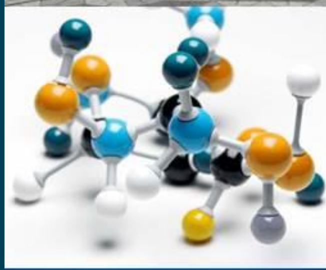
Fuel Cell Electric Buses – Potential for Sustainable Public Transport in Europe

A Study for the Fuel Cells and Hydrogen Joint Undertaking



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Date of publication: September 2015

Front cover pictures provided by: Daimler (EvoBus), DeLijn, Hydrogenics, Ruter

Executive Summary

The European Union and pioneering cities are establishing the public transport systems of the future

The European Union is pursuing an emissions reduction agenda as well as measures to preserve local air quality and to reduce harmful noise levels in public transport. With its Directives on Ambient Air Quality and Cleaner Air for Europe (2008) as well as on the Promotion of Clean and Energy-Efficient Road Transport Vehicles (2009) the EU has set first regulatory standards in this regard. Numerous European cities and regions have started initiating change in their public transport systems, for example with the European Climate Change Statement 2015 or in the Clean Bus Declaration of the C40 Cities Initiative.

Seeking alternatives to diesel buses is crucial for realising the emissions reduction agenda in public transport. Although some improvements in terms of reducing harmful environmental effects have been made with the EURO VI standard, it is expected that there is a limit to the "cleaning" of diesel buses. Hence, cities and bus operators are under pressure to shift to electric zero emission powertrains such as tramways, trolley, battery and fuel cell electric buses (FC buses). Diesel buses currently dominate the public transport market due to their high productivity, low deployment costs, technological maturity, operational reliability and flexibility, e.g. high daily ranges, fast refuelling and no infrastructure requirement along the routes. Many cities and bus operators are struggling with the currently conflicting objectives of shifting to zero emission public transport while keeping operational flexibility and maintaining budgets under control.

Fuel cell electric buses are crucial for reducing emissions while meeting operational requirements

The potential for greening urban mobility and associated benefits is enormous. FC buses reduce the external environmental and health costs induced by public transport. With lower noise levels, air quality improvement and vibration mitigation, cities can cut costs, increase property values and benefit from a "green" and modern image. Promoting the technology also contributes to reducing the dependency on fossil fuels and securing the high-tech industrial base and jobs in Europe.

Environmental benefits extend well beyond zero local emissions. Hydrogen as a road fuel yields significant potential for carbon neutrality on a well-to-wheel basis along the entire hydrogen value chain, including production and means of delivery. Hydrogen can be produced with electricity from 100% renewable energy sources. Hence, operating FC buses can be achieved with zero CO_2 emissions along the entire hydrogen value chain. By using hydrogen produced from renewable energy sources only, one standard FC bus would save approximately 800 tonnes of CO_2 in its lifetime of 12 years compared to a conventional diesel bus.

FC buses offer the best productivity and operational flexibility compared to other zero emission concepts. FC buses use power from a fuel cell stack and a battery and run on hydrogen which can be stored and refuelled at bus depots. In terms of costs, it is expected that FC buses compare similarly with other zero emission powertrains in the long run. However, they are superior in terms of operational performance: With ranges of 300-450 kilometres, refuelling times below 10 minutes and no infrastructure requirements on the routes, FC buses can be operated like conventional diesel buses while offering all the above mentioned advantages of electric vehicles. Hence, FC buses are the most flexible zero emission alternative.

FC buses have been operated on about 8 million kilometres in daily service in a number of European cities over the last 10 years, demonstrating that the technology is flexible in operation and safe. At the time of this writing, 84 FC buses are in service or about to start operations in 17 cities and regions in 8 European countries.

FC bus costs are expected to drop significantly and become increasingly competitive

The purchase price of FC buses has come down considerably by about 75% since the introduction of first prototypes in the 1990s. However, to enable a sustainable market-based commercialisation all stakeholders need to push for better and cheaper FC buses, larger scale projects as well as for an environment conducive to FC buses:

1. **All stakeholders need to engage to rapidly increase the total number of units on the roads.** This is a precondition for reaching the scale effects as well as the associated technological maturity and cost reductions.
2. **The industry needs to work on further reducing FC bus as well as infrastructure and hydrogen costs** significantly. Future FC bus costs will depend on the technology pathway followed. In a technology pathway that seizes synergies with the FC passenger car market overall FC bus deployment costs can reduce fairly quickly with a volume uptake of FC cars. In this case, costs could be on par with diesel buses within the next decade. Infrastructure OEMs and hydrogen providers need to take the necessary steps to realise acceptable costs.
3. **Bus operators need to be prepared to implement large-scale demonstration projects in the next years.** In order to further mature the technology, gather operational experience with larger FC bus fleets and stimulate market development, European bus operators and public transport authorities need to actively engage. Several deployment projects with 20 or more FC buses by location are expected to be realised in the framework of the FC bus coalition. Other interested bus operators and public transport authorities can benefit from participating in the coalition, e.g. by gaining useful information and tools and preparing for projects in cooperation with other committed locations.
4. **A supportive public framework is needed.** In order to support pioneering bus operators in carrying the costs of early technology deployment, respective funding mechanisms are required on European and national levels. Furthermore, levelling the playing field for fuel

costs can support FC bus rollout, as subsidies and tax exemptions currently favour the use of diesel fuel for some operators.

A broad coalition of stakeholders supports the commercialisation of FC buses in Europe

The European FC bus coalition aims at kick-starting the market rollout. The FC bus coalition has been established in order to identify the required number of FC buses to be deployed to bridge the gap towards commercialisation by reaching scale effects and reducing current costs. It has developed a common understanding of buyers and sellers of FC buses on the required roll-out in the next years and actively works on realising this roll-out. The coalition currently plans to implement large-scale demonstration projects with a total of approximately 300 to 400 FC buses in Europe by 2020. Currently, 45 public transport authorities and bus operators representing 35 cities and regions from 12 European countries are participating in the commercialisation initiative. The results of the first phase of this initiative are presented in this report. In the next phases of the initiative, the coalition will continue to foster commercialisation of FC buses. The great commitment to FC buses has been documented in a joint Letter of Understanding of public transport authorities and bus operators which has been handed over to the EU Commissioner of Transport at the TEN-T Days in Riga on June 23, 2015.

The industry partners are firmly committed to the initiative. Five FC bus manufacturers participating in the coalition have signed a Letter of Understanding underlining their commitment to the commercialisation of the technology. Participating hydrogen infrastructure OEMs and suppliers are currently working on solutions for large-capacity infrastructure for up to 200 buses to cater for large bus depots. In addition, the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) supports the initiative for commercialising FC buses in urban transport. It is a public-private partnership of the European Commission, industry partners and research institutions. It envisages putting a European funding scheme in place which will need to be supplemented by national or local programs and funds.

Interested European cities and regions are invited to join the initiative at any time. The coalition encourages interested bus operators and public transport authorities to engage in the commercialisation initiative and to bring forward the change to zero emission public transport in their cities. Becoming a partner is possible at any time.

This report provides an outlook for jointly achieving a commercialisation pathway. Building on the findings of the 2012 FCH JU technology study on alternative powertrains for urban buses[1], this report provides an assessment of the commercialisation pathway from an operational perspective. It reflects the actual situation in which operators deploy large scale demonstration projects in the next years from a rather conservative angle and argues why it makes sense to deploy FC buses now. The insights are based on first-hand data and assessments of the coalition members from the hydrogen and fuel cell industry as well as local governments and public transport operators in Europe.

[1] Available at http://www.fch.europa.eu.

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Acronyms

CCS	Carbon Capture and Storage
CNG	Compressed Natural Gas
EU	European Union
EUR	Euro
FC bus	Fuel Cell Electric Bus
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
GBP	British Pound
GHG	Greenhouse Gas
HRS	Hydrogen Refuelling Station
OEM	Original Equipment Manufacturer
PEMFC	Polymer Electrolyte Membrane Fuel Cell
RES	Renewable Energy Source
SMR	Steam Methane Reforming
TCO	Total Cost of Ownership
UK	United Kingdom
UN	United Nations
VAT	Value-Added Tax
WACC	Weighted Average Cost of Capital
WTW	Well-to-Wheel

The Potential of Fuel Cell Electric Buses

A. Introduction – The importance of FC buses for the future of public transport

There is a regulatory push for reducing emissions in public transport in Europe

The European Union has set itself ambitious targets for reducing emissions in the years ahead. For 2050, EU leaders have defined the goal of reducing Europe's greenhouse gas (GHG) emissions by 80% compared to 1990 levels; by 2030, a reduction of at least 40% of domestic GHG emissions shall be reached[2]. In order to meet these overall climate targets, the European Commission stipulated in its 2011 White Paper that GHG emissions from transport will have to be cut by at least 60% by 2050 compared to 1990[3]. Emissions reduction and energy sustainability are also key pillars of the European Energy Union that the European Council decided to create in 2014. At the same time, improvement of local air quality and reduction of noise pollution are important goals for the EU and its member states, as for example stated in the Directive on Ambient Air Quality and Cleaner Air for Europe (2008). With the introduction of the EURO VI standard for buses, significant improvements for reducing local emissions have been reached; however, such emissions are still not completely avoided. Therefore, stricter regulations are expected to be introduced on European, national and local levels that require further emissions reductions or penalise the cause of CO_2 and local emissions.

European countries are rethinking public transportation. Promoted by trends such as urbanisation, a shift in societal values towards more sustainability and the need to increase energy security as well as a more holistic perspective on costs, reducing emissions in public transport is placed firmly on the agenda of national and local governments in Europe. Some countries, e.g. the Netherlands, have already adopted national targets for reducing public transport emissions. Numerous European cities and regions have committed to initiate change in their public transport systems, for example with the European Climate Change Statement 2015 or in the Clean Bus Declaration of the C40 Cities Initiative.

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[2] European Council Conclusions on the 2030 Climate and Energy Policy Framework (23 and 24 October 2014).

[3] Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system (2011).

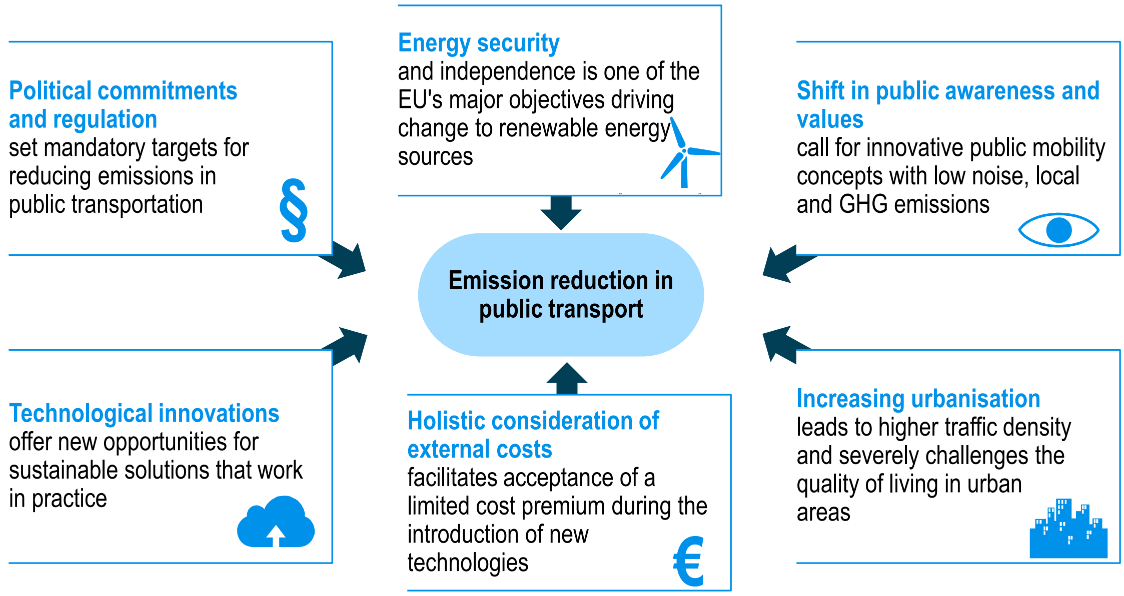


Figure 1: Trends supporting emissions reduction in public transport

To reach carbon-neutrality and zero local emissions, deployment of electric powertrains is required. Seeking alternatives to diesel buses is crucial for realising the emissions reduction agenda as they are hazardous to the environment: A EURO VI diesel bus emits approximately 120 kg of CO_2 per 100 km. They cause local air and noise pollution as well as vibrations that are harmful to health and impact the quality of living in our cities. Whereas significant improvements have been reached with the introduction of the EURO VI standard, further emissions reduction potential is limited. This poses challenges to cities and bus operators in Europe as performance characteristics of diesel buses today are still difficult to match with zero emission powertrains: They feature high productivity, low deployment costs, high technological maturity as well as operational reliability and flexibility. Many cities and bus operators therefore struggle with shifting to zero emission powertrains while preserving operational flexibility and maintaining budgets under control. The objective of this report is to provide an assessment of the commercialisation pathway for FC buses required to meet the aforementioned challenges.

FC buses are zero emission electric buses with a battery and a fuel cell

FC buses are built on a conventional chassis and contain a fuel cell system and an electric battery which form the heart of the powertrain. Fuelled by hydrogen, they emit only water vapour. A fuel cell system typically consists of auxiliary components (humidifier, pumps, valves, etc. grouped together as balance of plant) and a fuel cell stack which is made up of bipolar plates and membrane electrode assemblies. Hydrogen buses are electric buses that feature a longer lifetime and lower maintenance costs than diesel buses in the long run as abrasion is expected to be lower. Different technical solutions exist for the main architecture of the FC bus powertrain. It can comprise fuel cell stacks as direct energy source for propulsion in combination with super-capacitors and different sizes of batteries as energy storage. Some FC bus models use a larger battery and a smaller fuel cell stack which are normally referred to as "range extenders"; the analysis presented in this report focused on fuel-cell dominant powertrains only. The specific technical solutions used will largely determine the future cost development. Below we depict cost projections for two technological pathways; however, other approaches might emerge in the future as well.

The fuel cell converts chemical energy of hydrogen into electrical energy. The general operating principle is as follows: Hydrogen is fed into the fuel cell anode where it is split into protons (H+) and electrons (e-) by means of a catalyst. The membrane lets only protons (H+) pass; the electrons (e-) are forced to follow an external circuit, creating a flow of electricity. Oxygen from ambient air is fed into the fuel cell at the cathode. Oxygen, electrons from the external circuit and protons combine to form water and heat. To achieve sufficient electrical power to propel a vehicle, multiple cells have to be compiled into a fuel cell stack. The leading fuel cell type for automotive applications is the polymer electrolyte membrane fuel cell (PEMFC).

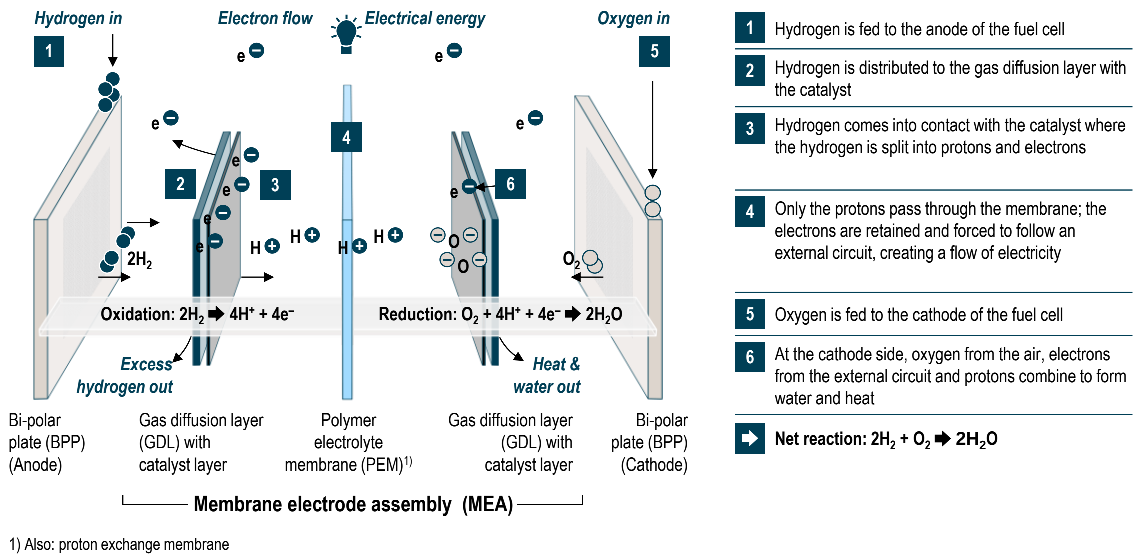


Figure 2: Schematic view of a polymer electrolyte membrane fuel cell (PEMFC)

Hydrogen can be produced from various sources with steam methane reforming and water electrolysis being investigated in this study: Steam methane reforming is based on gas as feedstock (e.g. natural gas, methane gas, biogas, etc.) while water electrolysis uses electricity as feedstock. Hydrogen can be trucked in by suppliers or produced on site with electrolysers at bus depots. Aboard the buses, hydrogen is normally stored in tanks on the roof. Hydrogen refuelling and storage infrastructure for the whole fleet is typically situated at bus depots. Further information on hydrogen production can be found in Chapter C.

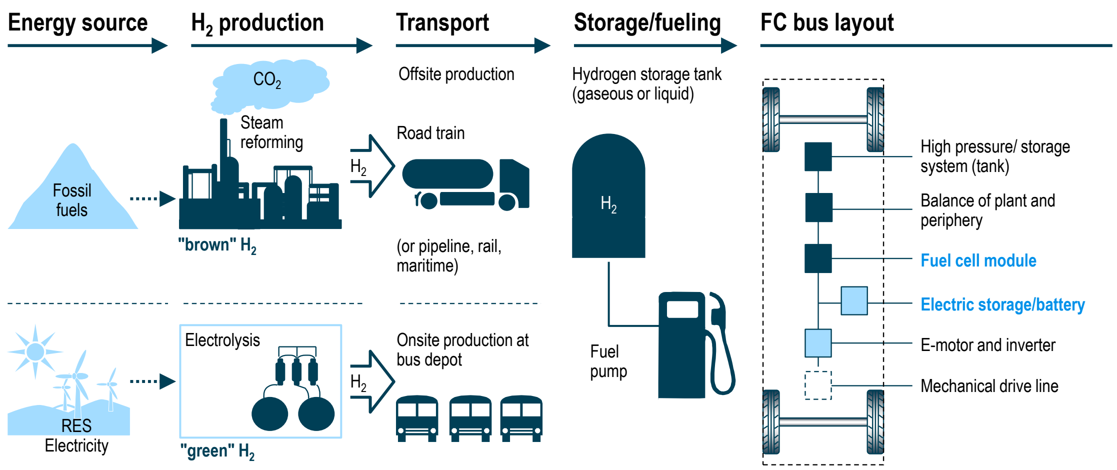


Figure 3: Hydrogen value chain and FC bus layout (simplified representation)

Different technology pathways for bus powertrain development design exist

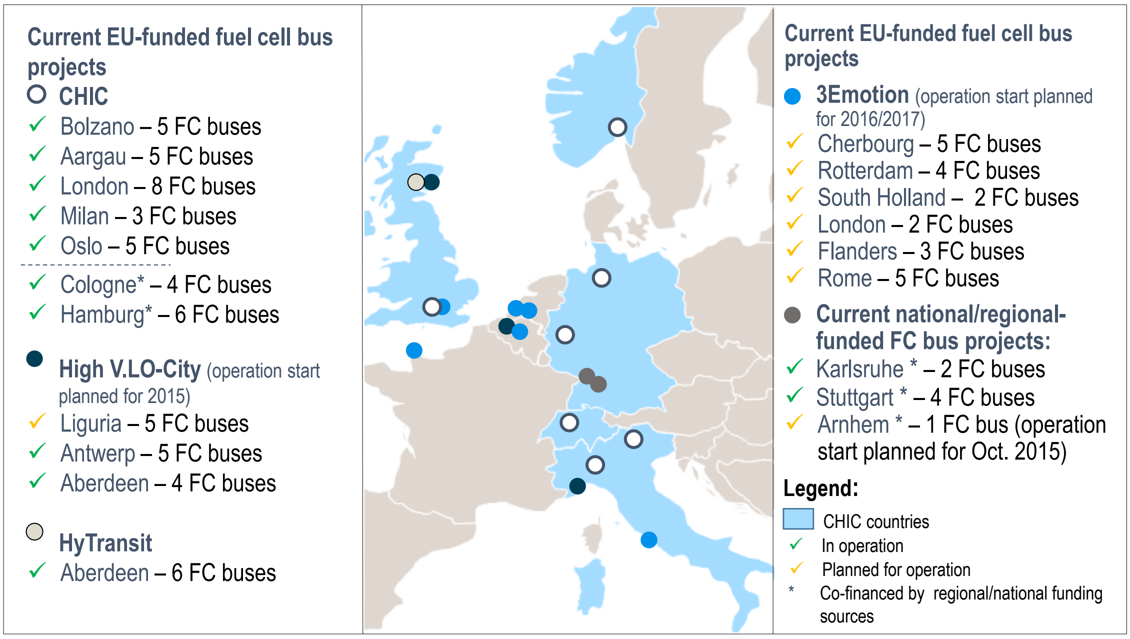
Firstly, in the "heavy-duty" pathway, the technical concept of the FC bus builds on dedicated fuel cell systems, which are specifically developed and manufactured for use in heavy-duty vehicles such as urban buses. This pathway is well-established and currently being applied in FC bus models in operation in major demonstration projects in Europe and elsewhere. It has proven as a viable technical option that works today and in the future.

Secondly, in the "automotive" pathway, it is envisaged to integrate the same type of fuel cells, systems and batteries of passenger cars for FC buses, thus achieving synergies and seizing economies of scale provided by potential FC automotive volumes. First FC bus models designed according to this pathway have recently been put in test service in Asia. Similar developments are being carried out in Europe and some buses are already in operation. The economic viability of this technological pathway strongly depends on the future achievement of automotive production volumes (~10,000 stacks/year) and utilisation of technical synergies. In order to be able to benefit from this technological pathway, the FC systems and other components used need to be available to all bus OEMs in the market.

FC buses are crucial for reducing emissions and improving local air quality

FC buses are the most flexible zero emission alternative as they can be operated like conventional diesel buses with ranges of 300-450 kilometres per tankful while offering the advantages of every electric vehicle: zero exhaust emissions, reduced noise (see below) and vibration levels and, therefore, higher passenger comfort.

Across Europe, cities demonstrate that the technology works in practice. Several completed and ongoing projects such as the Clean Urban Transport for Europe (CUTE), HyFleet: CUTE, Clean Hydrogen In European Cities (CHIC), High V.LO-City, HyTransit and 3Emotion projects support the development of the technology. Participating operators deploy FC buses in daily service on normal routes and demonstrate that FC buses can be integrated into existing transport networks, that they are safe and deemed more comfortable by bus drivers, passengers and the public. Currently, 84 FC buses are in service in Europe or about to start operation.



Source: CHIC project – Element Energy

Figure 4: Current FC buses in Europe and numbers of buses deployed

A broad stakeholder coalition promotes the commercialisation of FC buses

A European coalition of supply and demand side stakeholders aims to kick-start the market. Its overall objective is to roll out a total number of 300 to 400 FC buses in Europe by 2020 in order to achieve scale effects that are expected to bring down costs and deployment costs for operators. The initiative assesses the costs for bus operators and cities in its first phase and actively engages operators in preparing for the rollout of FC buses. Currently, 84 FC bus stakeholders such as bus operators, local governments, bus manufacturers, fuel cell technology providers, hydrogen infrastructure manufacturers and suppliers as well as associations and other market players are members of the FC bus coalition. At the end of the first phase of the initiative in June 2015, 45 bus operators and public transport authorities from 35 European cities and regions from 12 European countries are participating in the coalition and further locations have signalled interest to join. Joining the coalition is possible at any time for new participants.

The coalition is supported by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), a public-private partnership of the European Commission, industry partners and research institutions. It is supporting various FC bus demonstration projects across Europe, proving the applicability of vehicles in different climatic and geographical conditions and preparing for market rollout.

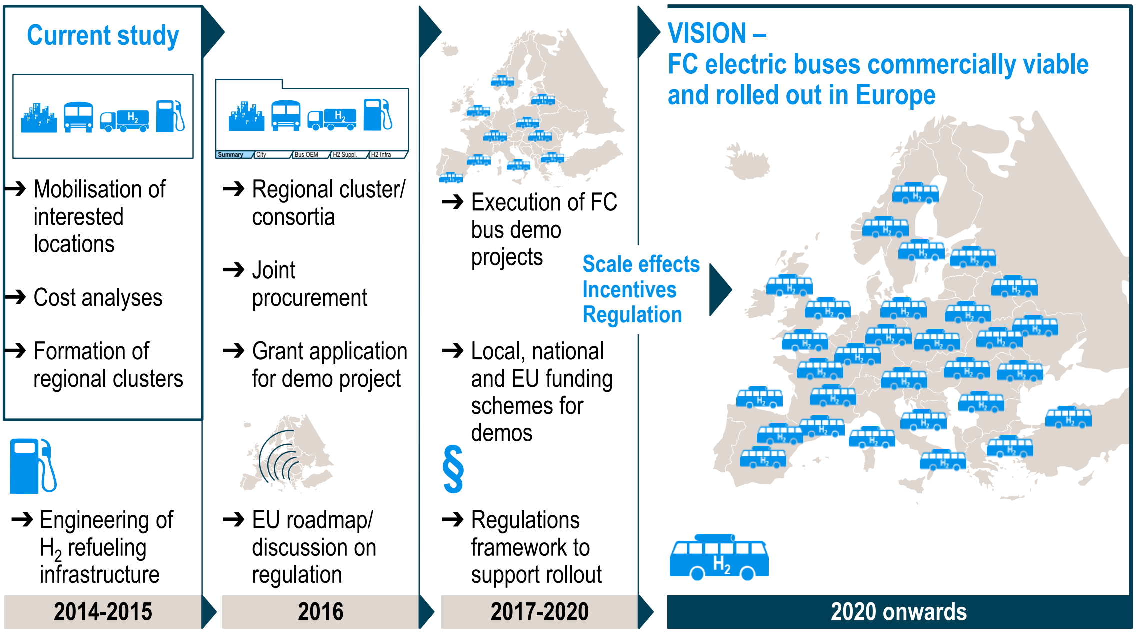


Figure 5: FCH JU commercialisation vision

This report provides an outlook for jointly achieving a commercialisation pathway

The report is structured in four sections: Section B presents a brief overview of future cost projections. Section C outlines the benefits of investing in FC buses on the basis of four key arguments. Section D provides an overview about the current FC bus coalition and outlines the expected future interest in FC buses in Europe. Section E explains how to get involved in the initiative.

B. Fuel cell electric buses and their projected costs

KEY MESSAGES

- **Future FC bus costs are expected to decrease significantly, provided the required production volumes can be achieved**
- **A conducive regulatory framework for fuel taxation would aid FC bus commercialisation**
- **Operating costs can be reduced further depending on local conditions**

Future FC bus costs are expected to decrease significantly

In 2012 the FCH JU published a detailed cost-based comparison of alternative powertrains for urban buses (Urban buses: Alternative powertrains for Europe)[4]. The current initiative focuses on promoting FC buses and provides an updated cost projection for the coming years. It also aims at supporting operators in assessing their location-specific costs and preparing for FC bus rollout. The cost analysis is based on proprietary industry data. Further information on the methodology and assumptions as well as on detailed results can be found in Annex 3 of this report.

The following sections present an overview of expected cost developments for both different technology pathways. As the main cost drivers of FC buses are powertrain components and the system integration, different pathways can have a high impact on FC bus purchasing prices and thereby also on the total costs of FC bus operation.

[4] Available at http://www.fch.europa.eu.

1. Future FC bus cost developments in the heavy-duty technology pathway

The heavy-duty technology pathway is well-established in the market and has achieved significant price reductions since first deployments of FC buses in Europe. FC buses currently in operation in Europe are based on FC bus models designed according to the heavy-duty technology pathway. Since first deployments in the 1990s, purchasing costs for these FC buses have fallen significantly by more than 75%.

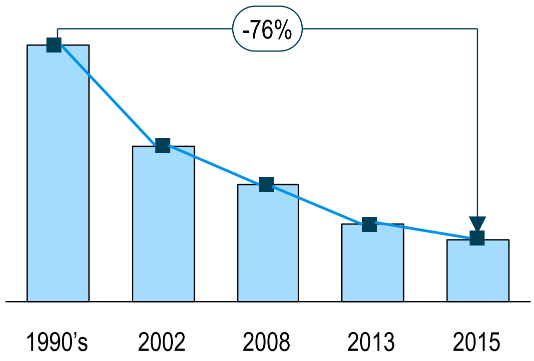


Figure 6: FC bus purchasing cost development since the 1990s [%]

Extensive operational experience has been gathered in Europe since their introduction in the last 15 years while establishing FC buses of this technology type (also compare Chapter C.3). Significant achievements have been made regarding the technological maturity development of these FC bus models and the availability levels reached. While final steps of the technology development are currently being taken, this technology pathway has proven a viable option for future market development. Through 2020, it is expected that the larger number of FC buses in Europe will be designed according to this technological pathway.

Overall costs for these buses are expected to decrease down to a cost premium of about 11-18% compared to conventional diesel buses on a per kilometre basis in the year 2030. The cost premium is driven by the costs associated with the introduction of a new technology, mainly reflected in a higher FC bus purchase price and thus, higher financing costs. In the first years of deployment, infrastructure costs for the hydrogen refuelling system, bus maintenance costs and hydrogen costs add to the premium until 2020. From 2020, bus maintenance costs are expected to converge to diesel bus levels and hydrogen fuel costs are assumed to be even lower than diesel costs on a per kilometre basis. Hence, in the medium term reducing the purchase price of FC buses as well as providing affordable infrastructure solutions for large FC bus fleets and cost-efficient hydrogen prices is crucial to bringing costs down. These assumptions suppose that current tax regimes for diesel remain and that no new taxation for hydrogen is being introduced.

Future costs strongly depend on the size of the market for FC buses. Hence, two scenarios were developed in order to account for potential variations of the future market size as well as the speed at which fuel cell costs will decrease. The "niche scenario" and the "production-at-scale scenario" portray the variance of potential costs depending on efficiencies and economies of scale achieved with varying market sizes and the related overall technological progress in the framework of the heavy-duty technology pathway. The scenarios reflect the effect that different economies of scale have on cost-down curves and prices. For the niche scenario to materialise, a cumulative number of 1,200-1,800 FC buses needs to be deployed on Europe's roads in total until 2025. For the production-at-scale scenario, a total cumulative volume of 8,000-10,000 FC buses is required until 2025. The latter represents about 7-9% of the expected total cumulative urban bus purchases in Europe in the period 2015-2025[5] (see Annex 3). The costs displayed in the following are applicable to the specified year only. They do not depict the average costs over the entire lifetime of an FC bus.

The purchase price of FC buses is expected to significantly decrease to approximately EUR 400,000-450,000 for a standard FC bus and approximately EUR 580,000-630,000 for an articulated FC bus in the year 2030 in the scale scenario of the heavy-duty technology pathway. This constitutes an additional purchase price decrease of 40-45% until 2030 compared to today's prices. A purchase price premium to the diesel bus is expected to remain also in the long term. Higher purchasing prices are also driven by high warranties that currently need to be provided by bus OEMs for FC bus systems (up to 5-10 years as compared to 2 years for diesel buses). With increasing maturity of the technology, these costs will be reduced.

Similar cost reductions are expected for bus maintenance as well as infrastructure investment and operations cost. Bus maintenance costs are expected to reach the same level as for diesel buses after 2020. Depending on which type of infrastructure is being installed, cost reductions of about 24% can be expected for hydrogen refuelling stations (HRS) with off-site H_2 production and of about 39% for HRS with on-site H_2 production by electrolysis. HRS maintenance and operating costs are expected to drop by about 35-40%[6].

[5] Estimation of total annual sales of urban standard and articulated buses based on FCH JU Study: Urban buses: Alternative powertrains for Europe (2012).

[6] Figures given for HRS with a refuelling capacity to cater for 20 FC buses.

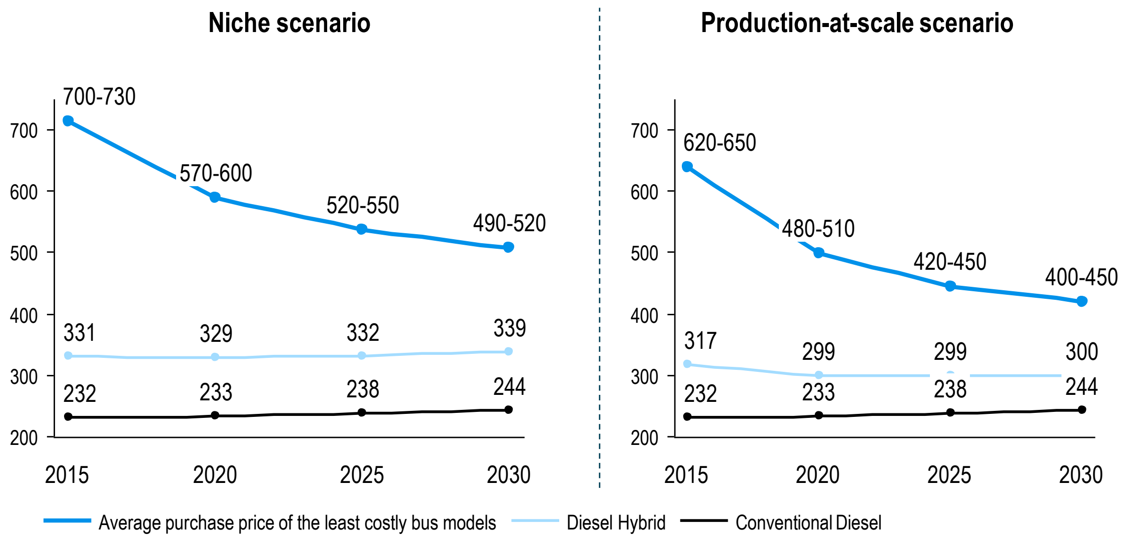


Figure 7: Purchase price development of standard FC buses according to different scenarios in the heavy-duty pathway [EUR '000]

Total Cost of Ownership (TCO) is expected to come down to EUR 3.3 per kilometre in 2030 from EUR 3.8 in 2015 for a standard bus[7]. TCO includes all overall costs of purchase and operation and take into account the costs of diesel replacement buses during downtimes of FC buses in the early years of deployments[8]. While most studies tend to disregard downtime costs for newly introduced bus technologies, this study explicitly includes this type of costs in its calculations to provide a more realistic assessment. Although costs are expected to come down by 5-7% by 2030 from 2015 levels, a cost premium compared to diesel buses of 11-18% is expected to remain in the year 2030. The lower overall cost decrease of 5-7% for FC buses between 2015 and 2030 despite significantly higher reductions for FC technology related cost components (bus purchasing and maintenance costs, infrastructure investment and operations costs) is mainly driven by two factors: A labour cost increase of 2% annually as well as an increase in feedstock prices for electricity and natural gas which causes higher hydrogen production costs. Due to an assumed 3% annual increase in diesel fuel costs until 2030, as well as the same assumed increase in labour costs, TCO of diesel buses even increase by about 30% in the same timeframe.

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[7] The term " standard bus" in the framework of this study includes both 12 m standard as well as 13.5 m buses which have a double rear-axis and higher passenger capacity.

[8] Total Cost of Ownership, as defined here, consist of total bus deployment costs plus costs for operating diesel replacement buses during downtimes of FC buses in order to deliver full daily service and to achieve the total annual bus mileage envisaged. In practice, downtime costs due to problems with a newly introduced technology need to be considered by operators. Hence, this TCO approach provides a more realistic perspective on the costs of FC bus deployment across the entire fleet (also see Annex 3).

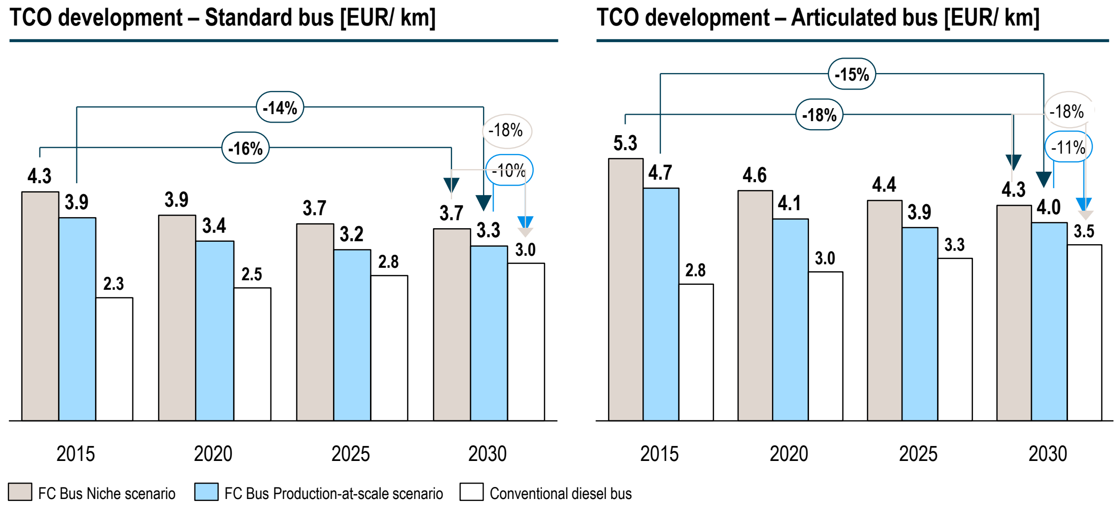


Figure 8: TCO development of FC buses compared to conventional diesel buses in the heavy-duty pathway [EUR/km]

Depreciation and financing costs constitute the largest share of FC bus-specific TCO, highlighting the effect of the purchase price of FC buses and infrastructure costs which drive the price gap between FC and diesel buses. Since labour costs are equally applicable to the diesel bus, they do not drive the price gap (see Figure 9: TCO split by components for standard FC buses according to different scenarios in the heavy-duty pathway [EUR/km]). Nevertheless, they constitute the largest part of real deployment costs for operators. For financing costs, a Weighted Average Cost of Capital (WACC) of 7% is considered.

A higher purchasing price will remain the largest difference between FC bus and diesel bus costs in overall TCO, as evidenced by higher depreciation and financing cost vis-à-vis the standard diesel bus.

Maintenance costs are expected to even out after 2020 and are already close to diesel bus maintenance costs today. Overall, the FC bus price difference is mostly offset by an assumed 3% annual increase in diesel fuel costs until 2030. In the base case for cost comparisons to diesel buses, a diesel price of EUR 1 in 2015 is assumed.[10]

[9] Labour costs in the scale scenario are slightly higher than in the niche scenario as a higher availability and higher number of kilometres driven are assumed for the FC bus (see Annex 3).

[10] Please note that the diesel comparison is based on EURO VI models.

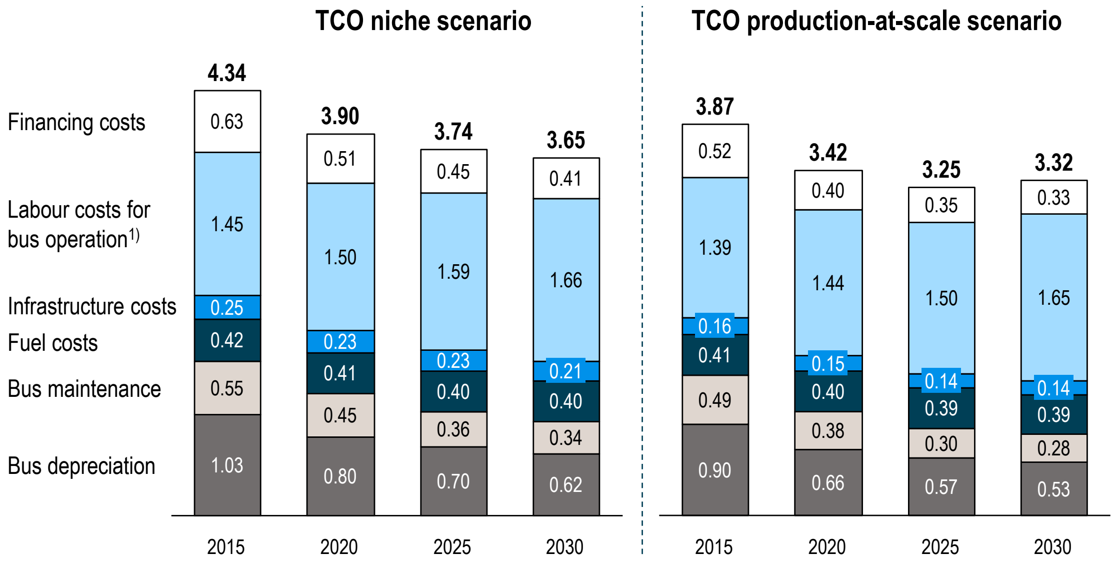


Figure 9: TCO split by components for standard FC buses according to different scenarios in the heavy-duty pathway [EUR/km]

Cost-efficient hydrogen prices as presented in this study are required to achieve competitive operational costs for FC buses compared to diesel buses. For TCO calculations shown in this study, hydrogen produced from steam methane reforming (SMR) with a price per kg of EUR 4.9 in 2015 (EUR 5.1 in 2020) has been considered as being the least costly option at the moment. Costs for hydrogen produced by electrolysis are assumed to be slightly higher (EUR 5.9 in 2015, EUR 6.2 in 2020[11]; also see Annex 4). In such a scenario, fuel costs for FC buses are lower than for diesel buses if no additional taxes or levies on hydrogen are being introduced in the future. This shows that regulatory and support frameworks greatly influence costs and have an impact on commercialisation. This is reflected in the current political discussions on EU level which debate penalising the use of fossil fuels in the future.

If operators were to pay current average diesel consumer prices, FC buses could be cost-competitive in 2030 also in the heavy-duty pathway. Assuming a diesel price of EUR 1.35 per litre in 2015 (current average consumer price in the Eurozone without subsidies and including all taxes[12]) suggests that the projected price gap of the heavy-duty pathway of 11% in 2030 could be already reached in 2025 and that the gap in 2030 could be decreased further to approximately 5%.

[11] Industry indication based on assumption that at least 20 FC buses are refuelled daily.

[12] Average diesel price across all EU countries including taxes since 2009. Source: Weekly Oil Bulletin of the European Commission.

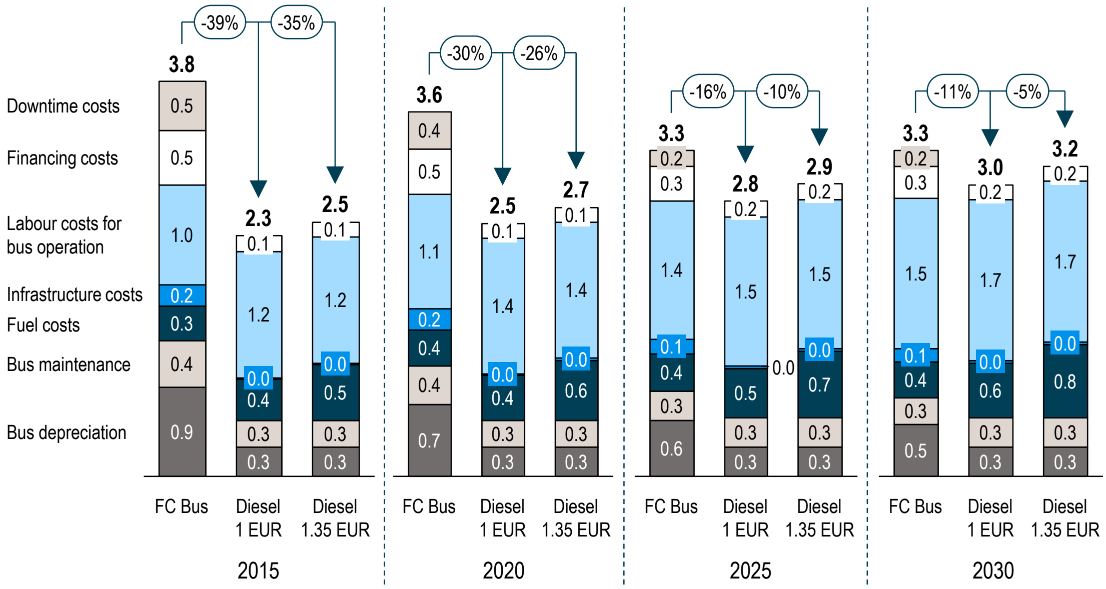


Figure 10: TCO comparison of standard FC and conventional diesel bus in the heavy-duty pathway [EUR/km]

In the face of current market developments, coalition members consider the niche scenario of the heavy-duty pathway to be most realistic until 2020. Hence, the figure below depicts the cost projections of the niche scenario until 2020 with the base case assumptions for feedstock prices, labour and financing costs as well as bus lifetime (see Annex 3). Deploying a higher number of buses in the initial years is a key condition for reaching the scale scenario of the heavy-duty pathway after 2020. If production-at-scale quantities cannot be reached in the initial years, it may be harder for the efficiencies and advances in technology to be reached that are assumed in the production-at-scale scenario in later years for this technology pathway.

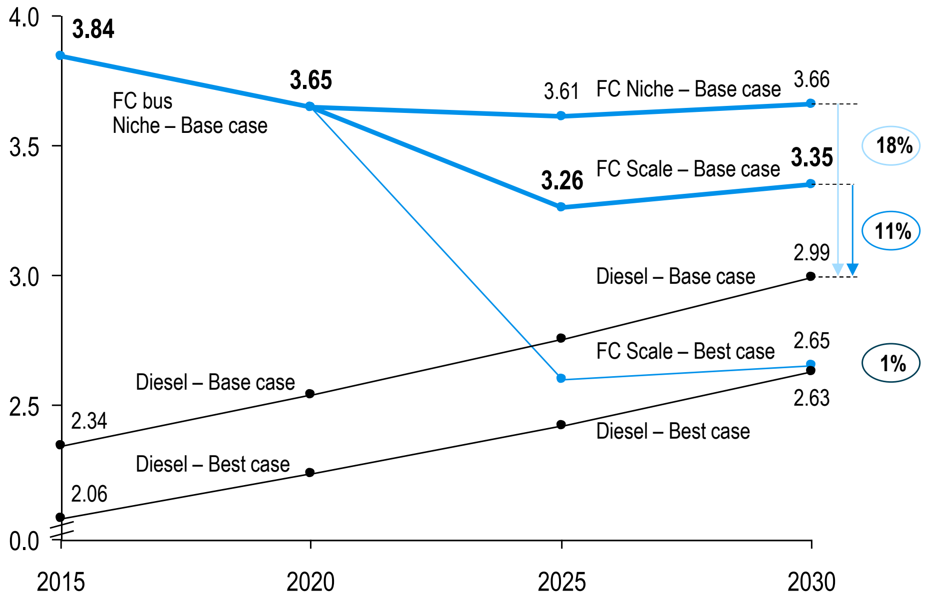


Figure 11: TCO for standard FC and diesel buses according to different scenarios in the heavy-duty pathway [EUR/km]

The costs may be significantly lower for some operators. Indicated cost projections above are applicable to the average European bus operator. However, the actual cost development depends strongly on operators' local conditions, which can change the case entirely. In order to demonstrate the influence of different cost drivers, a sensitivity analysis was performed. In a best case scenario with low feedstock/hydrogen prices, low financing costs and a longer bus lifetime, the overall costs of FC buses in the heavy-duty pathway can be on a par with diesel in the medium term. Lower electricity or natural gas and, thus, hydrogen prices can reduce TCO (see Annex 5 for details). A Weighted Average Cost of Capital (WACC) of 5% can further reduce TCO. With currently low interest rates, some public operators in particular should be able to achieve such financing rates. Assuming a bus lifetime of 18 years, there could be a TCO reduction almost closing the gap to the diesel bus. As mentioned above, assuming a longer lifetime of FC buses vs. diesel buses is a realistic expectation in general, if the drive train of FC buses proves the anticipated lower abrasion and, thus, lasts longer. Out of the three mentioned parameters, a longer bus lifetime carries the greatest potential for a reduction of overall TCO (see Annex 5). The sensitivity analysis demonstrates that costs can significantly differ from the average projections presented in this study. Interested bus operators and local governments will need to assess carefully how their specific local framework conditions influence the cost projections applicable to them in order to make an informed decision on deploying FC buses.

A comprehensive cost assessment tool has been developed in the framework of the study to help operators to analyse their actual FC bus deployment costs. The tool is available to all participants and allows for customised cost calculations using specific local costs (e.g. for labour or feedstock) as well as individual deployment schedules.

2. Future FC bus cost developments in the automotive technology pathway

Further cost reduction potential might arise from realising technical synergies and scale effects with the FC passenger car market. Currently, some OEMs are developing their next generation of FC buses intending to integrate the same type of fuel cell stacks and batteries in FC buses as in FC passenger cars. With this technology pathway, it is expected that additional cost reduction potential can be seized, if synergies with the FC passenger car market can be realised. First FC bus models constructed following this technological pathway have recently been put into test service by Toyota (Hino) in Asia. In Europe, 23 FC buses using passenger car FC stacks have been deployed in the CHIC and NaBuZ ("Nachhaltiges Bussystem der Zukunft " – "Sustainable bus system of the future" in Hamburg) projects. Paving the way towards this technological pathway, they have gathered substantial operational experience of over more than 700.000 km.

The cost reductions to be achieved in this technological pathway are highly dependent on the development pace of the FC passenger car market. Commercialisation activities for FCEVs are currently being realised in Europe and plans for the establishment of the required hydrogen refuelling infrastructure are being implemented in several countries. The pace and duration of FC passenger car uptake depends on a number of factors, e.g. the roll-out pace of the required hydrogen refuelling station network. Hence, it is difficult to predict when and to which extent this technology pathway will materialise for FC buses. Therefore, cost projections for the automotive technology pathway presented in the following are based on required production volumes of FC stacks for passenger cars only and do not refer to specific years in which these costs are expected to emerge. However, a number of OEMs are planning to launch FC passenger cars from series production in the European market from 2018 onwards so that annual sales of a few thousand vehicles can be expected before 2020. When considering current projections made by the industry in further FCEV market development, the FC passenger car production volumes required for the automotive technology pathway of FC buses to materialise may be reached in the 2020 – 2025 period. Additional to the required FC passenger car market development, significant annual production volumes for FC buses per OEM need to be reached to create sustainable demand for the industry, i.e. annual production volumes as projected in the heavy-duty pathway.

Below, respective cost projections are presented based on the assumption that this large-scale rollout of passenger cars materialises. In order to be able to benefit from this technological pathway, the FC systems and other components used need to be available to all bus OEMs in the market. Hence, the broad application of this pathway in the future FC bus market also depends on the establishment of an independent supply of such systems.

The main cost drivers of FC buses are the powertrain components and system integration, whereas the production costs for the base vehicle are expected to remain rather constant. Therefore, if significant component cost reductions from FC passenger car synergies can be realised, it can be expected that FC bus purchasing costs can decrease below the levels projected for the heavy-duty technology pathway. The potential for these cost reductions has been analysed by several specific technology and cost assessments carried out by TIAX, the U.S. DoE and in the framework of European projects funded by the FCH JU, such as AutoStack and AutoStack-Core.

It is expected that costs of fuel cell stacks and systems as well as batteries for FC buses can come down considerably when seizing synergies with FC passenger cars. For this, automotive components need to be able to offer the same quality and durability as heavy-duty stacks and systems for the use in urban buses. Expected major increases of unit volumes in the FC passenger car market will lead to significant economies of scale that buses can benefit from. The following production costs of the fuel cells stacks and batteries are considered achievable based on different volume scenarios:

Number of stacks produced/year	10,000	100,000
Stack cost [EUR/kW]	80	50

Number of batteries produced/year	200,000	450,000
Battery cost [EUR/kWh]	324	220

Costs of hydrogen storage systems can follow similar cost down curves in such a scenario, from well over 1,100 EUR/kg to around 750 EUR/kg and potentially beyond. The ultimate cost of on-board hydrogen storage systems will again depend on scale effects. However, due to different current pressure levels of the tank systems between cars (700 bar) and buses (350 bar) and related implications of other technical trade-offs such as system controls, the per-kg-costs of passenger car tanks may not be fully transferrable. Cost improvements from overall production scale effects are still to be expected, though.

In this technology pathway FC bus purchasing prices can reach the range of diesel hybrid buses. FC bus powertrain costs could come down to below EUR 120,000 and ultimately reduce further to below EUR 100,000. Assuming a base vehicle cost of EUR 180,000 and an adequate margin, the FC bus purchasing price could reach the range of current diesel hybrid buses (~350,000-320,000 EUR), thereby reducing overall costs for the deployment of the technology. For bus maintenance, infrastructure investment and operations as well as hydrogen costs, the same cost developments as in the heavy-duty pathway are assumed.

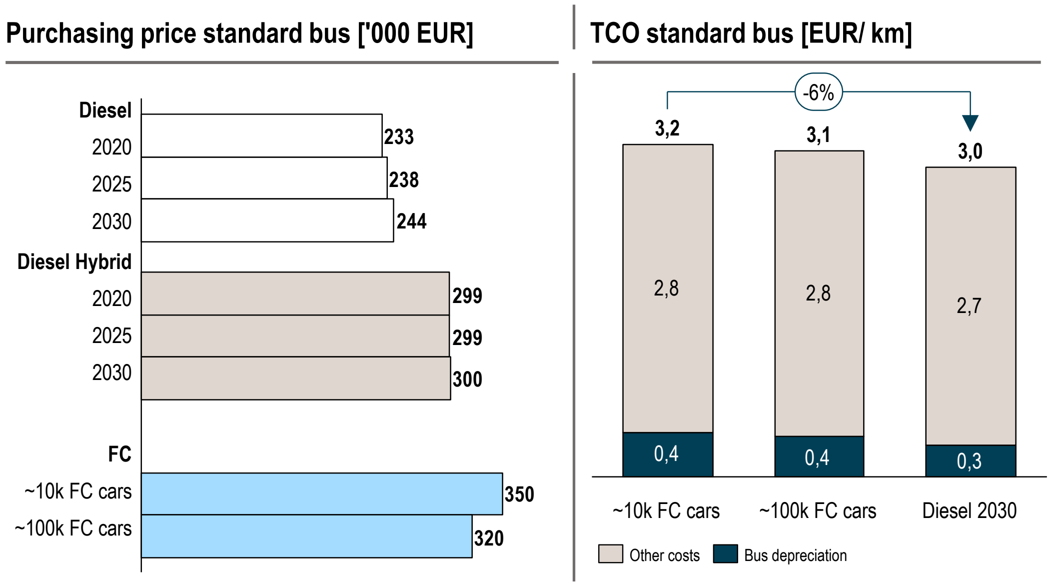


Figure 12: Purchase price [EUR '000] and TCO [EUR/km] development for standard FC buses in the automotive pathway

With this pathway, TCO could be close to diesel buses – assuming that the production volumes of automotive FC stacks per year reach required levels. Lower FC bus purchasing costs in the automotive pathway have a significant effect on overall costs. FC bus deployment costs are therefore expected to be closer to diesel bus costs. An approximation to cost parity could be reached, even if diesel fuel prices remain at EUR 1 per litre in 2015. As in the scenarios for the heavy duty pathway, it is assumed that diesel costs will see an average annual increase of 3% in the years ahead. Substantial FC bus purchasing cost reductions are expected to materialise, already if about 10,000 automotive FC stacks are produced annually – as outlined above, such a scenario can very likely be achieved before 2030. If bus operators were to pay consumer prices including taxes and without subsidies or the use of diesel fuel is effectively penalised, TCO for FC and diesel buses could increasingly converge.

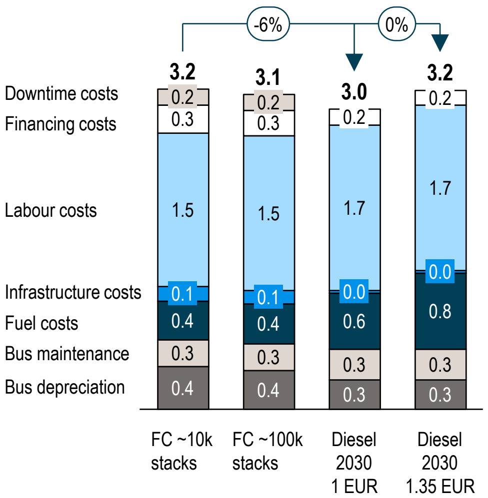


Figure 13: TCO comparison of standard FC and diesel bus in the automotive pathway [EUR/km]

As in the heavy-duty pathway, overall costs can be further reduced depending on local conditions. The same sensitivities as presented above also apply to overall FC bus deployment costs in the automotive as in the heavy-duty pathway: Buses can be depreciated over a longer lifetime of more than 12 years. Additionally, financing costs can be lower than 7% WACC. If also lower feedstock prices leading to lower hydrogen costs apply, indicated total costs can be further reduced. Such a scenario would lead to an even more beneficial cost development that is able to reach complete cost parity with the diesel bus already in earlier years.

To conclude, the cost development of FC buses will see substantial improvements in both pathways. Depending on the specifics of the two presented options, i.e. heavy-duty and automotive pathway, and whether the underlying assumptions materialise, the cost gap to diesel buses can be substantially reduced or even offset entirely. The heavy-duty pathway is linked to cost expectations that depend mostly on the development of the FC bus production numbers. The automotive pathway is directly linked with and depends on the commercialisation pace of FC passenger cars. The assumed cost reduction effects will become available if high volumes (10,000 units or more annually) will be manufactured. Only if these scale effects materialise, additional cost reductions can be seized to further reduce FC bus purchasing costs. The automotive pathway can offer a viable vision for commercialisation due to the lower cost expectations. Nevertheless, it is a technology pathway in the making, for which high volume serial production of FC passenger cars needs to develop.

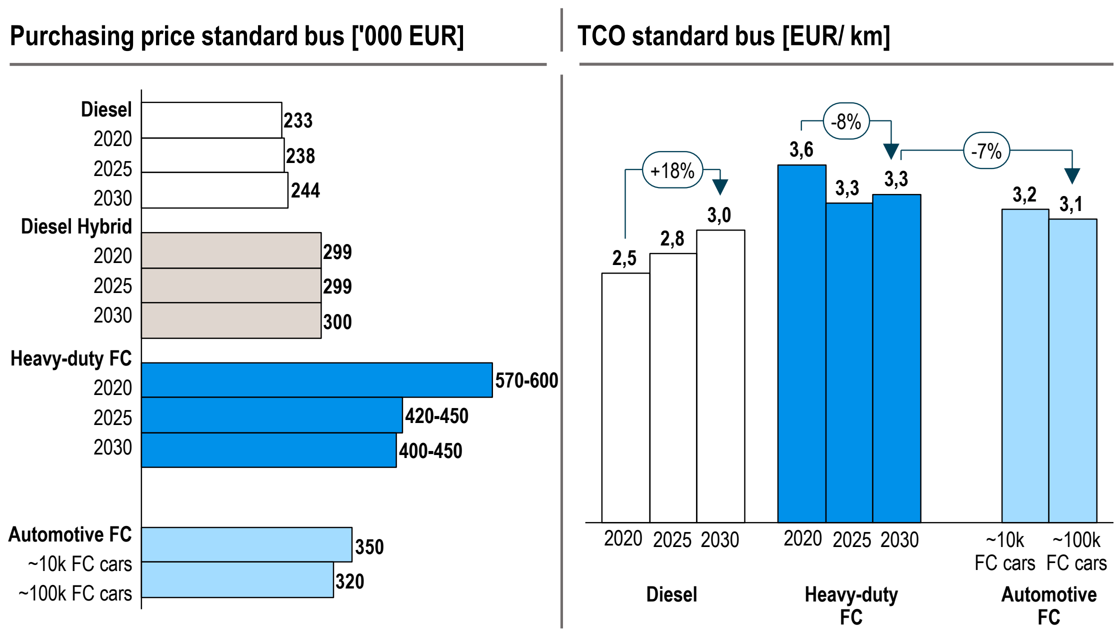


Figure 14: Comparison of standard bus purchasing prices ['000 EUR] and TCO [EUR/km] for different powertrain options and technology pathways

In the following, we will outline why deploying zero emission buses, and FC buses in particular, pays off for European cities and operators.

C. Benefits of investing in FC buses now

KEY MESSAGES

Investing in FC buses bears significant benefits for four reasons:

1. **Politically – There is a push for reducing emissions in public transport in Europe**
2. **Environmentally – FC buses help to reduce noise levels and to green cities and public transport**
3. **Economically – FC buses reduce external costs of public transport**
4. **Operationally – FC buses are the most flexible zero emission option**

Deploying zero emission powertrains is a paradigm shift marking the future of European transport. The following section presents four compelling reasons why FC buses can contribute to enhancing the quality of life in European cities, cut costs and safeguard Europe's energy future, thus inducing enormous direct and systemic benefits.

1. Politically – There is a push for reducing emissions in public transport in Europe

There is a political pressure to shift to lower GHG and local emissions in public transport. Driven by the detrimental impact on the environment, the limited availability of fossil fuels and the dependency on energy supplies from abroad, Europe's societal values and political decision makers are increasingly moving towards a low-carbon future. Regulation has been put in place with more concrete and stricter legislation expected in the years ahead. As mentioned above, the European Commission is committed to reducing its GHG emissions from transport by at least 60% by 2050 compared to 1990 levels. This target is expected to become binding for the member states in the near future. As it concerns local emissions, the EU Directive on Ambient Air Quality and Cleaner Air for Europe stipulates for example limits for harmful pollutants for cities above 250,000 inhabitants. Recently, the EU has launched legal proceedings (incl. fines) against countries that have violated the Directive.

Europeans perceive major environmental problems…

- 50% of Europeans think that **climate change** is one of the three most important challenges our world faces
- 81% say that **air pollution** is an important problem
- 72% of citizens say that **noise pollution** is a problem in their cities

…to be caused by the transport sector…

- 63% feel that **transport is a main threat to air quality**
- 56% of Europeans think pollution can be reduced by improving **public transport**
- 71% of European citizens say that **electric cars are the most environmentally friendly mode of transport**

…and want local authorities to solve them

- 56% of Europeans think that public transport can best be improved by **city authorities**
- 72% of Europe's population believe that public authorities **aren't doing enough to improve air quality**

Source: Eurobarometer "Climate Change" (2014); Eurobarometer "Urban Mobility" (2013); Eurobarometer "Air quality"(2013)

Figure 15: Summary of public perception of environmental challenges in public transport

Some countries and more and more municipalities have already set targets for reducing emissions in the transport sector. For instance, the **Netherlands** have committed to reducing their GHG emissions by 17% compared to 1990 levels by 2030 and by 60% by 2050. As one building block in the strategy towards achieving these ambitious goals, it is stipulated that public bus fleets shall be on zero emission powertrains exclusively by 2025. Recently, the Dutch Parliament asked the government for a common roll-out and investment agenda funded by local, regional, national and EU authorities for a zero emission public bus fleet; the initiative was strongly supported by the Dutch State Secretary. Furthermore, the City of **Hamburg** plans to purchase zero emission buses only from 2020 onwards so that its entire bus fleet is emission-free in the next 15-20 years. The local transport operator for the **Cologne Region**, RVK, plans to convert its entire fleet to alternative powertrains by 2030, while the **Oslo/Akershus Region** aims at running its entire public transport bus from renewable energy sources only by 2020 and cutting its GHG emissions in half by 2030. The City of **London** pursues an ambitious program of introducing low-emission powertrains to its bus fleet and has decided to establish an Ultra-Low Emission Zone (ULEZ) in 2020 in the central city. All these locations are currently testing FC buses in daily operations. Other European national and local governments are expected to stipulate the replacement of conventional diesel buses with zero emission vehicles shortly.

Emission reduction targets for transport in Europe (examples)

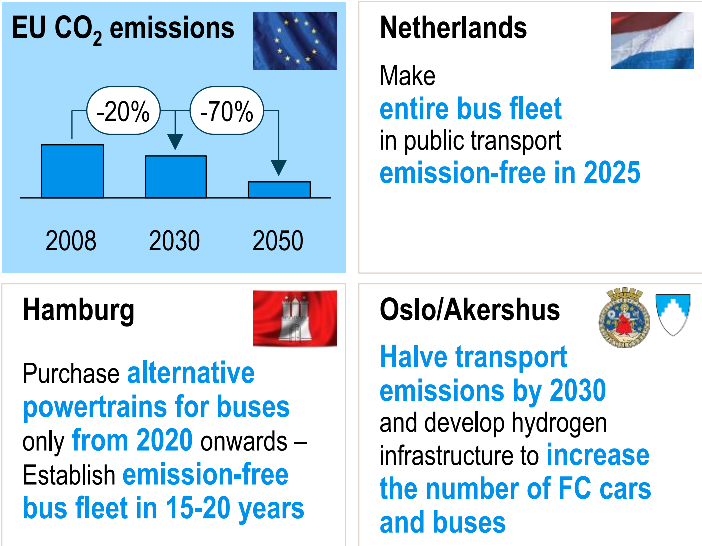


Figure 16: Examples for emissions reduction targets in Europe

Deploying zero emission vehicles now can minimise the potential risk of costly adaptation arising from a need to undertake a rapid replacement of diesel buses later due to possible stricter emissions reduction regulations. As buses in public transport have an average lifetime of 12 years, replacements need to be planned well in advance in order to keep up with regular replacement schedules and use buses to the end of their economic lifetime. In addition, the instalment of refuelling infrastructure, adaption of workshop and training of staff for the use of FC buses requires decent preparation time. Hence, operators that deploy zero emission buses now will be prepared when new regulations come into force and can safeguard reliable service provision also in the future at all times.

2. Environmentally – FC buses are electric buses which significantly reduce emissions

Urbanisation and growth in transport demand are expected to pose significant challenges to European cities in the near future. According to the UN's World Urbanisation Prospect, Europe's urban population is expected to increase from about 71% today up to 80% in 2030[13]. At the same time, the overall volume of passenger transportation is expected to grow by 1.4% annually with road transport to account for about 80% of total transport activity[14]. In order to reduce congestion and limit the emissions caused by road transport, European cities will need to increase the share of public transport and clean up their transportation systems.

The effects of traffic on the population are significant. The European Environmental Agency assessed that 60% of the population of Europe's largest cities are subject to harmful noise levels caused by traffic. The lion's share of the population in Europe's cities breathes dangerous air on a regular basis. Consequently, many European cities resorted to establishing environment protection zones in their centres to preserve local air quality and reduce noise. In some cases, even stronger measures such as circulation bans or speed reductions during pollution peaks have been implemented. The ambitious European and national climate protection goals also require contributions from the transport sector if they are to be achieved. By increasing the share of public transport within urban traffic and the deployment of alternative powertrains, these problems can be tackled.

FC buses make cities cleaner and quieter, thereby increasing quality of life. Emitting water only, FC buses are zero exhaust emission vehicles and can greatly contribute to reducing emissions in cities. Furthermore, they run at significantly lower noise levels. Standing and in motion, FC buses reduce perceived noise levels by almost two thirds compared to conventional diesel buses. With increased public awareness of sustainability and environment protection matters, the deployment of FC buses constitutes an important contribution to reaching emissions reduction targets and can raise a city's attractiveness and standard of living.

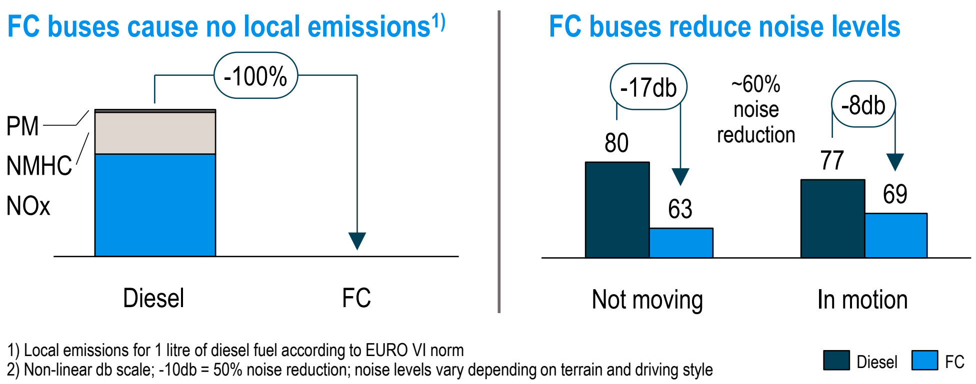


Figure 17: Comparison of local and noise levels of diesel and FC buses

[13] United Nations (UN): World Urbanization Prospect, 2014 revision.

[14] European Commission, DG Energy.

The potential environmental benefits of FC buses extend well beyond zero local emissions. Hydrogen as a road fuel also yields significant potential for carbon neutrality on a well-to-wheel (WTW) basis, i.e. along the entire hydrogen value chain including production and means of delivery. To seize this potential, it is important to increase the share of electricity from renewable energy sources (RES) in the European energy mix. The EU has set as its target to reach a share of 30% RES electricity by 2030[15]. A further increase of the share of RES electricity in the European electricity mix is required to unfold the full potential of hydrogen as a road fuel to become entirely carbon neutral from a WTW perspective.

Water electrolysis is crucial for greening mobility on a WTW basis as it offers a means of hydrogen production with electricity from renewable energy sources such as wind and solar power. Accordingly, zero emissions on a WTW basis can be achieved with hydrogen produced by electrolysis with 100% renewable electricity which is already possible today. If running only on such zero emission hydrogen, one standard FC bus would save approximately 800 tonnes of CO_2 in its lifetime of 12 years compared to a conventional diesel bus (EURO VI model).

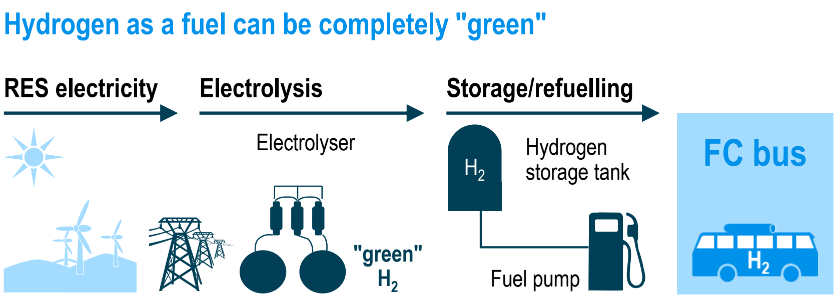


Figure 18: Carbon neutral hydrogen value chain

Operators will need to assess which hydrogen production option is the most viable in terms of reducing CO_2 emissions. Choosing electrolysis as the hydrogen production option does not automatically guarantee a lower carbon footprint on a well-to-wheel basis in all European countries. The carbon footprint of the electricity used for hydrogen production will need to be taken into account. This differs with the energy mix of European countries. For example, in Germany, currently over half of the electricity for hydrogen production needs to come from 100% renewable energy sources in order to achieve lower WTW CO_2 emissions than for hydrogen produced from steam methane reforming (SMR) with natural gas. This is due to the high share of approximately 45% of coal in the current German energy mix driving the carbon footprint. In Norway, with its significant share of hydro power in the energy mix, the carbon footprint of hydrogen produced from electricity off the grid is very small (only 5%) compared to the carbon footprint of hydrogen produced from SMR. Nevertheless, completely "green" hydrogen can already be produced today in all European countries if 100% RES electricity is used for generation, e.g. by wind or solar power being directly connected to water electrolysers or via green energy trading. Naturally, the same considerations apply to any electric bus model deployed: For reducing WTW CO_2 emissions, the carbon footprint of the electricity used for recharging needs to be considered as well as the one used for hydrogen production.

[15] Conclusions adopted by the European Council on October 23/24, 2014.

CO_2 footprint of electricity is crucial

CO_2 emissions of bus fuel (well-to-wheel) in 2015 [kg/100 km]

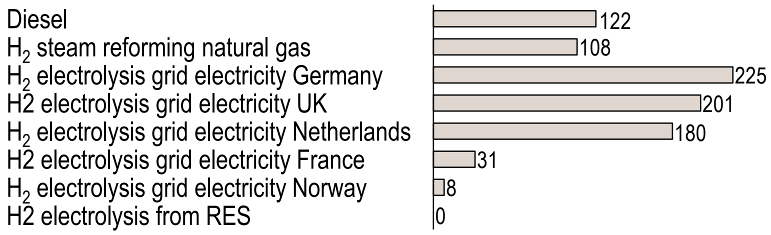


Figure 19: WTW CO2 emissions of diesel and hydrogen in 2015 [kg/100 km]

Currently, FC buses running on hydrogen from SMR have the advantage of zero local emissions while they have slightly reduced CO_2 emissions compared to diesel buses (EURO VI models): With 108 kg per 100 kilometres driven, FC buses with SMR hydrogen account for 14 kg less CO_2 emissions than conventional diesel buses with 122 kg on a WTW basis[16]. Carbon Capture and Storage (CCS) technology is currently in development which can further reduce the carbon footprint of SMR hydrogen by 68%[17]. However, the use of CCS comes with additional risks and costs which need to be analysed thoroughly. Further CO_2 reduction for SMR hydrogen also exists with the use of biogas as feedstock. The use of hydrogen produced from SMR can be an important first step in the early years of deployment from a cost perspective. In the long run, it can be replaced by hydrogen produced from electrolysis with RES electricity to reach full carbon neutrality from a WTW perspective and to significantly reduce CO_2 emissions of cities in Europe.

From a current economic point of view, SMR plays a role for the commercialisation of the technology and for advancing FC buses in the years ahead. The price of hydrogen from SMR is currently approximately 20% lower than hydrogen from electrolysis. As the least costly hydrogen production option in the coming years, it can support bus operators in rolling out zero emission FC buses and achieving the greening of urban transport in the near term while offering the potential for transitioning to zero emissions on a WTW basis in the long run. The hydrogen price from offsite centralised production with electrolysis could be within the range of SMR hydrogen, if low-priced spot electricity and the benefits from offering load balancing services can be seized. The technology to achieve such prices exists and, with a large-scale FC bus rollout, this can become an alternative for bus operators. Water electrolysis is currently the production option of choice in many bus depots where hydrogen is produced on site.

The commercialisation of FC buses can also support the systematic linking of energy and transport systems, as it can give a push to establishing hydrogen as a storage medium for electricity from renewable energy sources. Specifically hydrogen produced from electrolysis can

[16] For CO_2 emissions of diesel buses see FCH JU Study: Urban buses: Alternative powertrains for Europe (2012) and Concawe/ EUCAR/ EC Joint Research Centre: Well-To-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context (2007).

[17] Urban buses: Alternative powertrains for Europe (2012).

be a flexible mode of production, ramped up and down on short timescales. This can help to balance electricity grids, particularly in the face of challenges associated with an increasing penetration of intermittent renewable energy sources such as solar or wind power. Several "power-to-gas" projects producing hydrogen from peak electricity from renewables are currently under implementation in Europe.

3. Economically – FC buses reduce external costs of public transport

Cities can gain direct and indirect benefits that outweigh short-term costs. A study commissioned by the European Union estimates that annual external health, environment and infrastructure costs of buses in Europe amount to approximately EUR 19 bn[18]. The lion's share of these costs can be reduced with zero emission transportation, especially in the areas of noise, air pollution, climate change and energy production. The UK Government has recently estimated the external costs of the public transport system. Annual costs of urban road noise have been quantified at GBP 7-10 bn in England[19]. A study by TNO for the European Federation for Transport and Environment comes to the conclusion that by lowering all traffic noise by 5 db in the EU, savings of external costs of up to EUR 326 bn can be attained by 2030: EUR 8 bn in public expenditure, EUR 89 bn in health benefits and EUR 229 bn in property appreciation[20]. These figures indicate that the potential of reducing systemic costs is enormous and needs to be considered when assessing the direct costs that FC buses are expected to incur.

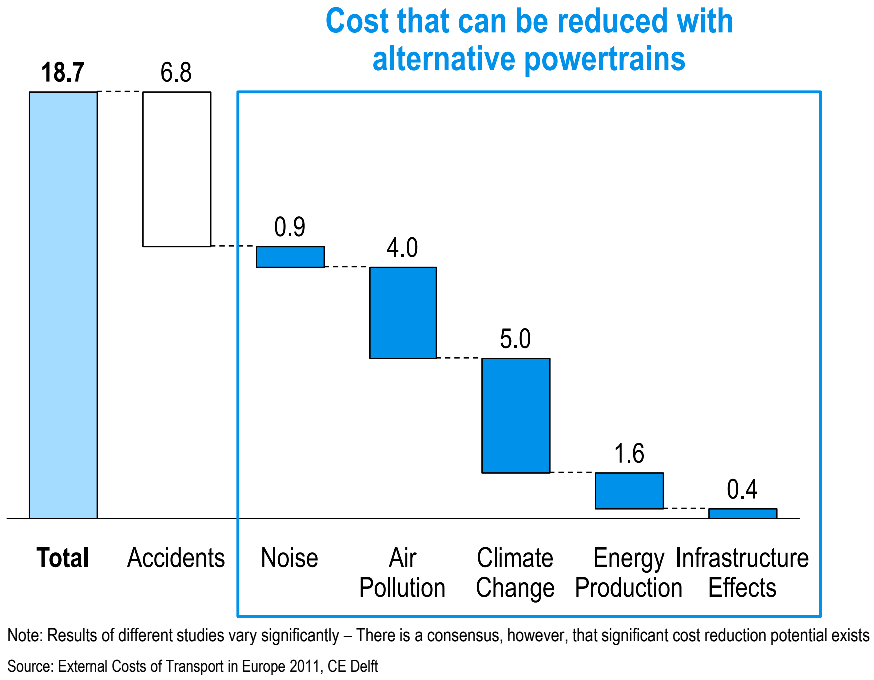


Figure 20: Annual external costs of buses in the EU that can be alleviated by deployment of FC buses [EUR bn]

European economies can greatly benefit from technological innovation. Currently, Europe is home to an innovation base for fuel cell electric vehicles, especially in the area of urban buses. It is currently the most advanced market for FC buses with a number of established

[18] External Costs of Transport in Europe (2011).

[19] Department for Environment, Food and Rural Affairs (2015).

[20] Reduction of vehicle noise emission – Technological potential and impacts (2012).

manufacturers developing the technology. However, US, Chinese, Japanese and South Korean companies are catching up very swiftly and have launched some new technological concepts recently. Promoting the commercialisation of FC buses contributes to securing Europe's technological innovation and high-tech industrial base and related economic benefits. The rollout of fuel cell electric vehicles can trigger long-term positive economic benefits and the associated creation of employment in Europe.

In Germany, FC vehicles rollout is estimated to create an economic value added of EUR 2.3 bn until the year 2020, generating approximately 31,000 additional jobs annually in the automotive industry alone[21]. These figures could be further increased by exporting FC and hydrogen-related technology. A study commissioned by the UK Government produced similar findings estimating that "switching from imported fossil fuels to hydrogen made in the UK would deliver a GBP 1.3 billion annual benefit to the UK economy by 2030"[22]. Hence, promoting the FC industry in Europe can strengthen its position as the leading market and leading supplier of this technology.

Furthermore, FC buses can help reduce the dependency on fossil fuels. Crude oil imports amounted to more than EUR 305 bn in the year 2013 for the EU 27 countries[23] – a large part of them having been used as fuel in the transport sector. The finite nature and instability of fossil fuel supplies from politically unstable regions constitute a major business risk for the European transport sector. Switching to sustainable fuels produced in Europe safeguards secure fuel supply and counteracts increasing diesel prices.

[21] Approaches for Successful Commercialisation of Hydrogen Mobility in Germany (2012).

[22] UK H_2 Mobility - Phase 1 Results (2013).

[23] Eurostat.

4. Operationally – FC buses are the most flexible zero emission option

Several complementary zero emission powertrains are currently available in the market. Besides FC buses, battery overnight, battery opportunity and trolley buses are zero emission options currently available in the market. Trolley buses are continuously powered with electricity by overhead lines along their entire routes across the city. Battery overnight buses are equipped with a large battery that is fully charged during the night at the depot to power the bus during daily operations. Battery opportunity buses have smaller batteries and are charged during the night at the depot as well as during the day at certain points along their routes by conductive or inductive fast charging stations. Depending on their respective operational needs, European cities and regions will need to decide which solution fits best for them. Taking into account their specific characteristics, FC and other zero emission powertrains are to be considered as complementary.

Zero emission option	Daily range	Route flexibility	Refuelling/ recharging time	Productivity
Opportunity E-Bus	+	-	-	-
Overnight E-Bus	-	+	-	-
Trolley	+	-	+	+
Fuel Cell	+	+	+	+ ✓

Figure 21: High-level comparison of operational performance of different zero emission bus concepts

FC buses offer highest operational flexibility and productivity

FC buses offer daily ranges of up to 450 km a day, thus being able to reach the same daily mileage as conventional diesel buses in urban bus systems in Europe. Battery overnight buses only serve significantly reduced daily mileages with one overnight charge of about 180-250 km. Battery opportunity buses can reach higher daily mileages, but only with frequent recharges during the day. Also trolley buses can serve higher ranges, but require overhead lines along their entire routes for constant electricity supply.

FC buses have full route flexibility, as they do not require any infrastructure along the route. On the other hand, trolley buses and battery opportunity buses require recharging infrastructure along their routes, which limits their route flexibility. Additionally, heavy investments in recharging infrastructure across the entire public transport network are required which also has a detrimental impact on the city landscape. City planning and permitting considerations can complicate the installation of city-wide recharging infrastructure.

FC buses require short refuelling times of below 10 minutes which are significantly lower than for battery bus concepts: Battery overnight buses need to be recharged at night for several hours. Battery opportunity buses need limited recharging during the night, but require frequent recharging stops of up to 15 minutes during the day. This limits the total daily operating time which can be achieved with these buses as compared to FC buses. Trolley buses require no refuelling time as they are constantly supplied with electricity by overhead wires.

Due to their operational advantages, FC buses offer increased productivity compared to battery bus concepts. Because of their short refuelling times they can be operated in passenger service the largest part of the day, whereas battery buses require significant time for recharging. Compared to battery opportunity buses they also require no time for refuelling/recharging during the day: As battery opportunity buses need to be recharged regularly during the day, they cannot be in passenger service during these timeframes which lowers their productivity. If the same frequency of schedule needs to be kept as today, it might even be necessary to deploy additional buses on battery opportunity lines, thus driving costs significantly.

Figure 22: Summary of operational advantages of fuel cell buses

Thus, FC buses can be operated like conventional diesel buses. FC buses offer the best operational performance compared to other zero emission options. In terms of acceleration, speed and gradeability, FC buses perform like conventional buses. Due to very low noise and vibration levels, they offer a smooth driving experience and a high degree of passenger comfort. Hence, FC buses have all the advantages of an electric vehicle, but combine these with the operational flexibility of conventional diesel buses.

Pioneering operators show that the technology works in practice

Extensive operational experience with FC buses in regular service has been gathered in the last 15 years. Pioneering bus operators and cities have been operating FC buses on about 8 m driven kilometres in the last 15 years in Europe and demonstrate that the technology works in practice and is safe. Currently, four FC bus projects supported by the FCH JU are ongoing (CHIC, High V.LO-City, HyTransit and 3Emotion). In these and other ongoing demonstration projects, a total of 84 FC buses are being operated or about to start operation in 17 cities and regions in 8 European countries. This number would be significantly enhanced by additional large-scale demonstration projects which are envisaged to be realised until 2020 in the framework of the FCH JU's commercialisation initiative. Whereas in most current battery bus demonstration projects buses are operated on selected or customised routes only which fit to the operational capabilities of these buses, FC buses have proven that they can be operated on normal routes in regular passenger service.

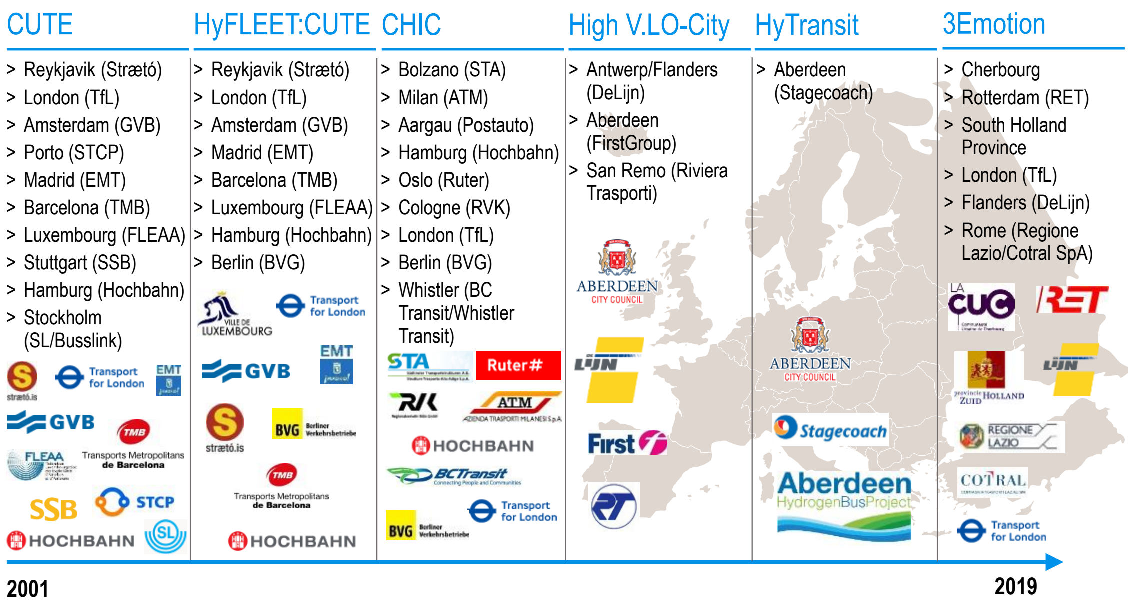


Figure 23: Former and ongoing FC bus demonstration projects

FC buses have reached an advanced stage of technology development since the first deployments in Europe more than 15 years ago. In contrast to first FC bus models, today's FC buses have a hybrid powertrain architecture including a fuel cell and a battery for improved energy management as well as breaking recuperation systems. Thereby, daily ranges could be extended from 60 to 300 and up to 450 km. Fuel efficiency has increased significantly from a consumption of about 25 kg H_2/ 100 km to 8-9 kg today. Required refuelling times have dropped from 25 min on average to below 10 minutes at the moment. Refuelling station availability also has improved significantly. The CHIC project is currently tackling remaining technical issues to improve FC bus availability which are systematically being addressed. Thereby, bus availability levels are now reaching the project target; nevertheless, further improvements are required for commercialisation. With regards to other zero emission powertrains, trolley buses are the most mature and established technology. Battery bus concepts are relatively new to the market and currently being tested in a number of first demonstration projects, in which good availability levels have been reached – even though such buses normally operate in selected or customised routes only which match their operational capabilities. A major challenge for battery bus deployments is the lack of a common standard for recharging infrastructure installations which needs to be overcome for a large scale roll-out.

Major cities support FC buses

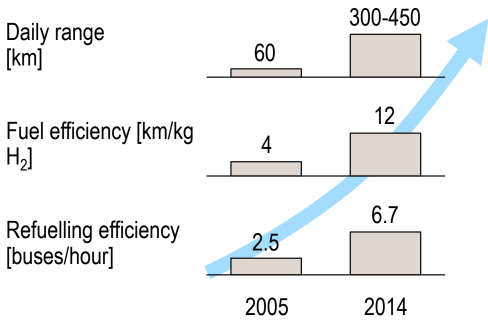
"The City of Hamburg envisages replacing its entire bus fleet by purchasing only emission-free buses from 2020, thereby increasing quality of life for all citizens."
Olaf Scholz, First Mayor of Hamburg

"We want London to be at the forefront of the low-emission revolution and getting these buses on the road is the first step."
Kit Malthouse, Former Deputy Mayor of London

FC technology has developed significantly

> Fuel cell buses and hydrogen infrastructure are rapidly approaching technological maturity, partly driven by past European demonstration projects

> No major safety problems have occurred so far – Currently 54 FC buses are operated in Europe



Source: CUTE Detailed Summary of Achievements; BC Transit Fuel Cell Bus Project, NREL; CHIC – Presentation of Emerging Conclusions; Roland Berger

Figure 24: FC bus technology development and major cities supporting its deployment

D. FC bus coalition and expected deployment of FC buses

A coalition of FC bus stakeholders is driving the progress

The FC bus coalition constitutes the framework of the commercialisation initiative supported by the FCH JU. It comprises local governments from various European cities and regions, bus operators as well as associations and government institutions representing the demand side of public transportation. Additionally, a good number of industry stakeholders such as bus manufacturers, technology providers as well as hydrogen and related infrastructure suppliers represent the supply side.

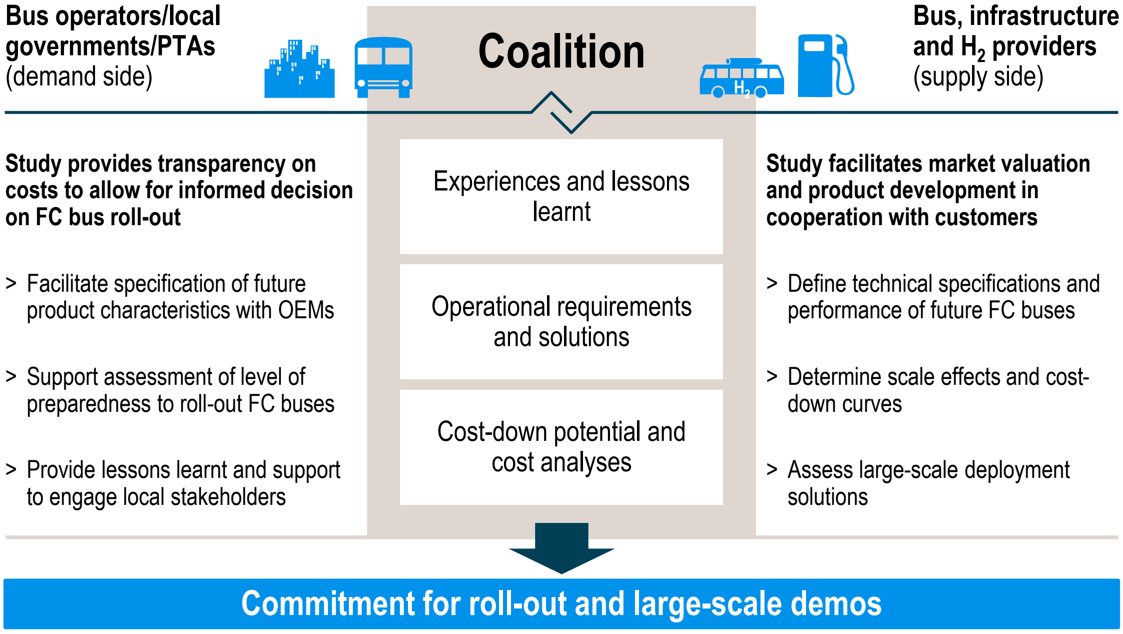


Figure 25: Set-up of the FC bus coalition for commercialisation of FC buses

Currently, 35 European locations are committed to assessing FC bus rollout options. Local governments and bus operators from 35 European cities and regions from 12 different countries are actively engaged so far and further locations are considering joining the FC bus coalition. The FC bus coalition is jointly preparing the path for FC bus commercialisation and facilitates exchange between operators and the industry on future product specifications, performance characteristics as well as the design of infrastructure solutions. Furthermore, it offers a platform for discussing overarching issues related to commercialisation, such as regulatory matters, financing and joint procurement options or operational preparation of bus operators. This initiative aims at supporting public transport representatives in evaluating FC bus deployment options and preparing the way to implementation of demonstration projects in the timeframe 2017 – 2020 as well as at creating long-term commitment beyond 2020.

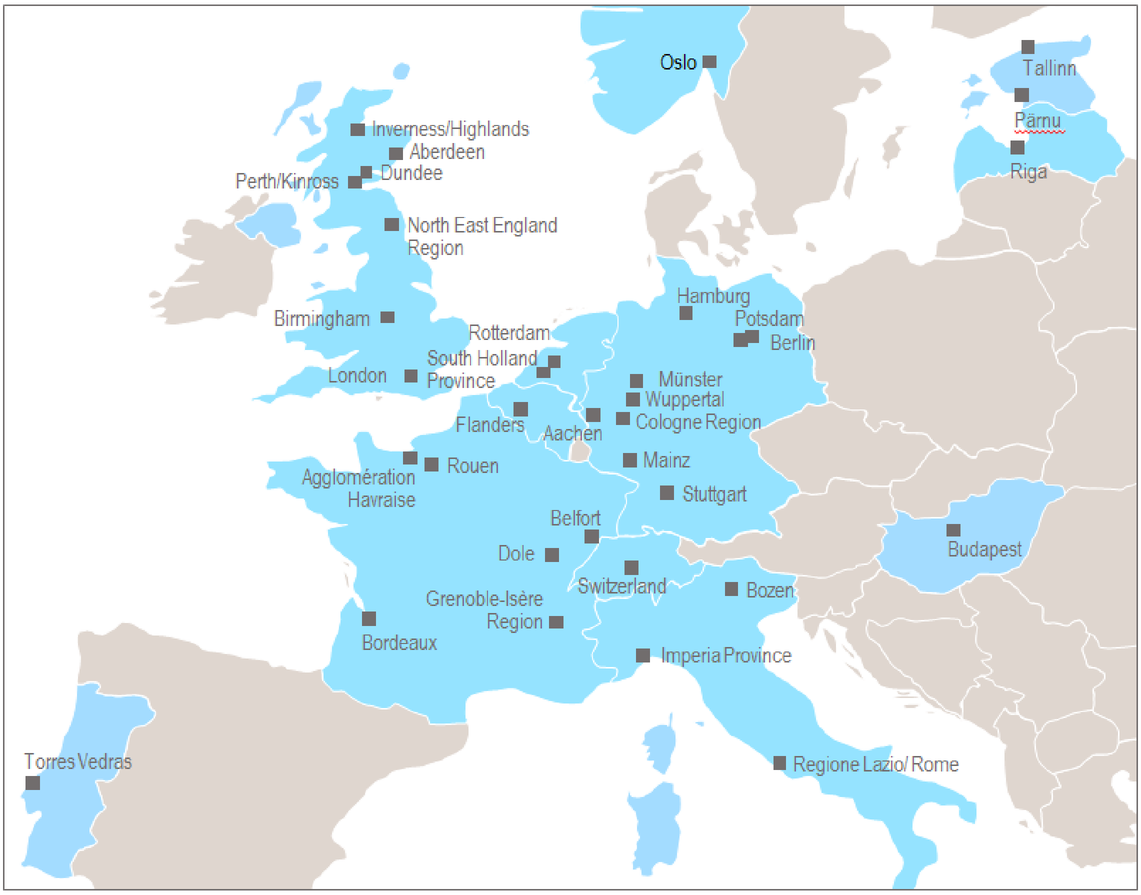


Figure 26: Participating locations by country (as of May 2015)

Bus operators and public administrations have signed a joint Letter of Understanding underlining their interest in future FC bus deployment. The letter is the first public statement of its kind in Europe supported by a significant number of public transport stakeholders. In the letter, the signatories express the need for action in public transport to reduce local and greenhouse gas emissions and to establish sustainable public transport systems for the future. Accordingly, operators underline their intention to deploy FC buses in the next five years. Signatories are convinced that public transport can serve as role model for illustrating the benefits of zero emissions powertrains to societies across Europe. FC buses are considered a viable and the most flexible zero emission powertrain solution. The joint Letter of Understanding was handed over to the EU Commissioner of Transport at the TEN-T Days in Riga on June 23, 2015 and can be found in the Annex to this report. Any operator interested in signing the LoU should contact the FCH JU (see below).

Letter of Understanding of Transport Operators and Public Authorities

The LoU was handed over to the EU Commissioner of Transport at the TEN-T Days in Riga on June 23, 2015

It has been signed so far by **33 organisations** (public transport operators and authorities, governments, transport associations) representing **23 cities and regions**

Bus OEM Letter of Understanding

The LoU was presented to demand side representatives in an Handover-Ceremony in Brussels, 12th November 2014

Left to right: First Mayor Olaf Scholz (Hamburg), Deputy Mayor Kit Malthouse (London), Filip van Hool (CEO Van Hool), Dariusz Michalak (Deputy CEO Solaris), Rémi Henkemans (Managing Director VDL Bus & Coach), Gustav Tuschen (Head of Product Engineering Daimler Buses)

Figure 27: Signees and public presentation of Letters of Understanding prepared in the framework of the initiative

Key industry stakeholders are committed partners in the commercialisation initiative

Fuel cell and hydrogen industry stakeholders support the commercialisation initiative. The supply side is represented by bus manufacturers, technology providers as well as infrastructure and hydrogen suppliers.

All bus OEMs participating in the initiative have signed a joint Letter of Understanding, thereby committing to the commercialisation targets of the initiative. They have expressed their conviction that by deploying significant numbers of FC buses until 2020, the technology will become fully mature and commercially viable, thereby contributing to a significant extent to European climate targets and addressing the future challenges of transport in Europe.

Bus manufacturers

Technology providers

Infrastructure/H_2 providers

Figure 28: Participating industry stakeholders

Hydrogen and infrastructure suppliers are currently developing large-scale infrastructure solutions for future rollout. To realise the large-scale replacement of conventional bus fleets by alternative powertrain solutions, affordable hydrogen supply and infrastructure solutions to cater for large FC bus depots will need to be developed. The FCH JU is supporting the technical design of such solutions by making dedicated infrastructure grants available and industry partners are investing at the same time in bringing forward large-scale solutions needed for full market introduction. Currently, a study on the future engineering design is ongoing.

Many bus operators and cities have already taken important steps to prepare for FC bus rollout

On average, the level of preparedness for FC bus rollout is well developed. Some locations already have FC buses in service and have already completed the most important planning and rollout steps, others are beginning to explore FC bus deployment options. Several areas have been identified in which participating locations currently see challenges for their rollout preparations: Assessing and complying with regulatory and safety requirements, identifying the most suitable infrastructure solution, securing local stakeholder support to switch to a potentially more costly technology as well as acquiring funding to close the expected financing gap to the diesel bus.

Operators and cities with experience in FC bus rollout demonstrate that challenges can be overcome. There are a number of coalition members who are well advanced in preparing for a large-scale rollout. For example, they have successfully fulfilled all requirements for the safe operation of FC buses and have successfully undertaken permitting processes to acquire new land for a large-capacity infrastructure in densely populated urban areas. In these locations, local governments are firmly committed to the rollout and have allocated funding to support operators in closing the cost gap. Other bus operators and local governments can benefit from their experiences in the framework of the initiative.

Within the coalition, several regional clusters of 5-10 cities and regions have been formed to jointly prepare large-scale FC bus demonstration projects. As framework conditions in terms of regulatory regimes, the structure of public transport as well as procurement systems differ between the European countries, the formation of regional clusters on a national level has been identified as a viable approach for the preparation of demonstration of FC bus projects within the coalition. Within the clusters, participants jointly work on mobilising and combining local, national and European (FCH JU) co-financing. Regional clusters with operators/local governments and, partly, with industry representatives are currently established for France, Germany, the Netherlands/Belgium, UK/Scotland and the North East of Europe. Interested locations are invited to join the regional clusters, but also individual locations from outside these regional clusters are welcome (see details at the end of this report).

Jointly procuring FC buses is expected to achieve price reductions. On the one hand, joint large orders provide the necessary volumes for the industry to further develop the technology and realise significant price reductions. On the other hand, joint large orders are expected to have a favourable impact on competition in the market and to create an additional incentive for the industry to reduce prices. While joint procurement on national or European levels is enshrined in European legislation and is encouraged by the European Commission specifically for the procurement of alternative powertrain vehicles, several practical questions are currently being solved by the participants. This concerns, for example, the standardisation of bus specifications, the harmonisation of bus procurement schedules as well as the conceptualisation of a contractual framework for joint procurement. These questions are currently being discussed in the regional clusters and approaches for implementation will be further developed with the support of the FCH JU during the next phase of the initiative.

Current planning for FC bus rollout within the coalition underlines the interest in the technology

Cities and regions currently represented in the coalition constitute a significant market potential for FC buses in the coming years. In total, all participating locations currently operate about 30,000 buses in their public transport systems. This represents approximately 8-10% of the current estimated total bus fleet in the EU 28, Switzerland and Norway, thereby constituting a significant share of the bus market in Europe[24]. Assuming a standard bus lifetime of 12 years, approximately 2,500 buses need to be replaced annually in the bus fleets of participating locations. If all the buses in the participants' bus fleets were to be replaced by FC buses using hydrogen produced from 100% RES electricity, about 2 m tonnes of CO_2 could be saved annually.

Currently, some of the participating locations envisage deploying between 20 or more FC buses by 2020. The envisaged size of future potential FC bus fleets differs between the participating locations, depending on their prior experience with alternative powertrains and the political commitment of their respective local governments. A part of the current coalition members plans to deploy 20 or more FC buses by 2020. Hence, a number of 300-400 FC buses could be achieved, provided that already engaged cities and operators obtain the required funding support from different sources to roll out FC buses.

The initiative will give a major push to further market development by quadrupling the current number of FC buses in operation in Europe. At the same time, such a large-scale deployment of FC buses will support scale effects and cost reductions as expected in the niche scenario of the heavy-duty pathway. This is an important contribution to the future development of the market. By creating sustainable and sufficient demand for the FC buses, the further technology development to full maturity and significant cost reductions will be supported. The initiative constitutes an important step towards reaching commercialisation in the sense of serial production, improved cost competitiveness and sustainable demand without public subsidies. The development of a fully commercial market will however require additional future efforts by all market stakeholders. The study and coalition offer a systematic approach to FC bus rollout and, thereby, lay the foundations for supporting the transition process so that commercialisation can be achieved.

Current trends in public transport drive the change to zero emission powertrains in the next years worldwide and in Europe in particular. In the last years, several new powertrain options

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[24] Estimation based on Eurostat data and European Commission: Study of passenger transport by coach (2009). Eurostat data indicates that size of bus fleet overall remained stable since 2009. Estimation excludes coaches. Please note that definitions of buses and coaches differ. Overall data availability is very limited; hence, estimation is very preliminary only.

and alternative fuels have become available in the market offering new opportunities for greening public transport systems: Biofuels (biodiesel, biogas and bioethanol) as well as hybrid, plug-in hybrid, battery and fuel cell bus models. Ongoing FC bus demonstration activities currently take place in 14 European cities in FCH JU-funded projects; further individual small-scale demonstration projects are also ongoing. In the Zero Emission Urban Bus System (ZeEUS) project, 10 European locations are testing different battery and plug-in hybrid bus concepts. Numerous other cities and regions are investing in hybrid, plug-in hybrid and electric buses at the moment. Currently, the deployment of all of these solutions incurs a cost premium compared to conventional diesel buses. These initiatives illustrate the readiness to invest in alternative powertrains and to attain immediate environmental benefits despite partly severe funding constraints in public transport. Additionally, many cities invest in upgrading their public transport system to provide better service quality to their citizens, for example by installing BRT (Bus Rapid Transit) services or tramway systems. In principle, these cities also constitute a market potential for zero emission powertrains offering environmental benefits and an improved customer experience.

The market share of zero emission powertrains is expected to grow significantly until 2020. The total bus market in Europe is expected to grow about 3-5% annually until 2020. Whereas the share of zero emission powertrains is difficult to estimate and is dependent on several important framework conditions (e.g. regulation, public transport financing, technology development), all currently available market analyses expect a significant increase in the share of zero emission powertrains in future bus orders. Findings from a UITP survey from 2013 among 63 cities in 24 European countries indicate that that 60% of the respondents are willing to renew their fleet's composition and that 40% would like to invest in electric powertrains (hybrid and fully electric vehicles).[25]

Required deployment levels for commercialisation can be reached in a European ramp-up scenario. This scenario considers deployment plans of operators in the coalition as well as operators that yet need to be mobilised. The framework of this scenario is the assumed total cumulative volume of 8,000-10,000 FC buses required until 2025 to reach the cost projections of the production-at-scale scenario of the heavy-duty pathway. The 35 currently participating locations of the FC bus coalition are committed to deploying 300 to 400 FC buses until 2020 in the framework of this initiative. These are included in the ramp-up scenario. Beyond 2020, it is assumed that these locations start replacing larger parts of their fleet with FC buses within their regular annual replacement schedules: It is assumed that these pioneering locations deploy 20 FC buses each in 2021 and continue to deploy up to 40 FC buses each year until 2025. This would sum up to 1,400 FC buses in 2025. In order to reach the target number of 8,000 buses, further locations willing to deploy FC buses need to be engaged. For the ramp-up scenario as shown below, it has been assumed that from 2015 onwards each year 15 new locations can be attracted which intend to deploy FC buses in the future. This number conservatively reflects the growth rate of the existing coalition in its first year. If these additionally mobilised locations start deploying FC buses from 2021 onwards with a modest annual deployment schedule of 10 FC buses going up to 15 buses in 2025, significant volumes of FC buses can be reached (see

[25] UITP (2013).

Figure 29). Alternatively, a more limited number of locations would need to start deploying higher volumes of FC buses each from 2021 onwards; if the current number of 35 participating locations is not increased, each of these locations would need to deploy about 50 FC buses annually from 2021 onwards to reach the target cumulative volume of 8,000-10,000 FC buses by 2025.

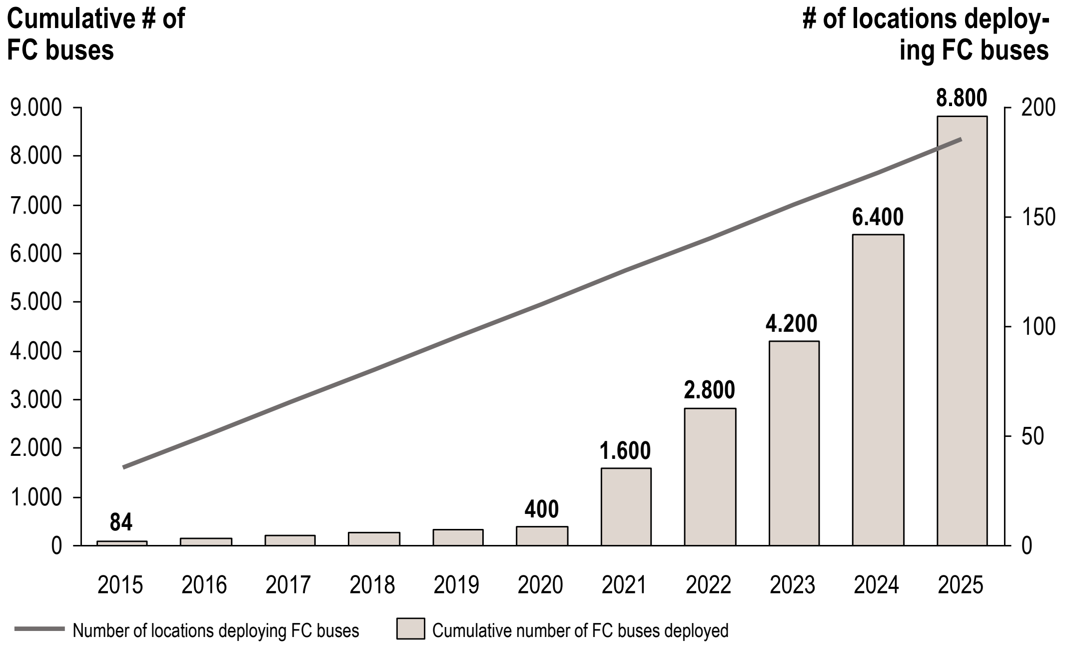


Figure 29: Ramp-up scenario for FC buses in Europe

E. Next steps and how to get involved in the FC bus coalition

The pathway to clean transport has been prepared – now is the time to engage

The FC bus coalition is committed to taking the next step in market development. 45 local governments and public transport operators from 35 European cities and regions have formed a strong coalition with the industry to prepare and implement large-scale demonstration projects. Extensive operational experience has been gathered and high technology maturity has been reached with ongoing demonstration projects. Now is the right time to act - a strong European network and EU support scheme are available to provide funding support and share accumulated knowledge and lessons learnt.

The FCH JU manages a dedicated funding program to support commercialisation of hydrogen and FC technologies. During the period 2014-2020 approximately EUR 650 m have been allocated to realise all FCH JU projects. A part of these funds is expected to be allocated for large-scale FC bus demonstration projects. Locations willing to go forward with FC bus rollout shall have the opportunity to apply for FCH JU grants to co-fund their projects.

The zero emission future is coming – act now to be prepared. Early engagement allows to realize the benefits of zero emissions today, to build up in-house knowledge and practical experience as well as is an active contribution to taking responsibility for preparing the future of our public transport systems. Acting now avoids the risks associated with making a rapid shift later when stricter regulation has come into force.

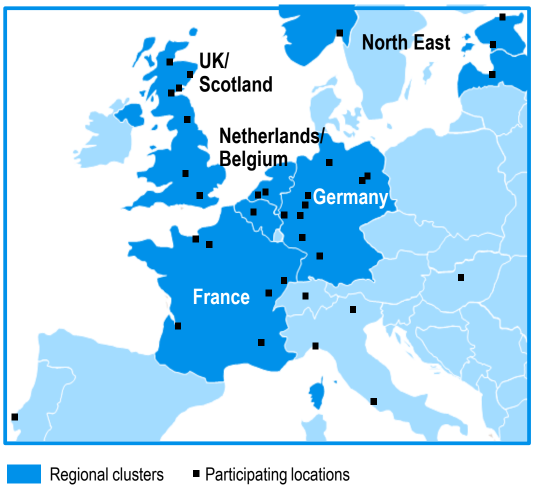
All stakeholders need to engage in a joint effort to reach commercialisation

The industry needs to further develop their products and offer competitive prices in order to allow for large-scale deployments of FC buses. Significant cost reductions both for FC buses and related infrastructure in terms of investment and operations costs are required to reduce overall costs. Similarly, the cost-efficient hydrogen prices as presented in this study are required to achieve competitive operational costs of FC buses. Additionally, products need to be developed further to reach full technological maturity and improved reliability. Suitable service support needs to be in place to allow for operation of larger fleets.

Making large-scale demonstration projects to foster commercialisation requires support from local and national authorities. This involves, firstly, financing parts of the cost premium in comparison to conventional diesel buses, and, secondly, assessing which regulation promotes alternative powertrains best, e.g. reducing subsidies for the operation of diesel buses, ensuring a competitive tax regime for hydrogen as a fuel, simplifying permitting procedures for the construction of new refuelling infrastructure and bus depots, etc. During the next phase of the initiative, participating locations and regional clusters will need to mobilise the required match funding at national and local levels.

Further cities and operators need to engage and jointly prepare for large-scale deployment projects. Preparing joint procurement of FC buses is expected to stand at the centre of the work in regional clusters. Jointly procuring FC buses in cooperation with other bus operators and/or public transport authorities in the same region can help to achieve the scale effects required for a price reduction. Joint procurement will require dedicated structuring, coordination and preparation among participants, especially against the background of comprehensive procurement regulations in the European Union.

Regional clusters



Next steps

1. **Developing a European cooperation approach** for all participating locations
2. **Defining a viable joint deployment schedule** to take part in FCH JU calls
3. **Developing a joint procurement approach** to drive down purchasing costs
4. **Mobilising required match funding** from governments and other funding programs
5. **Mobilising further locations to join the initiative** to increase impact on market
6. **Disseminate know-how and lessons learnt** to help preparing for demo projects

Figure 30: Regional clusters of the FC bus coalition and next steps in the initiative

Participating in the initiative offers several advantages

Participants have access to a broad knowledge base and a number of useful tools[26]. Within the coalition, experienced cities and operators share their experiences and lessons learnt in FC bus deployment. Dedicated knowledge and information sharing activities are carried out. Furthermore, the coalition provides easy access to industry partners which are active in the field. A number of useful tools have been developed which participants can access: The self-assessment questionnaire helps to evaluate the respective level of preparation that interested cities and operators have already reached and shows in which areas further work is required. The cost assessment tools allows for a calculation of individual FC bus deployment costs depending on respective envisaged deployment schedules and local costs for e.g. feedstock, labour, financing etc. Furthermore, useful communication material has been prepared which supports discussions with local stakeholders.

[26] Also available at www.fch.europa.eu.

1 **Exchange experiences and lessons learnt** with coalition members who have already realised FC bus projects

2 **Establish contacts** to bus OEMs, infrastructure providers and H_2 suppliers as well as other bus operators which can be useful for own project developments

3 **Get insights in future expected costs** for FC bus deployment develop an individual high-level cost analysis for your location

4 **Receive support in communication** to convince politicians and the public to support deployment of FC bus technology

5 **Partner with other cities and operators** to realise potential cost savings from combined purchases

6 **Gain the opportunity to receive funding** from the FCH JU in the next phases of the initative

Figure 31: Overview on benefits of participation in the initiative

Participants jointly prepare for participation in future FCH JU calls to receive funding support. In the first phase of the initiative, a structured approach for realising commercialisation has been formulated which is now being set into practice. Participating in the joint work of the coalition is the optimal way to prepare for participation in future FCH JU calls to receive European funding support for FC bus demonstration projects.

If you wish to receive more information or engage in FC bus commercialisation, get in touch:

FCH JU Project Manager: Mr. Carlos Navas, carlos.navas@fch.europa.eu

Also see www.fch.europa.eu for further information.

Annex

Annex 1 – Letter of Understanding of Public Transport Operators and Public Authorities

Letter of Understanding

On the deployment of fuel cell electric buses in urban transport in Europe

From The signatory public transport operators and public authorities

To Whom it may concern

Preamble

The greenhouse gas effect and its impact on the world climate have been at the centre of political, societal and corporate attention in recent years. There exists a common understanding in Europe that CO_2 emissions need to be significantly reduced in the near future. At the same time, reducing noise levels, preserving local air quality and limiting harmful pollutants have become a pressing issue for many cities and regions throughout Europe. While increasing urbanisation and growing demand for mobility necessitate action, there is a common understanding that increasing the share of public transport and promoting zero emission powertrains are important levers for reducing harmful emissions. It is expected emission reduction measures will also be required from future European legislation.

In addition, fossil fuels will become increasingly scarce in the coming years with an expected significant rise in fuel prices which constitutes a major cost and operational risk to public transport operators. Starting a transition process now to sustainable public transport solutions avoids the risk to do a rapid shift later when stricter regulations have been set in place and dependency on fossil fuels is setting public transport operations at risk.

Fuel cell electric urban buses are a viable alternative powertrain solution that is a key lever to reducing emissions in public transport. They have been operated on more than 5.5 m kilometres on European roads by pioneering cities and bus operators proving that the technology works in practice and that it is safe. Fuel cell electric buses are the most flexible zero emission alternative as they can be operated like conventional diesel buses with ranges of 300-450 kilometres per tankful while offering the advantages of all electric vehicles: zero tailpipe emissions, reduced noise and vibration levels and, therefore, high passenger comfort. While bearing many advantages, fuel cell electric buses are expected to incur a limited cost premium compared to conventional diesel buses in the years ahead.

Common objectives of the signees

In line with the objectives as defined by the European Union and its Member States, we, the undersigning European bus operators, cities and regions, aim at reducing local and greenhouse gas (GHG) emissions and establishing sustainable transport systems for the future. We acknowledge our responsibility for preserving local air quality as well as reducing noise levels and are convinced that public transport can serve as role model, illustrating the benefits of zero emissions powertrains to societies across Europe.

Accordingly, we, the public and private transport operators as well as cities and municipalities as listed below, intend to deploy and integrate fuel cell electric urban buses into our bus fleets within the next five years. We consider fuel cell bus deployment as part of a long-term shift of our fleets to alternative and zero emissions powertrains. As part of the European initiative for the commercialization of fuel cell electric buses facilitated by the Fuel Cells and Hydrogen Joint Undertaking, the coalition of signing public authorities and bus operators intends to deploy in total of 300 – 400 fuel cell buses as a first step in Europe in the time frame 2016 to 2020. We expect that the costs for this deployment of FC buses comply with the results of the analysis that has been carried out in the context of the fuel cell bus commercialization initiative.

We herewith express our commitment and readiness to take a part of the operational risk of introducing a new technology and to allocating resources to manage the overall deployment, including the construction of hydrogen refuelling infrastructure and the adaptation of our workshops to meet safety requirements. We are furthermore aware that we will need to contribute a part of the additional financial resources associated with the introduction of the new technology within the initial market phase.

In order to achieve the necessary scale effects and the expected price reductions from technical optimizations until adequate market prices for fuel cell buses, we intend to jointly procure fuel cell buses with other public authorities and bus operators – thus aiding commercialization.

Prerequisites of deployment of fuel cell buses

Our commitment is based on the understanding that the financial burden and operational risk of introducing this new technology need to be carried jointly by all involved stakeholders. Suitable support and funding mechanisms need to be put in place at EU and/or national levels in order to match our commitment to financing a part of the additional burden.

Furthermore, our commitment is based on the understanding that suitable bus models as well as service and support systems are available on the market which fulfil the performance requirements necessary to provide reliable public transportation services. While we acknowledge that a limited cost premium for the new technology needs to be taken into account in the next years, it is paramount that the current purchasing price of fuel cell buses is being reduced further.

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establishing sustainable transport systems for the future. We acknowledge our responsibility for preserving local air quality as well as reducing noise levels and are convinced that public transport can serve as role model, illustrating the benefits of zero emissions powertrains to societies across Europe.

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List of Signees

Aberdeen City Council (United Kingdom), also on behalf of

Dundee City Council (United Kingdom)
Highland Council (United Kingdom)
Perth and Kinross Council (United Kingdom)
HITRANS (Highlands and Islands Transport Partnership) (United Kingdom)
NESTRANS (Transport Partnership for Aberdeen City and Shire) (United Kingdom)
Scottish Cities Alliance (United Kingdom)

Akershus County (Norway)
Autonome Provinz Bozen - Südtirol (Italy)
Syndicat Mixte des Transports en Commun (SMTC) du Territoire de Belfort
Birmingham City Council (United Kingdom)
BKK Centre for Budapest Transport (Hungary)
Bordeaux Métropole (France)
ESWE Verkehrsgesellschaft mbH (Germany)
Greater London Authority (United Kingdom)
HOCHBAHN (Hamburg) (Germany)
Hansabuss AS (Tallinn) (Estonia)
Hansa Bussiliinid AS (Tallinn) (Estonia)
Mainzer Verkehrsgesellschaft (MVG) (Germany)
Ministerium für Bauen, Wohnen, Stadtentwicklung und Verkehr des Landes Nordrhein-Westfalen (Germany)
City of Oslo (Norway)
Pärnu City Government (Estonia)
Regionalverkehr Köln (RVK) (Germany)
Rigas Satiksme (Latvia)
Rotterdamse Elektrische Tram (RET) (Netherlands)
Ruter AS (Norway)
Stadtwerke Mainz (Germany)
Stuttgarter Straßenbahnen (SSB) (Germany)
Verband Deutscher Verkehrsunternehmen (VDV) (Germany)
Verkehrsverbund Rhein-Ruhr (VRR) Germany)
ViP Verkehrsbetrieb Potsdam (Germany)
Wuppertaler Stadtwerke (WSW) Mobil (Germany)

One additional PTO from a major German city

Annex 2 – Letter of Understanding of bus OEMs

Letter of Understanding
On the Development and Market Introduction of Fuel Cell buses

From EvoBus, MAN, Solaris, Van Hool, APTS/VDL
To To whom it may concern

Preamble

Projections made by the International Organization of Public Transport (UITP) based on models of the International Energy Agency have demonstrated that, by 2025:
- 60% of the world population (4.5 bn people) will be living in urban areas
- Mobility in urban areas will increase by 50% compared to 2005
- The number of trips by privately owned motorized vehicles will increase by 80%

As a result, the GHG emissions and urban traffic fatalities will increase both by 30%.

In a business as usual scenario, the situation is unsustainable. Our generation has both the responsibility and the technical means to act now.

Public transport, in particular heavy duty urban buses, can play a major role in reversing this negative spiral for it has attractive market characteristics and provides operational prerequisites that are supportive of a technology launch.

Over the last decade, governments and the industry have given special attention to the introduction of hydrogen as a road transport fuel. Whereas hydrogen is not the only answer to the challenges ahead, it offers an effective way of coping with them:
- Zero tailpipe emissions, reduced well-to-wheel emissions, noise levels and vibrations
- Meets the energy challenges when using renewables
- Allows the development of a green economy and jobs

1. Market characteristics

Public entities or private operators acting in a legal public framework provide public transport. Hence, the markets are meeting political and environmental objectives (such as affordable and improved mobility, city air quality concerns, CO2 emissions, renewable energy policies). The public procurement process allows for regulated competition and funding is structured differently than for private mobility.

2. Operational prerequisites

Urban bus applications with stop-and-go traffic, changing loads, low commercial speed in all climates with virtually non-stop operation, are among the harshest service conditions. Hence it is believed that this application will help further mature the technology, driving cost down while increasing durability and reliability of fuel cells.

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Within this extreme application environment, a set of operational conditions are favorable:
- Only depot refueling stations are required as the buses resume their departing point at the end of the day;
- A controlled operating environment: skilled drivers and trained mechanics.

3. Development and Roll-out of Hybrid Fuel Cell Buses

All signing Bus OEMs believe that a gradual and consistently growing number of fuel cell buses are required to reach the level of integration needed to make an impact.

Whether derived from automotive stacks or designs for heavy duty application, the hybrid fuel cell buses will, together with the latest battery technology, allow for the operational prerequisites of urban bus service: flexibility, operational range and reliability, at an acceptable premium and competitive to other zero local emission alternatives.

To achieve these goals, the signing bus OEMs anticipate that between 2017 and 2020 around 500 – 1000 urban buses can be put in service. As the bus industry is diverse, it is expected that various models, ranging from 8 meters to 24 meters, will be developed to meet specific market and application requirements. Each OEM will make its own judgment to develop, demonstrate and offer standard mainstream and/or niche products in the above time frame.

The above target is expected to be subject to supportive EU, national and local policies and continued reduction of vital cost components, including:
- Continuing funding schemes (public and private)
- Impact of the new European Directive on Clean Fuels
- Cost of fuel (in particular the discrepancy between the kWh price of electricity and green hydrogen), the cost of the fuel cell and the cost of the battery

It is expected that by 2020, the products will be commercial to the point that the above volume is reached and the above conditions continue to develop favorably. This implies that the purchase cost of the bus compared to a standard diesel bus will need to be supported or compensated by the CO2 abatement cost and the cost of the other pollutants in accordance with the European Directive.

The hydrogen refueling infrastructure should be put in place on a commercial basis, i.e. that the energy providers have their own programmes to develop, fund and implement the infrastructure based on each specific business case. Unlike private cars, the infrastructure and energy providers for urban bus application will know exactly what the fuel supply needs to be, at what cost it becomes competitive and are able to conclude multi-annual contracts with the operators.

In support of the above understanding, the parties hereto have signed this letter of understanding on the date(s) set herein below.

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Annex 3 – Cost analysis principles, methodology and assumptions

Cost projections for FC buses in Europe have been developed in an interactive process

Reliable cost projections for FC buses are crucial to the commercialisation initiative. In view of limited public budgets of many municipalities and public bus operators as well as the tight cost planning of private operators, making available cost projections for purchasing and operating costs of FC buses are crucial to inform the decision-making process to rollout FC buses. The cost projections presented in this report provide a first high-level indication to operators. They have been developed in an interactive process and joint exercise with the coalition industry partners, i.e. bus manufacturers, technology providers, infrastructure manufacturers and hydrogen suppliers.

The study follows six guiding principles for the cost analysis

1. Market orientation – Technological solutions considered and prices presented are available on the market and reflect industry expectations. Not only did the Clean Team ensure the validity of the data points obtained, they also verified that they are based on assumptions which are reasonable for market conditions.

2. Least costly option – Overall, the study presents the least costly options. In order to show the potential of the technological solutions, the Clean Team identified, compiled and presented the lowest data points provided to arrive at the final figures while ensuring the figures are reliable.

3. Comparability – Comparability of the data presented is ensured by verifying that figures provided and presented are based on the same assumptions. Not only was this methodology used when calculating the least costly option of data points, but also when considering underlying macroeconomic factors as well as comparing costs of FC buses with those of diesel buses.

4. Technological development –Increasing efficiency is dynamically reflected in the data presented. For example, technological gains in FC bus availability and fuel consumption are considered. A bus purchased in 2015 is considered to have a lower availability throughout its lifetime than a bus purchased in 2020 or later. Additionally, the overall fuel consumption of FC buses is expected to decrease as new bus models are brought to the market and the overall technology develops.

5. Sensitivities – The effect of influencing factors have been assessed in a sensitivities analysis. Besides the base case calculations, sensitivity analyses were performed to help operators envisage the potential effects of varying different base assumptions. Overall, this approach allows the study to portray a realistic base case and show more optimistic and conservative scenarios. Sensitivity analyses were performed for three parameters: Feedstock prices (electricity and natural gas), financing costs and bus lifetime.

6. Confidentiality of industry data – A Clean Team approach was applied for sanitising and anonymising the detailed data points obtained from coalition members in three steps. First, the Clean Team confirmed the validity of information sets obtained. Second, the Clean Team sanitised and anonymised all data provided by coalition members. Third, the Clean Team considered expert figures if needed to ensure data sets were fully anonymous. Overall, at least four data points were used in each figure presented.

The study presents two scenarios for cost development in the heavy-duty pathway

Two scenarios are presented in order to account for potential variations of the future market size of FC buses as well as the speed at which the fuel cell technology will develop. These scenarios portray the variance of the potential costs depending on efficiencies and economies of scale achieved with varying market sizes and the related overall technological progression. The scenarios reflect the effect that economies of scale have on related cost-down curves and prices.

Scenarios	2015-2016	2017-2020	2021-2025	2026-2030
Niche				
No. of FC buses produced yearly by each bus OEM	30-50	50-80	80-120	80-120
Total # FC buses	180-300	600-900	1,200-1,800	1,200-1,800
Production-at-scale				
No. of FC buses produced yearly by each bus OEM	80-120	120-500	500-1,500	500-1,500
Total # FC buses	480-720	1,440-6,000	7,500-22,500	7,500-22,500

Figure 32: FC bus market development scenarios

The niche scenario considers a conservative deployment schedule. It is assumes that each FC bus OEM is considered to produce between 30 and 50 FC buses in 2015 through 2016 and increase this amount to 80 to 120 FC buses by 2021 through 2030. Accordingly, a total market size of 600-900 FC buses is assumed in 2020 and up to 1,800 buses in 2030. Hence, the niche scenario presents a conservative cost estimate, a limited deployment and limited scale effects.

The production-at-scale scenario is more optimistic in that it assumes higher production levels and higher scale effects, leading to a lower cost. This scenario considers 80 to 120 buses are produced per bus OEM in 2015 to 2016 and this amount increases to 500 to 1,500 by 2021 through 2030. Accordingly, a total market size of up to 6,000 FC buses is assumed in 2020 and up to 22,500 buses in 2030.

Synergies with adjacent industries and global fuel cell technology deployment are assumed in order to factor in the price reductions resulting from technology gains and scale effects globally. However, the synergies considered for the heavy-duty pathway are limited in their impact as only overall production scale effects are assumed. Components are still assumed to be specifically designed and manufactured for the use in urban buses alone. Synergies are considered from industries such as fuel cell passenger cars, fuel cell forklift trucks, fuel cell stationary backup applications and electric vehicles.

The following volumes were considered for the compilation of price projections and relevant synergies:

	Industry	2014	2015-16	2017-2020	2021-2025	2026-2030
Realistic assumptions (global annual production per OEM)	FC passenger cars	100-300	750	2,000	20,000	175,000
	FC forklift trucks	5,000	8,750	22,500	75,000	120,000
	FC stationary backup applications	2,000	3,000	7,000	25,000	50,000
	BEVs/PHEVs	10,000-40,000	40,000	70,000	125,000	175,000

Figure 33: Synergies with adjacent industries

Cost projections in the automotive pathway base on expected developments of the FC passenger car market

FC bus costs in the automotive pathway have been calculated based on the assumption that the same type of FC stacks and batteries can be used in FC passenger cars and buses. Therefore, additional synergies compared to those assumed in the heavy-duty pathway scale scenario have been considered. The potential for these cost reductions has been analysed by several specific technology and cost assessments carried out by TIAX, the U.S. DoE and in the framework of European projects funded by the FCH JU, such as AutoStack and AutoStack-Core. Future FC bus costs in the automotive pathway have been compiled in an independent assessment based on a component level of FC buses. The data is provided and supported by industry experts as well as the available studies cited above. The FC stack size was assumed at 100 kW, the battery size at 50 kW and the H_2 storage at 45 kg.

	Assumptions
Fuel Cell Stack	> FC stack with 100 kW for standard FC bus > FC stack development from car industry can be fully transferred to bus industry > Number of stacks produced: 1,000 in 2015; 10k in 2020; 100k in 2030 > 1 stack replacement in 12 years assumed
Lithium-Ion Battery	> Battery with 50kWh > Number of batteries produced: 30k in 2015; 195k in 2020; 460k in 2030
H_2 Tank	> In general 45 kg capacity to achieve range (total of 3 tanks) > Synergies with cars possible but limited due to different geometry and size > 3,000 units per year produced
Balance of Plant	> ~25% of production cost of powertrain components
Base Vehicle	> EUR 180,000 constant (as conventional diesel bus; no cost-down potential assumed due to mature market)

Note: prices of other components based on projections from study "Urban buses: Alternative powertrains for Europe"

Figure 34: Assumptions applied for FC buses in the automotive pathway

Total costs include bus and infrastructure costs

The total costs presented contain all bus and infrastructure costs. Five cost components constitute FC bus costs: The bus depreciation (i.e. purchasing price), maintenance, fuel costs, labour and financing costs. The infrastructure costs are split into three components: The infrastructure depreciation, annual infrastructure maintenance and the infrastructure financing costs.

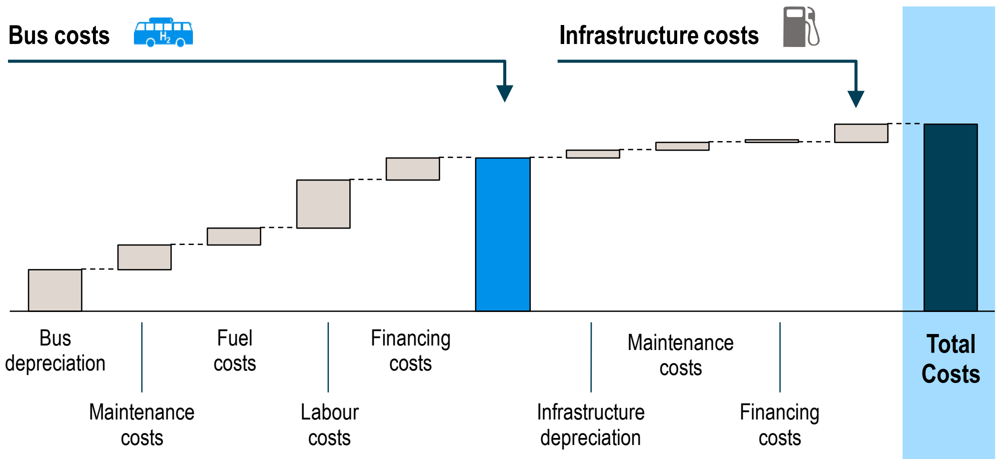


Figure 35: Costs considered in calculation

The study presents Total Cost of Ownerships (TCO). Usually, Total Cost of Ownership (TCO) reflects the costs incurred by FC buses, excluding downtime costs. However, to reflect increased downtimes of FC buses compared to diesel buses in early years of deployment, the study additionally includes costs for operating diesel replacement buses during downtimes of FC buses in order to service the envisaged routes and achieve the full annual target distance of travel. In practice, downtime costs due to problems with a newly introduced technology need to be considered by operators (see below). Hence, this TCO approach provides a more realistic perspective on the costs of FC bus deployment across the entire fleet.

Until the availability of FC buses is equal to diesel buses, TCO in this study will be lower than conventional TCO. Conventional TCO does not take into account replacements and therefore assumes a lower distance travelled. Hence, per kilometre costs of the FC buses without replacement are higher. With replacement buses, TCO in this study assume a higher annual distance travelled. Accordingly, TCO in this study is lower than conventional TCO since the fixed costs depreciate over a higher number of kilometres travelled by FC and diesel buses. Conventional TCO and TCO in this study will be equal when the availability of FC buses is the same as that of diesel buses (see sections below for availability assumptions).

The assumptions guiding the cost projections for FC buses were agreed on jointly

All cost projections were provided for FC buses that perform according to the following characteristics: minimum range of 250 km, maximum speed 80 km/h, acceleration time to 30 km/h of 10 seconds as well as a gradeability of 12% at 20 km/h. In terms of HVAC and passenger capacity, the characteristics are comparable to diesel buses.

All cost projections were provided for FC buses that exhibit the below characteristics:

Bus characteristics	Standard bus	Articulated bus
Range per day	250 km	250 km
Maximum speed	80 km/ h	80 km/ h
Acceleration [time to 30 km/ h]	10 seconds	10 seconds
Gradeability	12% at 20 km/ h (50% load)	12% at 20 km/ h (50% load)
HVAC	Heating and A/C (28-30 KW)	Heating and A/C (30-32 KW)
Passenger capacity	32 seated, 4 standees per sqm	45 seated, 4 standees per sqm
Penalties	Same as for diesel bus	Same as for diesel bus
Warranties	2 years for conventional powertrain components; 5 years for FC stack, batteries and electric motor	2 years for conventional powertrain components; 5 years for FC stack, batteries and electric motor

Figure 36: FC bus characteristics

The FC bus is assumed to have a lifetime of 12 years to align with the lifetime of the diesel bus. The potential extension of the bus lifetime and the resulting necessary number of fuel cell stack replacements are factors considered in the sensitivity analysis performed as part of the study.

The maintenance costs for FC buses are comprised of four categories: Maintenance costs of the fuel cell module and the fuel cell stack replacement, maintenance of the conventional parts and maintenance of other powertrain components. Two replacements of the fuel cell stack are assumed during the 12 year life of the bus. Labour costs for maintenance are included in the maintenance costs category.

FC bus consumption was estimated based on a combination of drive cycles, assuming that 50% of the distance travelled is SORT 1 and the remaining 50% is SORT 2. Consumption may vary significantly for cities with extreme temperatures or mountainous terrain.

A lower availability of FC buses is assumed in the next years. Experience from current FC bus projects suggest that technological problems with the power management of the traction system can cause downtimes. Hence, availability of FC buses is assumed at 85% in 2015, increasing to 95% from 2025 in the scale scenario of the heavy-duty pathway. Lower availability leads to a lower assumed distance travelled by the FC buses. Availability in the study is defined as missed shifts due to unforeseen events, excluding scheduled maintenance.

The figure below displays the assumed availability for FC buses, planned maintenance and kilometres driven assumptions made. The kilometre driven assumptions seen below are those the study assumes when calculating the TCO figures (excluding replacement) on a per kilometre basis.

Bus availability and mileage considered		2015	2020	2025	2030
Heavy-duty niche	Avg. availability across fleet [%]	82%	87%	90%	95%
	Planned maintenance [days/ year]	15	12	10	9
	Kilometres driven per year [km/ year]	57,400	61,422	63,900	67,640
Heavy-duty scale	Avg. availability across fleet [%]	85%	90%	95%	95%
	Planned maintenance [days/ year]	12	10	8	7
	Kilometres driven per year [km/ year]	60,010	63,900	67,830	68,020

Figure 37: Bus availability and mileage assumptions considered for the heavy-duty pathway

These assumptions apply to the heavy-duty pathway only; such detailed projections have not been made for the automotive pathway as operational experience is still limited and powertrain performance can only be evaluated more precisely when next generation buses will be available in the market. However, also for buses in the automotive pathway considerably reduced availability is to be expected, depending on the speed with which this technological pathway is developing.

		Heavy-duty niche scenario	Heavy-duty scale scenario/ Automotive
Financing costs	▪ WACC	▪ 7%	▪ 7%
Labour costs	▪ Salary bus drivers ▪ Cleaning services	▪ 80,000 EUR/ bus in 2015 increasing by 2% annually ▪ 3,500 EUR/ year/ bus in 2015 increasing by 2% annually	▪ 80,000 EUR/ bus in 2015 increasing by 2% annually ▪ 3,500 EUR/ bus in 2015 increasing by 2% annually
Infrastructure (depreciation & maintenance)	▪ Infrastructure lifetime ▪ Infrastructure capacity ▪ Workshop adaptation costs	▪ 20 years ▪ 20 buses ▪ EUR 250,000	▪ 20 years ▪ 100 buses ▪ EUR 500,000
Fuel costs	▪ Fuel consumption	▪ Standard: 8.6 kg/100 km in 2015 to 7.3 kg/ 100 km in 2030 ▪ Art.: 13.0 kg/100 km in 2015 to 11.8 kg/ 100 km in 2030	▪ Standard: 8.6 kg/100 km in 2015 to 7.3 kg/ 100 km in 2030 ▪ Art.: 13.0 kg/100 km in 2015 to 11.8 kg/ 100 km 2030
Bus main-tenance & bus depreciation	▪ Bus lifetime ▪ Bus availability FC bus ▪ Distance traveled	▪ 12 years ▪ 2015: 82% = 57,400 km/ year 2020: 87% = 59,200 km/ year 2025: 95% = 61,600 km/ year 2030: 95% = 65,200 km/ year ▪ 68,000 km/ year (FC bus and diesel) ▪ 57,400 in 2015 (FC bus only)	▪ 12 years ▪ 2015: 85% = 60,010 km/ year 2020: 90% = 63,900 km/ year 2025: 95% = 67,830 km/ year 2030: 95% = 68,020 km/ year ▪ 68,000 km/ year (FC bus and diesel) ▪ 60,010 in 2015 (FC bus only)

Figure 38: Summary of main assumptions for all scenarios

Results are presented by comparing FC bus operating costs with those of diesel buses, since operators currently regard conventional diesel buses to be the benchmark in terms of cost. For this purpose, cost factors applicable to both bus types have been aligned, e.g. labour and financing costs. If not otherwise indicated, diesel costs of EUR 1.00 per litre have been assumed.

		Heavy-duty scale scenario/ Automotive	Diesel bus
Financing costs	▪ WACC	▪ 7%	▪ Same as FC bus
Labour costs	▪ Salary bus drivers ▪ Cleaning services	▪ 80,000 EUR/ bus in 2015 increasing by 2% annually ▪ 3,500 EUR/ bus in 2015 increasing by 2% annually	▪ Same as FC bus ▪ Same as FC bus
Infrastructure (depreciation & maintenance)	▪ Infrastructure lifetime ▪ Infrastructure capacity ▪ Workshop adaptation costs	▪ 20 years ▪ 100 buses ▪ EUR 500,000	▪ Same as FC bus ▪ Same as FC bus ▪ None
Fuel costs	▪ Fuel consumption	▪ 8.6 kg/100 km in 2015 to 7.3 kg/ 100 km in 2030	▪ 40 litres/100 km in 2015 to 36 litres/ 100 km in 2030
Bus main-tenance & bus depreciation	▪ Bus lifetime ▪ Bus availability	▪ 12 years ▪ 2015: 85% = 60,010 km/ year (TCO) 2020: 90% = 63,900 km/ year (TCO) 2025: 95% = 67,830 km/ year (TCO) 2030: 95% = 68,020 km/ year (TCO)	▪ Same as FC bus ▪ 2015: 95% = 68,020 km/ year 2020: 95% = 68,020 km/ year 2025: 95% = 68,020 km/ year 2030: 95% = 68,020 km/ year

Figure 39: Summary of assumptions for comparison of FC and diesel standard bus

Underlying assumptions for refuelling infrastructure and hydrogen consider two options

Two production options were assessed for four capacity thresholds: Off-site production with Steam Methane Reforming of natural gas (SMR) and on-site production with water electrolysis. In each case, on-site hydrogen storage and refuelling infrastructure is required and considered in the cost analysis. The capacity thresholds are taken into account, when assuming differing deployment plans of operators. The results presented in the following for the heavy-duty niche scenario assumes a number of 20 FC buses per bus operator and a corresponding infrastructure capacity of 600 kg per day. Results presented for the heavy-duty scale scenario and the automotive pathway assume a number of 100 FC buses per bus operator.

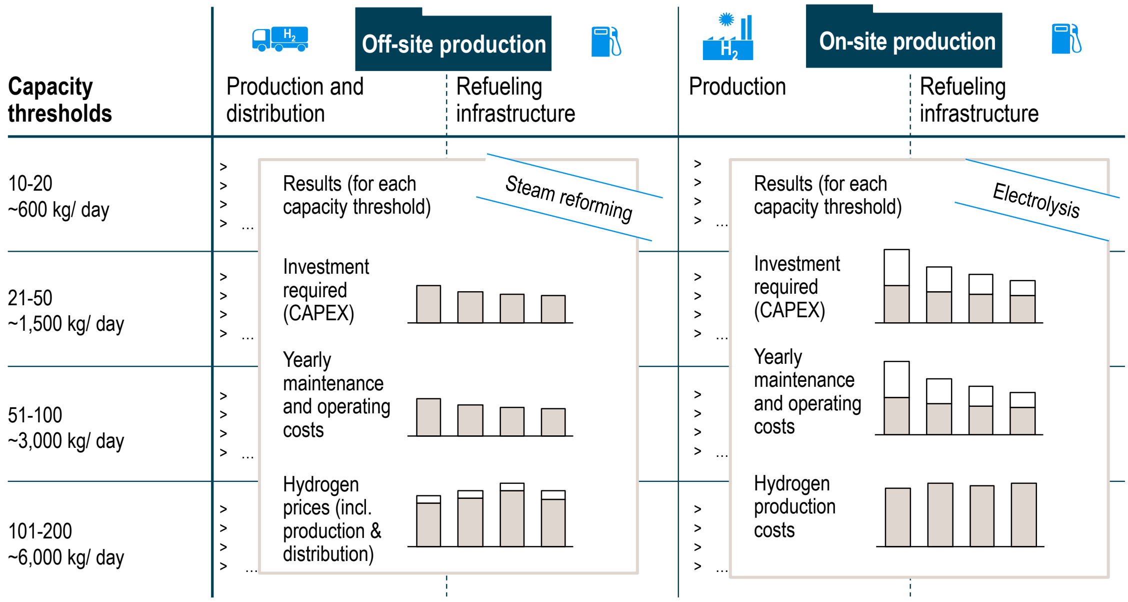


Figure 40: Capacity thresholds of infrastructure solutions considered in the cost analysis

Projected hydrogen prices vary depending on the production option and feedstock prices. As will be outlined further below, hydrogen produced with SMR is considered to be the least costly option in the next years. Hence, in case it is not stated otherwise, the presented costs below assume that hydrogen was produced off-site with SMR. Natural gas prices of 42 EUR/ MWh are assumed in 2015, taking into account industrial pricing with all taxes and levies included based on data from Eurostat. It is assumed to increase by 1% annually. Distribution costs for hydrogen are included as transportation of hydrogen for 100 kilometres from an off-site production location to the on-site storage facility. Storage is assumed at 350 bar.

Cost projections were provided for a hydrogen infrastructure exhibiting the below characteristics:

Infrastructure characteristics	Off-site production	On-site production
Production capacity	(4 capacity thresholds)	(4 capacity thresholds)
Reserve capacity to be held in storage	200%	200%
Time for refueling for whole fleet	6 hours	6 hours
Refueling time per bus	9 min	9 min
Distance to refueling station	100 km	n.a.
Availability	98%	98%
Lifetime	20 years	20 years
Least costly production method	To be provided by OEM	To be provided by OEM

Figure 41: Characteristics of refuelling infrastructure

Water electrolysis with electricity is the production method assumed for on-site production. For calculating the costs of hydrogen produced, an electricity price of 110 EUR/ MWh hour is assumed in 2015, increasing by 1% annually.

The study assumes average feedstock prices; hence, a sensitivity analysis was performed for prices of electricity and natural gas. Since feedstock and hydrogen prices can vary significantly depending on the country of operation, applicable taxes or subsidies and the type of entity, four different sensitivities are calculated for the presented price of hydrogen and therefore, the total fuel costs. The best case scenario is calculated assuming prices are 15% lower than the base case in 2015. This discount on the base case increases to 30% by 2030. The upside scenario assumes prices are 10% lower than in the base case from 2015 through 2030. The downside scenario assumes prices are 10% higher than in the base case from 2015 through 2030.

Feedstock [EUR/ MWh] – Base case

Electricity prices [EUR/ MWh]

2015	2020	2025	2030
110	116	122	128

Natural gas prices [EUR/ MWh]

2015	2020	2025	2030
42	44	46	49

Feedstock prices [EUR/ MWh] – Variance

		2015	2020	2025	2030
A. Best case variance	Price -30%	94	92	91	89
		36	35	35	34
B. Up-side variance	Price -10%	99	104	109	115
		38	40	42	44
C. Down-side variance	Price +10%	121	127	134	140
		46	49	51	54

Figure 42: Feedstock prices for sensitivity analysis

Annex 4 – Detailed cost results infrastructure and hydrogen

Hydrogen production from Steam Methane Reforming is expected to be the least costly option

Two hydrogen production methods were analysed in the study: off-site steam methane reforming (SMR) of natural gas and a truck-in solution as well as on-site water electrolysis with electricity. In both cases, on-site storage and refuelling infrastructure are required.

Off-site hydrogen production through SMR is expected to be the least costly option for some years to come. The price of hydrogen from natural gas SMR is currently approximately 20% lower than hydrogen from electrolysis and the price gap is expected to widen to about 24% in 2030. Hence, it is expected to play a role in commercialisation in the next years.

One kg of hydrogen from SMR is expected to cost approximately EUR 5 in 2015, whereas the price of hydrogen produced on-site with water electrolysis is expected to be approximately EUR 6 in the same year. This applies for infrastructure to cater for 20 FC buses, i.e. with a capacity of 600 kg of hydrogen per day. Displayed hydrogen prices include all production costs (CAPEX and OPEX), margin as well as distribution costs in the off-site option.

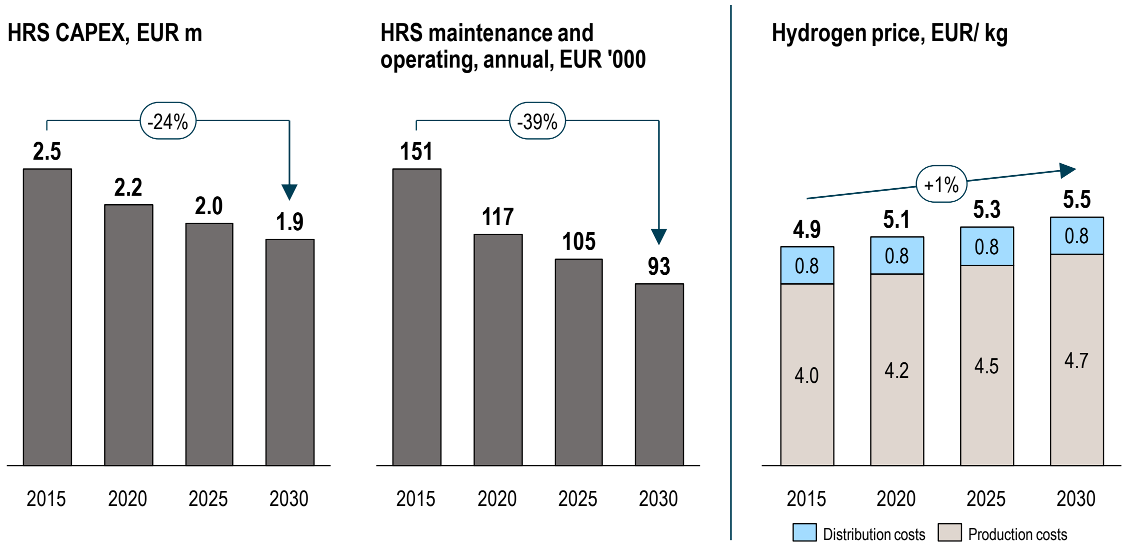


Figure 43: Infrastructure and hydrogen costs off-site production with SMR, station for 20 FC buses

CAPEX for the hydrogen refuelling infrastructure (HRS) is expected to come down by 24% between 2015 and 2030 for a station for 20 FC buses while the decrease for the OPEX is expected to be even larger. Hydrogen prices are expected to increase by approximately 1% annually until 2030 for both SMR and electrolysis. This increase is mainly driven by assumed increasing prices for natural gas and electricity which are partially offset by technological efficiencies.

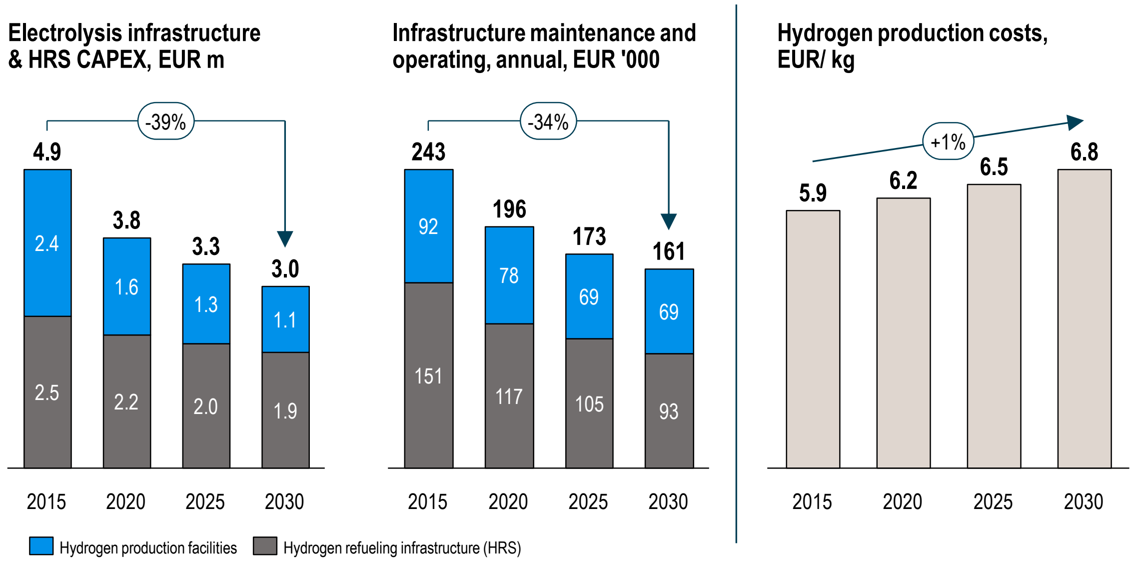
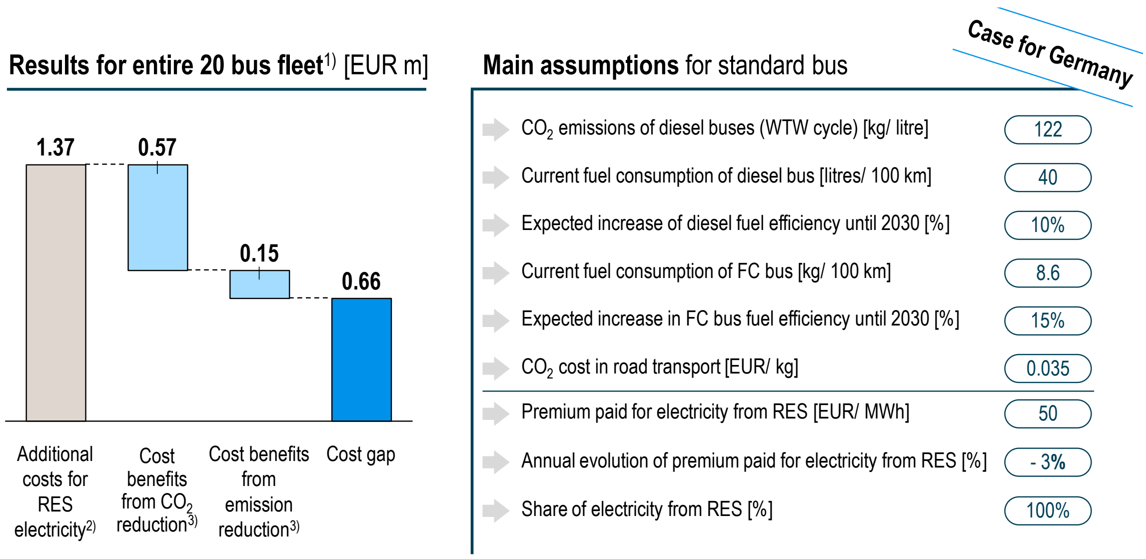


Figure 44: Infrastructure and hydrogen cost, on-site with electrolysis, station for 20 FC buses

The costs for using exclusively RES for hydrogen production through electrolysis varies between countries. They are comparatively lower in countries with a high share of RES in the energy mix, such as Norway, and higher in countries with a low share of RES electricity. Taking the stipulations of the EU Clean Vehicles Directive into consideration, the annual additional net costs of operation with hydrogen from 100% RES vs. hydrogen from grid electricity amount to EUR 6,000 per bus in Germany.



1) Deployment schedule of buses divided evenly for 2015 – 2030 period 3) Compared to producing hydrogen from electricity from the grid
2) Savings according to Directive 2009/33/EC, benefits considered constant

Figure 45: Cost analysis of fleet operation with hydrogen from 100% RES electricity

Under very specific circumstances, such as using low-priced spot electricity and offering grid balancing services, the price of 100% RES electricity can become so low that hydrogen can be produced within the price range of SMR produced hydrogen. This demonstrates that the technology requires regulatory support to become commercially viable, e.g. by significantly penalising the use of diesel-fuel and the associated carbon footprint.

Annex 5 – Sensitivity analysis

The sensitivity analysis was performed for three parameters: Feedstock prices, financing costs and bus lifetime. Out of these three parameters, a longer bus lifetime (e.g. 18 years instead of 12 years) bears the greatest potential for a reduction of TCO. The results presented below assess the TCO in the heavy-duty niche scenario with 20 FC buses. Lower natural gas and, thus, hydrogen prices can reduce TCO by 0.1-EUR 0.2 per kilometre:

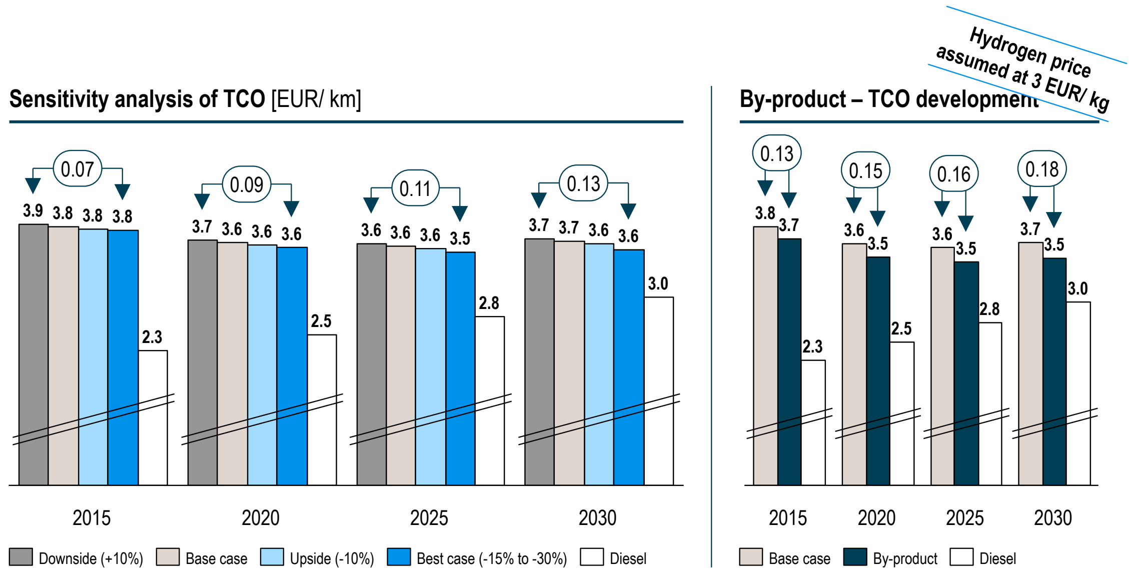


Figure 46: TCO in sensitivity analysis of feedstock prices for the heavy-duty pathway – Hydrogen from natural gas SMR

A Weighted Average Cost of Capital (WACC) of 5% can reduce TCO by EUR 0.17 in 2015, rather than 7% in the base case:

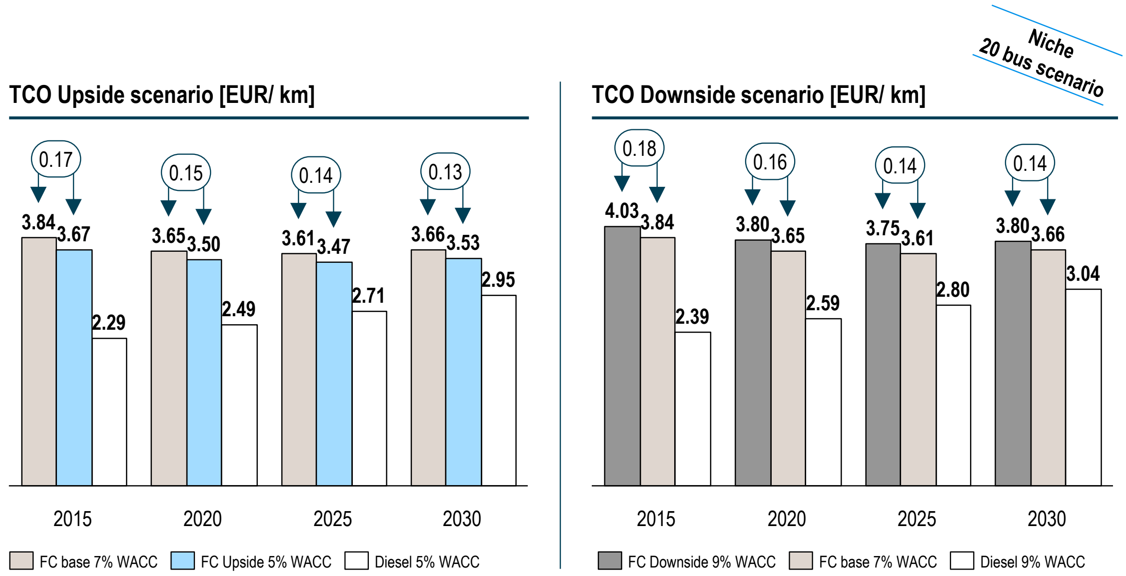


Figure 47: TCO in sensitivity analysis of financing costs for the heavy-duty pathway [EUR/km]

Assuming a bus lifetime of 18 years can lead to a TCO reduction of EUR 0.29 in 2015 and of EUR 0.20 in 2030, significantly closing the gap to the diesel.

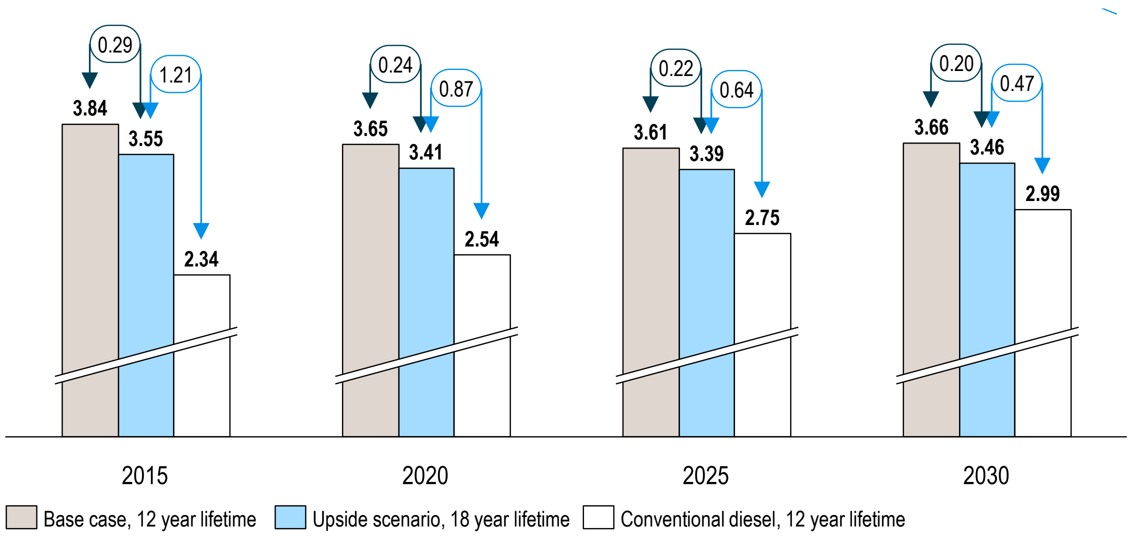


Figure 48: TCO in sensitivity analysis of bus lifetime for the heavy-duty pathway [EUR/km]