potential market failure issues that are inherent to any new technology. This means that proactive measures are required to accelerate market introduction beyond "early mover" cities and regions in order to achieve the necessary economies of scale.

Diesel hybrid buses reduce both local and GHG emissions, but there is a limit to the reductions that can be achieved (~20 percent). However, since any elements parts of their powertrains are similar to those of zero local-emission buses, diesel hybrids are an attractive bridging technology for the medium term, in addition to helping zero local-emission technologies reach critical volumes.

Europe requires the gradual deployment of zero local-emission buses – as of today

Zero local-emission powertrains can be available at lower TCO than conventional diesel buses even before 2030, as shown in Chapter 4 ("Upside potential"). However, this can only be realised if deployment of these buses at-scale commences within the next decade. It is therefore essential that policymakers and bus operators, manufacturers and component providers collaborate and synchronise their efforts.

[Public authorities as funding agencies] Continuing the momentum initiated by pilot projects is key to achieving aggregate numbers, which in turn will drive down the costs of major components. While several funding schemes are currently in place at an EU and national level, the majority end in 2015 or 2016. It is therefore imperative to set up further follow-up programmes comprising a number of local projects and focusing on the transition to a commercial market over the next 5 to 10 years. Policymakers and other sponsors should consider different financial structures (e.g. subsidies, project bonds, partnerships, low-cost financing) to support these pilots and the subsequent (pre-)commercialisation phase.

[Public authorities and bus operators] For powertrains that are already at or near the point of commercialisation, gradual fleet procurement needs to be initiated as of today. Indeed, with a lifetime of 12 years or longer, buses that are purchased this year will remain part of the fleet at least until 2024. An aspirational change in the bus fleet by 2020 would therefore have to be initiated in the immediate future. Sustained periodic purchases are also key to the commercial success of bus manufacturers and component suppliers. Finally, the case for commencing the procurement of zero local-emission buses is even more pronounced in those cities or regions where local conditions are favourable, e.g. there is a cheap supply of hydrogen as a by-product; hydrogen is used as medium to balance renewable electricity; there is sheddable electricity during the night, or where hydrogen fuel cell deployment can be combined with investment in CCS.

A gradual, but steady move to zero local-emission powertrains will allow the development of industry experience and expertise in key areas such as operation and maintenance. It will also generate a clearer view on which technologies are best suited to specific scenarios and local needs, and in turn help accelerate their development.

The deployment of zero local-emission buses in European cities should be further accelerated

[Bus manufacturers and component providers] On the supply side, bus manufacturers, component suppliers and infrastructure providers need to develop concrete and detailed masterplans, indicating the technical and commercial viability of their products over time. This will enable the market to make longer-term commitments that are essential to increasing the learning rates of zero local-emission powertrains.

In order to achieve further cost reductions, manufacturers of buses and bus components need to collaborate on innovation and standardisation by sharing experiences gained in pilots and early deployment in the form of benchmarks or other quantitative metrics. Learnings from regions outside Europe should also be proactively exchanged, with insights and results incorporated into plans for the European market. Since a large element of the drivetrain technology for a hydrogen fuel cell bus and an opportunity e-bus is similar, efforts should be made to share experiences, benchmark across both powertrains and codevelop components.

[Public authorities as regulators] In order to achieve a stable investment climate for zero local-emission powertrains, a change in the legal framework on a European or national level is necessary. Potential legislative changes are already being developed in a number of areas (see Chapters 4 and 5), but greater clarity is required on future alternative fuel taxation, carbon taxes, air quality legislation and other issues in order to sustain stable, long-term investments.

Next steps

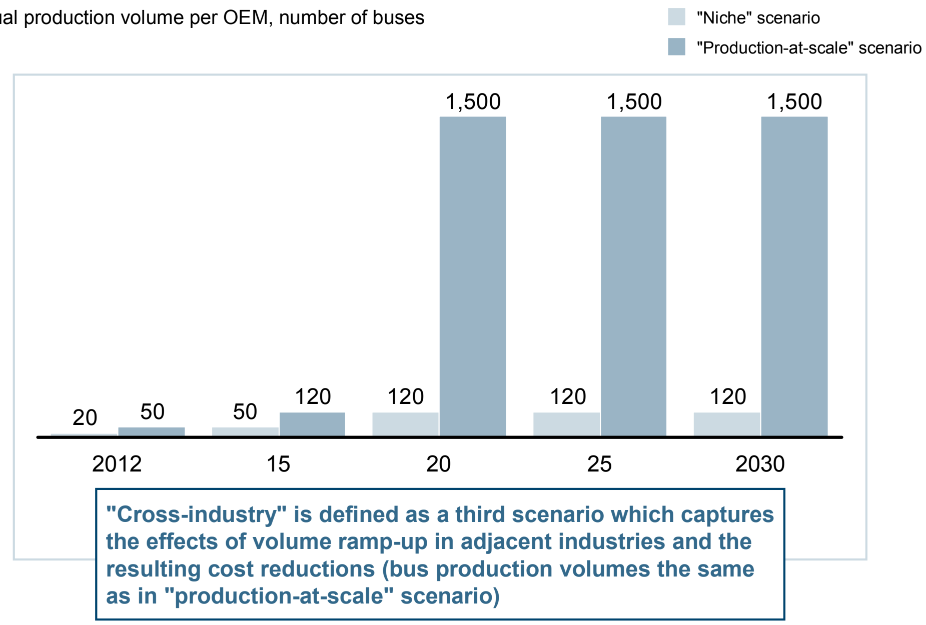
The European Fuel Cells and Hydrogen Joint Undertaking (FCH JU) invites public authorities, transport operators, bus manufacturers, component providers and other interested organisations to partner with them in the next phase of study. The aim of this phase is to detail the roadmap towards the implementation of hydrogen fuel cell technology in urban transport in Europe. This would ideally focus on a select number of interested cities and/or regions, from which insights would lead to recommendations on a pan-European level. Interested parties are invited to contact the FCH JU at fch-ju@fch.europa.eu or www.fch-ju.eu.

Annex 1
Input data

Exhibit 26

RAMP-UP OF THE THREE PRODUCTION VOLUME SCENARIOS FOR BUSES WITH ALTERNATIVE POWERTRAINS

Annual production volume per OEM, number of buses



SOURCE: Study analysis

Exhibit 27

ELECTRICITY MIX IN THE ENERDATA RECOVERY SCENARIO

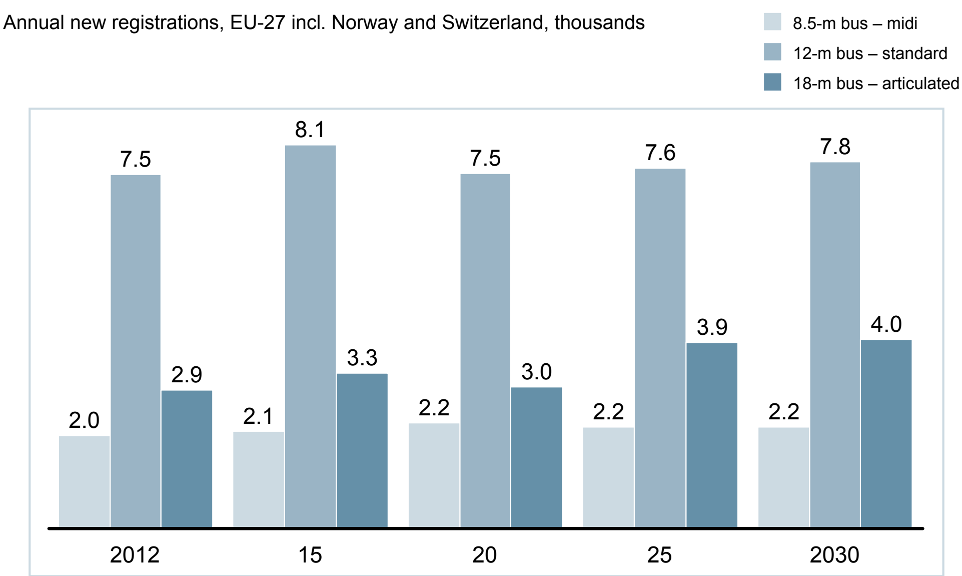
European average[1] electricity mix and price, percent[3]

1 Average of Belgium, France, Germany, Italy, Netherlands, Spain and UK
2 Based on industrial prices (high volume)
3 Numbers do not add up due to rounding

SOURCE: Enerdata Recovery Scenario

Exhibit 28

EXPECTED DEVELOPMENT OF THE EUROPEAN URBAN BUS MARKET



SOURCE: Study analysis

Exhibit 29

INFRASTRUCTURE COSTS FOR THE POWERTRAINS IN SCOPE

CAPEX | OPEX | x.xx EUR/bus km[2] | 2030 | MEDIUM DEPOT SIZE

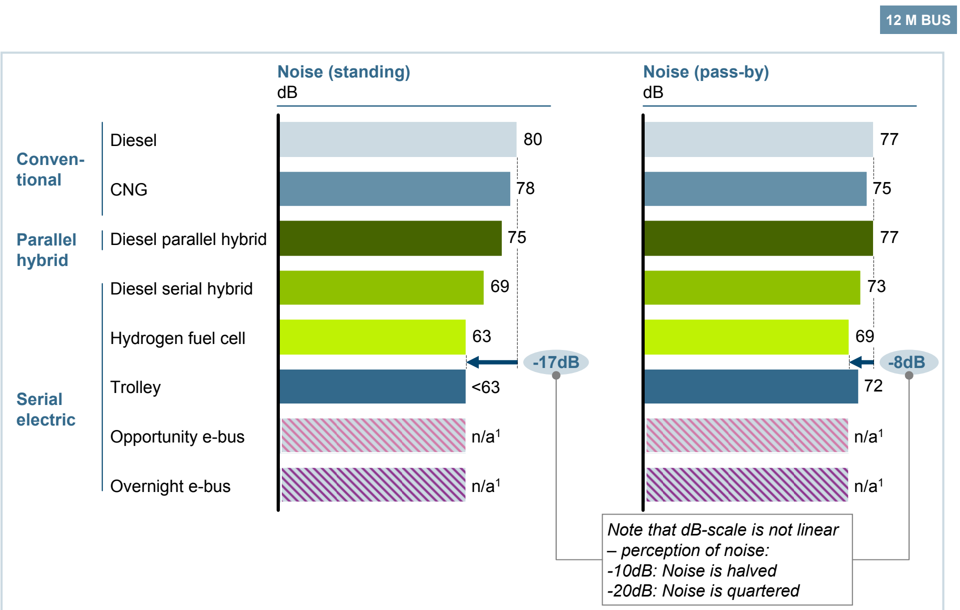
		Description	Investment required[3] EUR thousands	Total yearly costs[1] EUR thousands p.a. (CAPEX)	(OPEX)	(Total)	EUR/bus km[2]
Conventional	Diesel	Filling station with 4 dispensers	324	26	133	159	0.03
	CNG	Fast-filling station	3,194	256	493	749	0.15
Parallel hybrid	Diesel parallel hybrid	Filling station with 4 dispensers	324	26	133	159	0.03
Serial electric	Diesel serial hybrid	Filling station with 4 dispensers	324	26	133	159	0.03
	Hydrogen fuel cell	Medium-size gaseous 500-bar station	3,753	301	345	646	0.13
	Trolley	Overhead wiring, transformers, ~85-km network	38,250	3,069	1,199	4,268	0.84
	Opportunity e-bus	~8-9 routes equipped with 2 charging poles each	7,333	588	465	1,053	0.21
	Overnight e-bus	85 charging spots within depot	3,490	280	349	629	0.12

1 Based on WACC of 5% and 20 years' lifetime 2 Based on 85 buses and 60,000 km p.a. 3 Not incl. infrastructure required to produce or transport fuel to the depot (e.g., pipeline)

SOURCE: Study analysis; EUCAR/CONCAWE/EC JRC 2011

Exhibit 30

NOISE EMISSIONS OF THE POWERTRAINS IN SCOPE



1 No measure figures available yet – expectations are similar to hydrogen fuel cell bus

SOURCE: Study analysis

Annex 2

Data on core cost components, hydrogen production, GHG footprint and energy efficiency

Cost components for fuel cell and battery systems

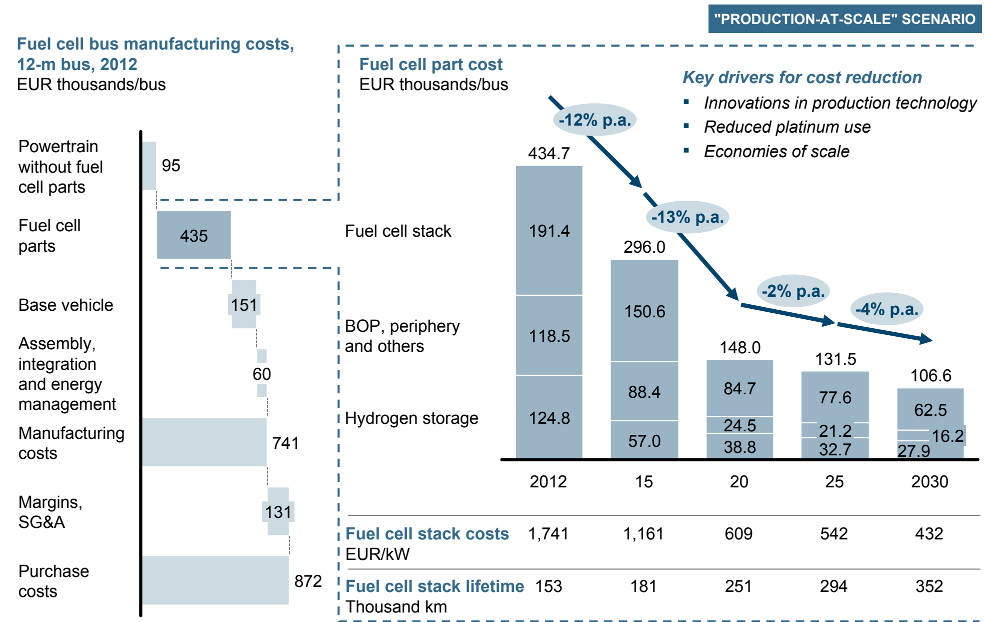
The purchase cost of a hydrogen fuel cell bus will reduce by 53 percent by 2030, driven by cost reductions of up to ~74 percent for major powertrain components (fuel cell system, electric storage) – see Exhibit 31.

Cross-industry effects could lead to a further reduction in component costs for the fuel cell stack of ~74 percent and BOP/periphery of ~26 percent: these effects would lead to a total reduction potential of ~45 percent in purchase cost compared to the niche scenario (including the ~28 percent reduction from the "production-at-scale" scenario). The hydrogen fuel cell bus would therefore benefit significantly from the large-volume application of fuel cells in adjacent industries (Exhibits 32 and 33).

- Fuel cell system costs (cost of fuel cell stack, balance of plant (BOP), periphery and hydrogen storage tank) are expected to decrease by ~12 percent p.a. until 2020 and continue at ~3 percent p.a. until 2030.
- Opportunity e-bus and overnight e-bus also benefit significantly (~36 percent for overnight e-bus) from cost reductions for batteries due to higher production volumes. In the case of the cross-industry scenario, these costs could reduce to a total of -50 percent (Exhibit 34).

Exhibit 31

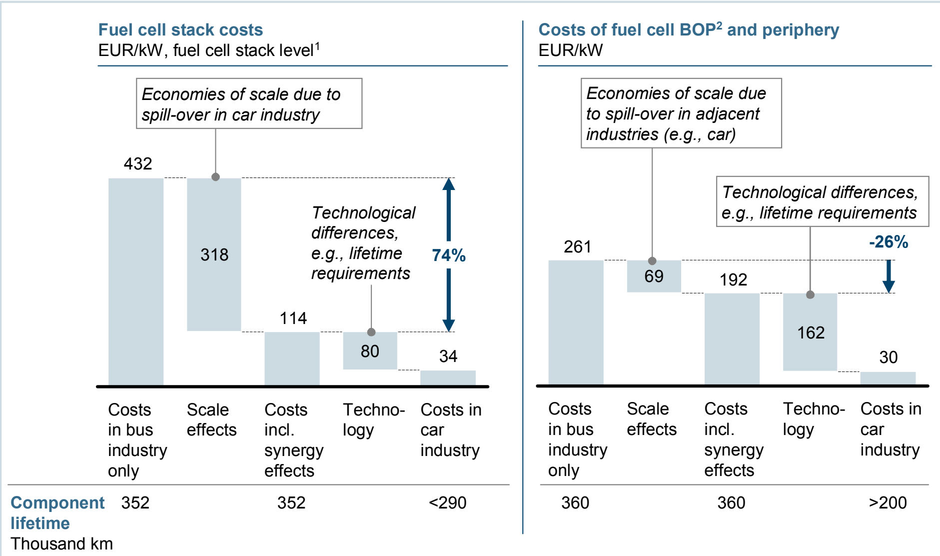
FUEL CELL COMPONENT COSTS FALL BY ~12% P.A. UNTIL 2020, THEN BY ~3% P.A. UNTIL 2030



SOURCE: Study analysis

Exhibit 32

CROSS-INDUSTRY EFFECTS DUE TO SYNERGIES BETWEEN CAR AND BUS TECHNOLOGIES COULD REDUCE FUEL CELL STACK COSTS BY 80% BY 2030



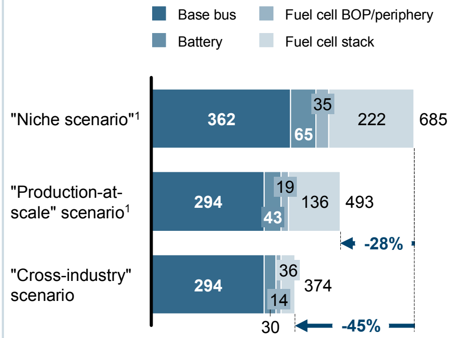
1 Average cost, fuel cell stack per kW fuel cell power without periphery, BOP and other fuel cell components 2 Fuel cell balance of plant

SOURCE: "A portfolio of powertrains for Europe: a fact-based analysis – the role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles"; study analysis

Exhibit 33

PRODUCTION-AT-SCALE' AND 'CROSS-INDUSTRY' EFFECTS REDUCE THE PURCHASE PRICE OF THE HYDROGEN FUEL CELL BUS BY 45% BY 2030, COMPARED TO THE 'NICHE' SCENARIO

Purchase cost hydrogen fuel cell bus, 12-m bus, EUR thousands



	Initial component costs			Component replacement costs		
	Battery	Fuel cell BOP/ periphery	Fuel cell stack	Battery	Fuel cell BOP/ periphery	Fuel cell stack
"Niche scenario"[1]	35	33	104	31	2	118
"Production-at-scale" scenario[1]	23	19	74	20	–	62
"Cross-industry" scenario	16	14	19	14	–	16

- Volume effect of **"production-at-scale"** scenario vs. **"niche" scenario** leads to **reduction** in purchase price **of 28%**
- Additional **cross-industry effects** from car industry on fuel cell system components **and battery yields total cost reduction of ~45%**

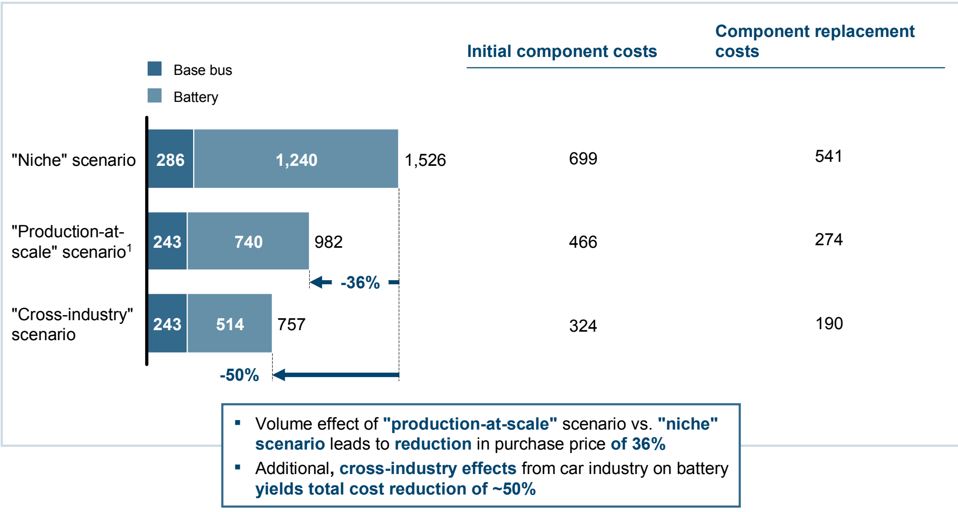
1 Do not add up due to rounding

SOURCE: Study analysis

Exhibit 34

‘PRODUCTION-AT-SCALE’ AND ‘CROSS-INDUSTRY’ EFFECTS REDUCE THE PURCHASE PRICE OF THE OVERNIGHT E-BUS BY A TOTAL OF 50% BY 2030, COMPARED TO THE ‘NICHE’ SCENARIO

Purchase cost hydrogen fuel cell bus, 12-m bus, EUR thousands



1 Do not add up due to rounding

SOURCE: Study analysis

Hydrogen supply costs and GHG footprint

The base case chosen for this study is a balanced mix of production technologies, representing all the technologies with the potential for large-scale deployment in Europe in 2030 (including CCS); different pathways explain how costs and emissions could be at the lower end of the range (Exhibit 35).

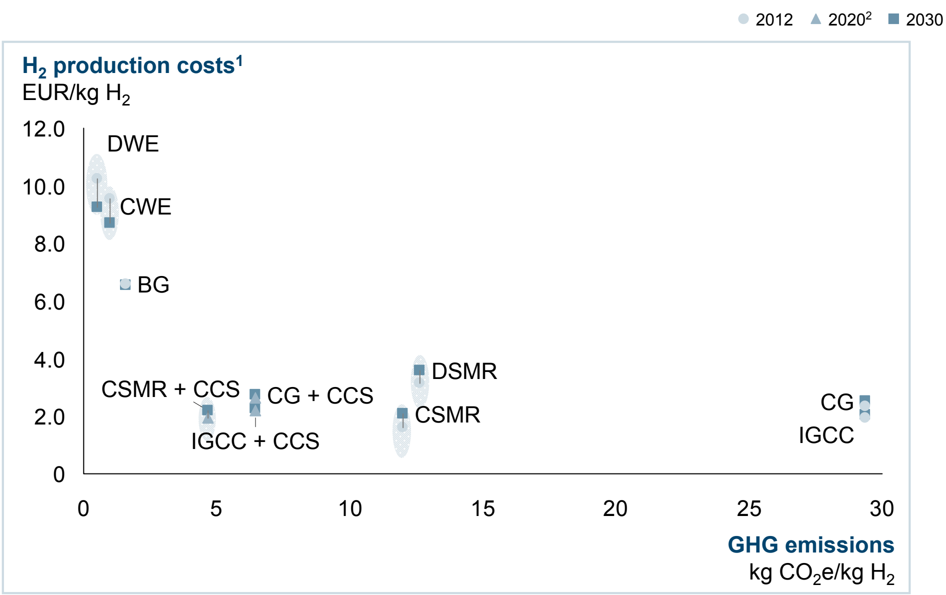
The price of hydrogen (i.e. for production, distribution and dispensing) for either the base case or one of the two pathways (see Exhibits 38 and 39) ranges from EUR 3.8 to 8.4/kg H2 and GHG emissions from zero to 4.7 kg CO_2e/kg H2, depending on local conditions.

a) Hydrogen production

- Different hydrogen production methods show a wide range of costs and GHG emissions:
  - Costs range between EUR 1.9 and 10.3/kg H2
  - Emissions range between zero and 29.4 kg CO_2e/kg H2.
- Fossil-based technologies are the most cost-effective, but their GHG emission level depends strongly on the availability of CCS. It should be also noted that CCS is a technology currently under development and under public scrutiny, especially in densely populated areas.
- Production costs are highly dependent on feedstock and electricity prices which rise over time.
- WE profits from expected efficiency improvements, which offset increasing electricity prices.

Exhibit 35

AN OVERVIEW OF COSTS AND GHG EMISSIONS FOR ALL PRODUCTION METHOD

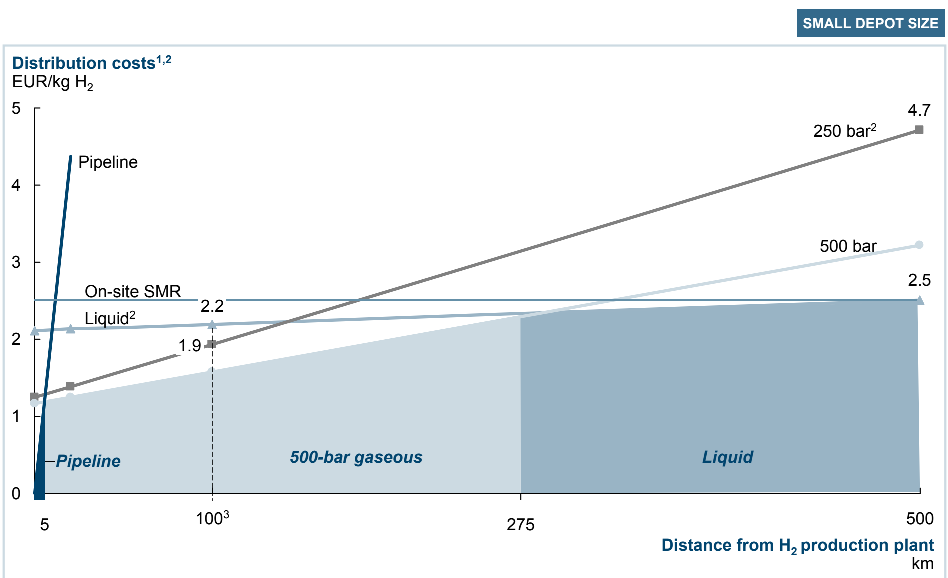


1 All costs based on large production capacities
2 Assumption: CCS is available on a large scale from 2020

SOURCE: Study analysis; EUCAR/CONCAWE EC JRC

Exhibit 36

FOR DISTANCES OVER 5 KM, 500 BAR GASEOUS DISTRIBUTION IS THE LOWEST-COST OPTION; LIQUID DISTRIBUTION IS ONLY APPROPRIATE FOR DISTANCES OF >275 KM



1 Assuming 90% truck, trailer and conditioning utilisation
2 Cost of liquid filling station is EUR 0.68/kg H_2 lower than 500-bar station: to reflect this, EUR 0.68 is deducted from liquid distribution costs; similarly, 250-bar station is EUR 0.17/kg H_2 more expensive than 500-bar station and thus, EUR 0.17 is added to 250-bar distribution costs
3 100 km based on Clean Team data; other ranges calculated, assuming following payload of trailers: liquid 3.5 t, 500 bar 0.8 t, and 250 bar 0.4 t

SOURCE: Study analysis

- A promising development for water electrolysis is its ability to provide load balancing services based on PEM technology, which is essential in an electricity grid that includes a large share of renewable energies. This is included in one of the two pathways – see Exhibits 38 and 39.

b) Hydrogen distribution

- Distribution costs differ, mainly depending on the distance from a hydrogen production plant (Exhibit 36). For short distances, pipelines are a cost-effective method of distribution; however, costs rise sharply if the distance increases. Distribution by truck with 500 bar gaseous containers is the most cost-effective method for distances greater than ~5 to 20 km, depending on station size. For distances greater than ~250 to 300 km, distribution by truck with liquid containers becomes cost competitive.

- On-site production is another option: in this study it was found that for medium-sized stations (1.75 tonnes H2/day), distributed SMR is cost-competitive with central SMR if the filling station is more than ~150 km away from the central SMR plant.

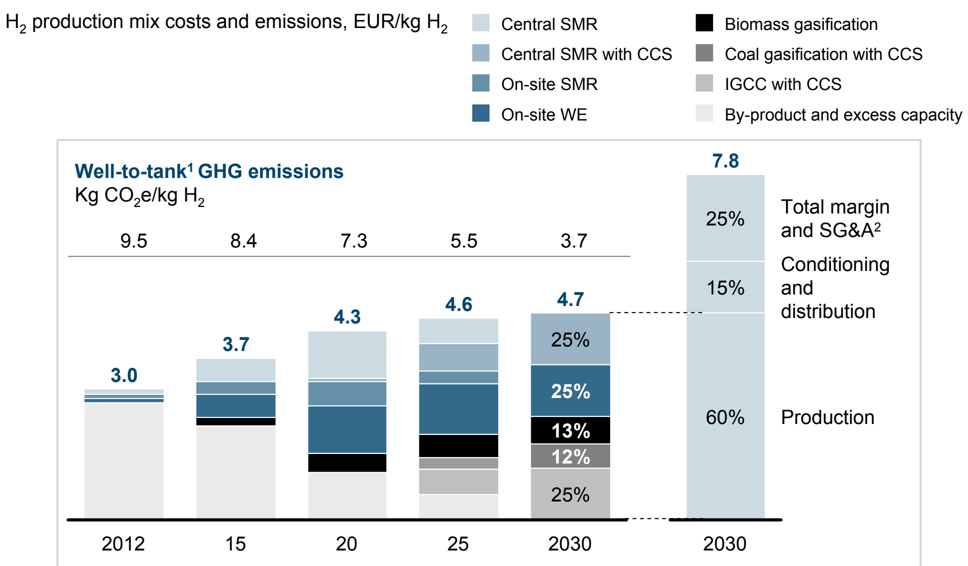
c) Composition of hydrogen base case and specific pathways

The base case represents all the main technologies with the potential for rapid, large-scale deployment in Europe in 2030 (Exhibit 37). In 2030, SMR, IGCC and WE each take up a share of 25 percent. CCS also represents a large share (62 percent) as it offers a cost-effective way of producing low-carbon hydrogen.

- Until 2020, total hydrogen demand is relatively low, utilising a large share of excess hydrogen from existing assets (as a by-product from industrial sites and centralised SMR).

Exhibit 37

THE BASE CASE ASSUMES A MIX OF ALL AVAILABLE PRODUCTION METHODS IN 2030 WITH 60% REPRESENTED BY SMR AND 5-10% BY OTHER TECHNOLOGIES



1 Total GHG emissions from production, distribution and dispensing; EU electricity mix used for WE
2 For central production, conditioning and distribution, 28% of the total price is taken as margin and SG&A; for on-site production, 14% is taken

SOURCE: Study analysis; EUCAR/CONCAWE EC JRC

- After 2020, when hydrogen demand increases and CCS becomes available, a balanced scenario is assumed, reflecting the diversity of resources available in different parts of Europe. Most new-build plants based on fossil fuels will have CCS installed. As hydrogen production volumes will scale-up quickly, a large share of CCS is achieved in a much shorter period than is possible for electricity generation. New electric power plants with CCS are only expected to replace depleted plants and hence limited capacity with CCS will be added.

- The base case also assumes an average distance from a hydrogen plant of 100 km (one-way distance), which is performed most cost-effectively by trucks with 500 bar gaseous containers.

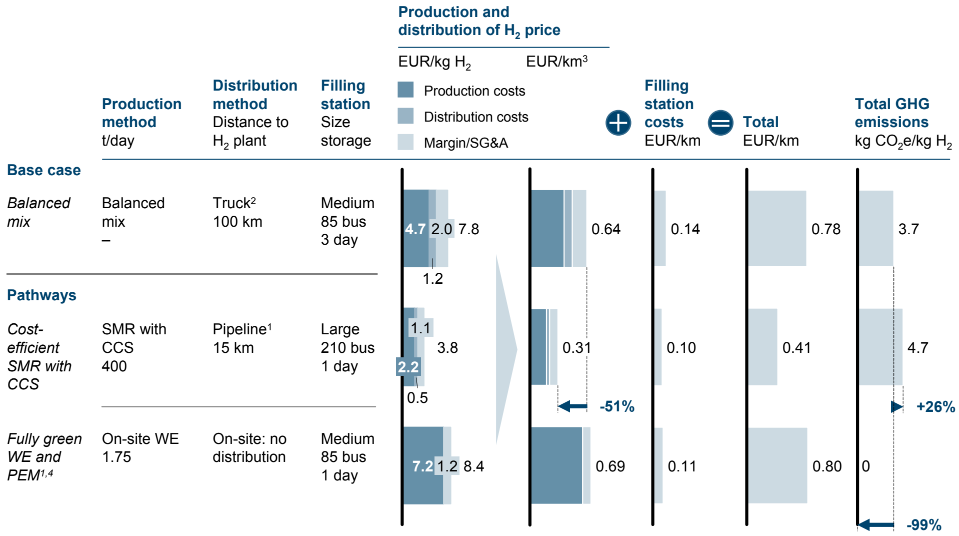
- The resulting hydrogen price for the base case is EUR 7.8/kg H2 for production and transportation to the filling station. Apart from production and distribution costs, it also consists of an average margin and percentage for overheads of 25 percent of the total price. In the long-term, this margin may be significantly lower if a marginal cost market perspective for established markets is applied. Nevertheless, based on uncertain future market developments, a conservative approach has been taken.

In addition to the base case, two specific hydrogen pathways were considered until 2030 (Exhibit 38). These show the significant variety in hydrogen prices (up to ~50 percent cheaper) and emissions (up to ~99 percent lower) depending on local factors, including the prices of feedstock and electricity, plus the distance from existing plants.

1. **Low-cost SMR and CCS:** this pathway assumes a large filling station (for 210 buses) in close proximity to a SMR and CCS plant, which offers the lowest cost hydrogen production, but with an increase in GHG emissions (~26 percent). A pipeline connection avoids trucks having to drive in and out continuously to supply the daily hydrogen consumption of 210 buses (4.2 tonnes per day).

Exhibit 38

BY 2030, SMR AND CCS REDUCE HYDROGEN COSTS BY 51% AND WATER ELECTROLYSIS FROM RENEWABLE ENERGY SOURCES REDUCES GHG EMISSIONS BY 99%



1 No Clean Team data: industry interviews
2 500-bar gaseous
3 Using consumption of 8.2 kg H_2 per 100 km
4 Assuming 10% efficiency improvement and 15% electricity discount for grid services
SOURCE: Study analysis; industry interviews; EUCAR/CONCAWE/EC JRC 2011

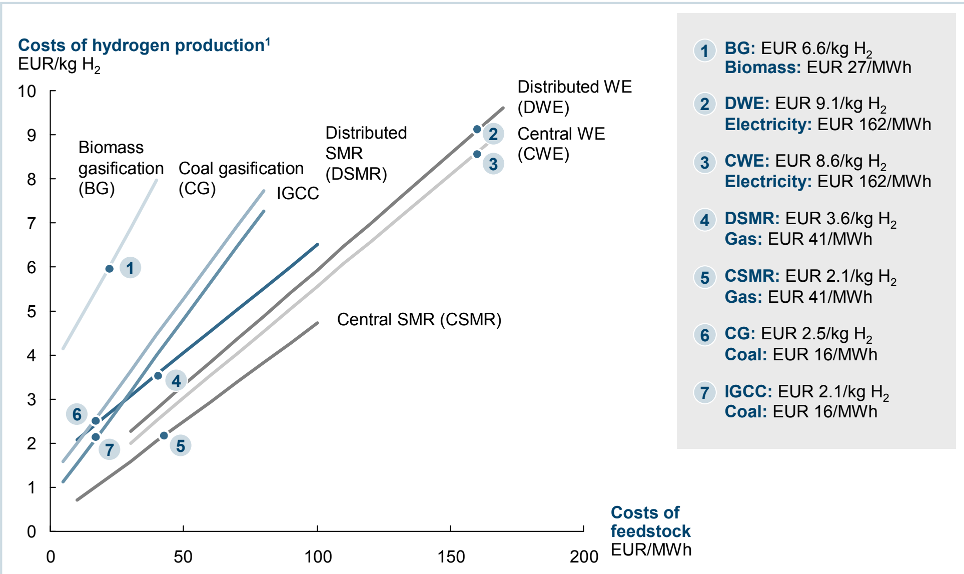
2. **Green PEM:** this pathway assumes a medium filling station (for 85 buses) in the locality of a wind farm. The on-site water electrolysis installation with PEM technology is assumed to be directly linked to the wind farm, ensuring fully green electricity. During periods of strong wind, the PEM installation can work at 300 percent capacity (at slightly lower efficiency levels). A significant discount on the electricity price during these periods results in 15 percent lower electricity price (on average). Based on industry estimates, the PEM technology is also assumed to work at 10 percent higher efficiency (on average) than current state-of-the-art technology. No distribution is required for this on-site production pathway.

Both pathways assume a mature hydrogen market with a delivery infrastructure in place. Filling stations therefore only have storage sufficient for one day, compared to three days in the base case.

- For large-scale hydrogen production methods, more than 70 percent of the total costs originates from feedstock and electricity consumption. Local feedstock prices therefore determine the most cost-effective hydrogen production method. Exhibit 39 shows the threshold prices for different production methods compared to the base case for this study.

Exhibit 39

THE COST OF HYDROGEN PRODUCTION IN 2030 DEPENDS HEAVILY ON FEEDSTOCK – ESPECIALLY IN BIOMASS AND COAL GASIFICATION

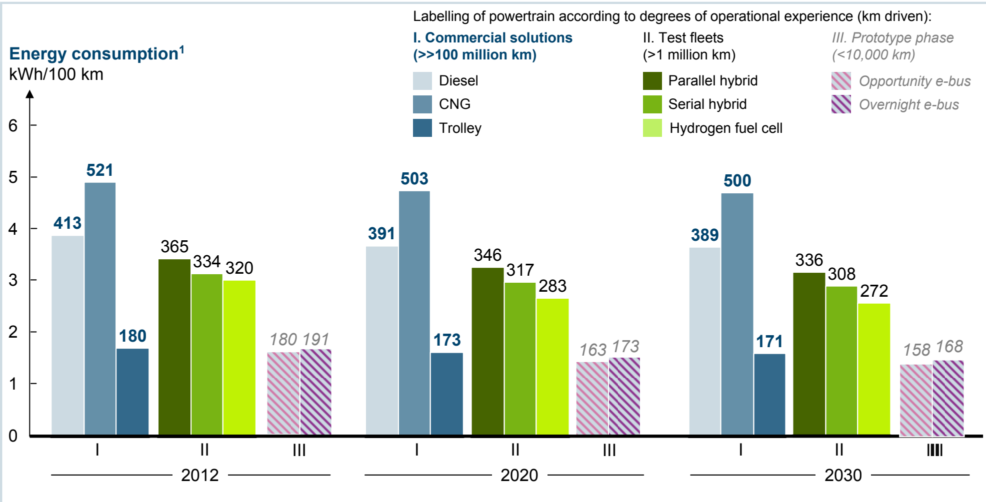


1 Production costs are based on large scale, i.e., 4.2 t/day for distributed methods; 400 t/day for central SMR and coal; 1,000 t/day for IGCC

SOURCE: Study analysis

Exhibit 40

A COMPARISON OF ENERGY CONSUMPTION FOR INDIVIDUAL POWERTRAINS



1 Powertrain energy consumption only; does not include losses in charging or losses in the production and distribution of the fuel and electricity

SOURCE: Study analysis

Glossary

APU	Auxiliary Power Unit
BBL	Barrel of Oil
BG	Biomass Gasification
BOP	Balance of Plant
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CCS	CO_2 Capture and Storage
CG	Coal Gasification
CH4	Methane
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CSMR	Central Steam Methane Reforming
CWE	Central Water Electrolysis
DSMR	Distributed Steam Methane Reforming
DWE	Distributed Water Electrolysis
EC	European Commission
EIA	Energy Information Administration (USA)
EU	European Union
FC	Fuel Cell
GHG	Greenhouse Gas
GDP	Gross Domestic Product
GJ	Gigajoule
H2	Hydrogen
H2O	Water
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
kg	Kilogramme
kW	Kilowatt
km	Kilometre
m	Metre
MWh	Megawatt Hour
O2	Oxygen
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
P.A.	Per annum
PEM	Proton Exchange Membrane
R&D	Research and Development
SG&A	Selling, General and Administrative Expenses
SMR	Steam Methane Reforming
SORT	Standardised On-Road Test
TCO	Total Cost of Ownership
TTW	Tank-to-Wheel
UITP	International Association of Public Transport
VAT	Value Added Tax
WE	Water Electrolysis
WTT	Well-to-Tank
WTW	Well-to-Wheel

Cover photos:

Bus, petrol fuel pump, gas fuel pump	www.istockphoto.com
H2	www.fotolia.de
Combo 2 plug: product of Phoenix Contact (www.phoenixcontact.nl)	Phoenix Contact

For more information on this study, or the next steps, please contact the FCH JU:
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