JIVE (D3.22) | JIVE 2 (D3.6/D4.3)

Env. Impacts and Ext. Cost Benefits of FCBs Comp. of FCBs with BEBs

Anna Zimmerer, Stefan Eckert,
Vanessa Roderer

ZERO EMISSION

JIVEs / MEHRLIN projects

@fuelcellbus www.fuelcellbuses.eu

Clean Hydrogen Partnership
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Main authors: Anna Zimmerer (Sphera) AZimmerer@sphera.com
Stefan Eckert (Sphera) SEckert@sphera.com
Vanessa Roderer (Sphera) VRoderer@sphera.com

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Executive Summary

PART I – Environmental Impacts and External Cost Benefits of Fuel Cell Hydrogen Bus Systems

As fuel cell buses operate locally emission free, of a pure fuel cell bus fleet would result in the complete avoidance of combustion related nitrogen oxides and particulate matter emissions. In contrast, the reduction in Global Warming Potential strongly depends on the hydrogen production pathway and the electricity mix used. With the assumption of hydrogen from electrolysis using electricity from wind power throughout the JIVE sites, an overall Global Warming Potential reduction of 82 % can be achieved.

Because within the JIVE projects only a small share of the bus fleets was replaced by fuel cell buses, this only leads to a small reduction of Greenhouse Gas emissions compared to the diesel-only fleets because of the large overall fleet size. The absolute and relative avoided emissions as well as the emission reduction potential associated with a pure fuel cell bus fleet differ for each site depending on the site-specific conditions.

These results are also reflected by the external costs avoided. These are dominated by the costs for greenhouse gas emissions which account for more than 90 % of the total external costs. With the replacement of diesel buses by fuel cell buses, the Greenhouse Gas emissions are the only remaining cost component of the external costs.

In accordance with the results on avoided environmental impacts, the hydrogen production by electrolysis using electricity from wind power results in the lowest external costs. When the entire fleet is replaced, external costs can be reduced by 84 %. Related to the vehicle kilometre, this corresponds to a reduction from 16.2 € ct/km for a diesel bus to 2.5 € ct/km for a fuel cell bus.

PART II – Comparison of fuel cell with battery electric bus systems against operational, economic and environmental parameters

The comparison of the environmental performance of fuel cell buses and battery electric buses reflects the additional energetical effort to produce the hydrogen, compared to the direct use of electricity in battery electric buses. While the results of the assessment strongly depend on the used electricity mix and the hydrogen production pathway and thus cannot be generalised, the conversion losses associated with hydrogen generation will initially always be an advantage for battery electric buses in terms of environmental impact.

The economic assessment reveals lower total cost of ownership for the battery electric buses at both sites under the current conditions and the assumptions made. However, the relative advantageousness of the battery electric bus is in the order of 10 % only, and it's not completely unlikely that a further reduction of the fuel cell bus or hydrogen price may reverse the situation.

When long and demanding routes shall be served, fuel cell buses are advantageous in terms of their higher operating range and their flexible deployability, as they can be used flexibly on any route without having to think about recharging options.

This advantage must be weighed against the disadvantages, such as the efficiency losses incurred in hydrogen production and the currently still higher costs. The space requirements and options for the installation of an hydrogen refuelling station or, on the other hand, the necessary charging infrastructure, must also be included in the decision in favour of fuel cell or battery electric buses.

However, if additional buses had to be considered for BEBs due to their range limitations, this would be a major advantage for FCBs and significantly improve their rating compared to BEBs, both from an environmental and economic point of view.

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List of Abbreviations and Terms

BEB	Battery Electric Bus, sometimes referred to as 'battery-only bus' because a Fuel Cell Bus also carries a small battery that supports the fuel cell and recovers energy when breaking
CO_2e	Carbon Dioxide Equivalents
EU	European Union
FC	Fuel Cell
FCB	Fuel Cell Bus (an electric bus powered by a fuel cell that runs on hydrogen fuel, supported by a small battery for e.g. energy recovery)
FCH JU	Fuel Cells and Hydrogen Joint Undertaking, first phase of the FCH JU under the EU 7th Framework Programme; abbreviation also commonly used for the FCH 2 JU
FCH 2 JU	Fuel Cells and Hydrogen 2 Joint Undertaking, second phase of the FCH JU under the EU Horizon 2020 Framework Programme; the FCH 2 JU was re-launched in 2021 as the Clean Hydrogen Partnership
GHG	GreenHouse Gas
GWP	Global Warming Potential
H_2	Hydrogen
HRS	Hydrogen Refuelling Station
JIVE	Joint Initiative for Hydrogen Vehicles across Europe, project co-funded by the FCH 2 JU under the European Union's Horizon 2020 Framework Programme (2017 – 2024)
JIVE 2	Second Joint Initiative for Hydrogen Vehicles across Europe, project co-funded by the FCH 2 JU under the European Union's Horizon 2020 Framework Programme (2018 – 2024)
LCA	Life Cycle Assessment

LFP	Lithium Iron Phosphate; Battery Chemistry
LTO	Lithium Titanium Oxide; Battery Chemistry
MLC	Managed LCA Content
NOx	Nitrogen Oxides
NPV	Net Present Value
PM 2.5	Particulate Matter with diameters of 2.5 micrometers or smaller
SMR	Steam Methane Reforming
TCO	Total Cost of Ownership

0 Introduction

0.1 Context

Based on the monitoring and analysis activities within WP3 of JIVE and JIVE 2, a report on *External Costs and Benefits of Fuel Cell Hydrogen Bus Systems* (JIVE D3.22) and a report on *Environmental Impacts and External Cost Benefits of Fuel Cell Hydrogen Bus Systems* (JIVE 2 D3.6) are stipulated in the respective Grant Agreements. While the titles differ, both reports shall assess the impact of fuel cell technology in public transport on public health and urban living by (i) determining the environmental profile in terms of emissions avoided, and (ii) analysing the associated external costs avoided as a result of operating locally zero emission fuel cell buses (FCBs). Thus, Part I of this report comprises the combined assessment of environmental impacts and related external costs for both projects under the common title *JIVE (D.22)/JIVE 2 (D3.6) Environmental Impacts and External Cost Benefits of Fuel Cell Hydrogen Bus Systems.*

Additionally, for JIVE 2 a *Report comparing fuel bus systems with diesel and battery electric systems against operational, economic and environmental parameters* (JIVE 2 D 4.3) is specified in WP4. Apparently, there is a significant overlap and strong linkage to the above mentioned Deliverables, both in terms of the topic and the specified methodology. Furthermore, in the course of the projects it became apparent that diesel buses no longer represent a technology to be considered in future decision making by Public Transport Operators (PTOs). This is why the latter Deliverable was included in this report as Part II under the title *Comparison of fuel cell with battery electric bus systems against operational, economic and environmental parameters*.

0.2 Structure of the report

All Deliverables address the environmental and economic assessment of FCBs. To obtain a realistic picture and provide the PTOs with results that relate to their specific operating conditions, the analysis was based on the real bus performance at each site whenever possible. The values for the actual bus deployment were taken from the performance assessment carried out in WP3 of the JIVE projects.

To obtain the complete picture, the environmental as well as the economic assessment have to cover the entire life cycle of the vehicles, both for the Life Cycle Assessment (LCA) and the Total Cost of Ownership (TCO) analysis. Details on the applied methodology can be found in the introductory chapter on methodology, as both parts of this report are based on the same methodological foundations.

In Part I, environmental impacts and external costs avoided by FCB operation compared to diesel bus operation are assessed. This part comprises results based on data from all JIVE / JIVE 2 sites[1] using a rather generic approach. In Part II, FCBs are compared to BEBs against environmental, economic and operational parameters. In this part, in-depth data and information from two exemplary sites are used at which both bus systems are deployed. Figure 0-1 provides an overview of the report.

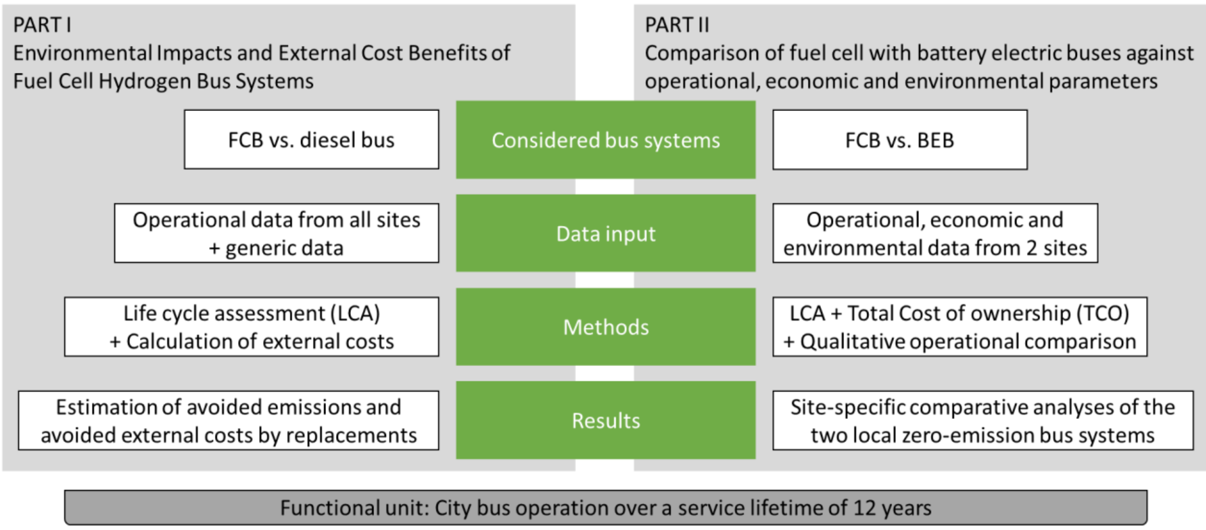

Figure 0-1: Report overview

[1] In the following, no distinction is made between the JIVE and the JIVE 2 project, because all analyses were performed with the common JIVE / JIVE 2 data base. Projects and sites are therefore commonly referred as the JIVE projects and sites, respectively.

1 Methodology

While the specific intention of the two parts of this report is different, the methodological basis is very similar. The different statements are then derived by applying different assumptions and modifying the parameter settings. This is why the combined report starts with a common chapter on methodology. The detailed assumptions underlying the specific calculations for each part are then described at the beginning of Part I and Part II, respectively.

1.1 Data monitoring and performance assessment

From the continuous operational data analysis, which covers the period from January 2020 through December 2022, data is available for up to 200 fuel cell buses (FCBs) from 14 transport operators throughout Europe. During this period, the buses drove more than 10 million kilometres and sometimes more than 500 km on a single day.

The data analysis is based on the parameters as described in the Performance Assessment Handbook. The provided operational data from the operators was checked for consistency and quality, and then entered and evaluated in Sphera's web-based Corporate Sustainability Software (formerly SoFi). The data is provided on a daily basis and used to evaluate the operating performance over the project duration. The data used for establishing this report include all data available up to December 2022.

1.2 Additional data collection and survey

The data monitoring and performance assessment as described in Chapter 1.1 was only carried out for the FCBs operating in the framework of the JIVE projects. However, the evaluation of the environmental impacts and external cost benefits of FCBs should to be performed against the conventional diesel bus fleet of each site. Accordingly, as diesel buses were not included in the regular data evaluation, an additional survey was carried out at all operators to obtain the principal figures for their diesel bus fleet, namely number of buses, average diesel consumption, and average yearly distance driven.

For the in-depth environmental and economic comparison of FCBs and BEBs, operational data for BEBs were required in addition to the FCB data. The intention was to compare FCB and BEB data for sites utilizing both drive train technologies in parallel. Within the project consortiums, four sites were identified where FCBs and BEBs were deployed in the same fleet und thus under comparable operating conditions. All four sites were contacted and additional operating data for BEBs were requested. However, it proved to be unexpectedly difficult and protracted to obtain the BEB data. In the end, two sites provided BEB data that were sufficiently complete to be included in the analysis. Accordingly, these two datasets formed the basis for the detailed LCA and TCO analysis (see Chapter 4). For site 1, data comprises values from 34 BEBs over a period of 7 months. From site 2, average operational values were received. Some remaining data gaps were filled with values from literature and/or previous project experiences with BEBs.

1.3 Life Cycle Assessment

A methodology based on the Life Cycle Assessment (LCA) according to standard EN ISO 14040/44 (Deutsches Institut für Normung e.V., 2006) was used for the ecological assessment. LCA represents a method by which potential environmental impacts associated with a product or service over its entire life cycle (cradle-to-grave) are systematically assessed. This comprises the extraction of raw materials, the production of semi-finished products, the production, the use phase including maintenance and repair, as well as recycling and disposal at the end-of-life, also including all respective upstream processes.

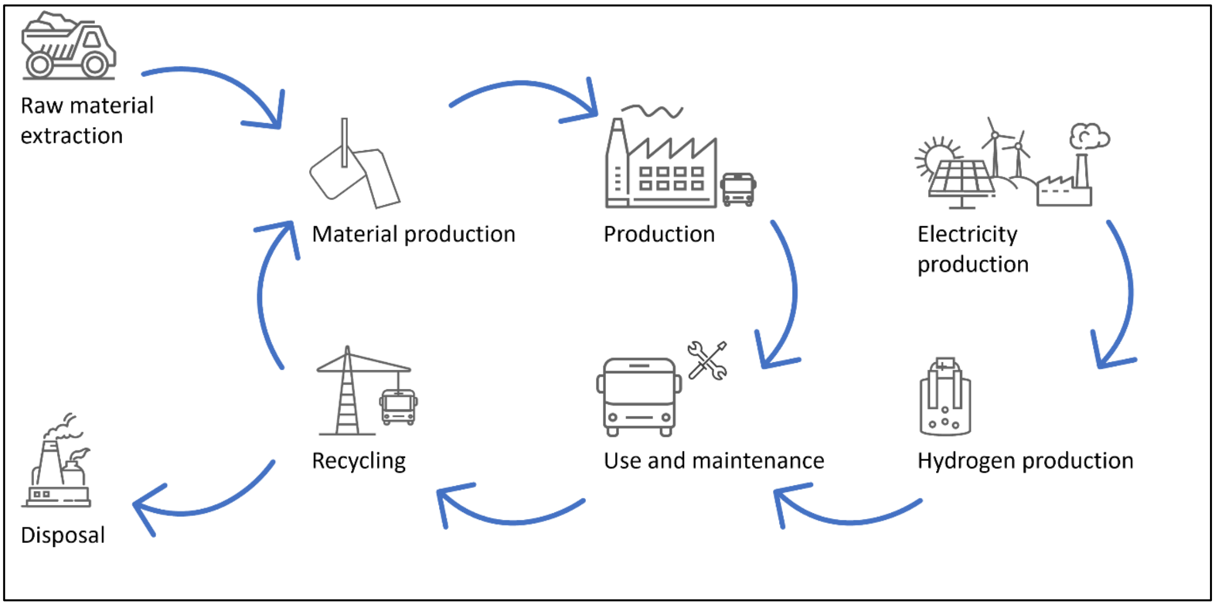

Figure 1-1: Life cycle of a fuel cell hydrogen bus with hydrogen from electrolysis

For the LCA, the resource consumption and emissions along the entire life cycle are determined and added up. Their impact is then expressed in terms of environmental indicators (e.g. greenhouse gas emissions). The objective of the assessment is to show the ecological impact over the life cycle that result from the deployment of the different bus systems.

The functional unit used as basis for the present LCA on bus drivetrain systems is defined as city bus operation over a bus lifetime of 12 years. The city buses for public transport are characterized by different drive concepts and, in the case of BEBs and FCBs, a fully electric heating concept. The chosen configurations are based on current bus models from European manufacturers.

The production of the buses was divided into the production of the bus basis, which was assumed equal for all considered bus models except for the weight, and the production of the components specific for the respective drivetrain technology. This comprises the high-voltage electronics for both bus types, and for BEBs the battery, while for FCBs the fuel cell, the battery and the hydrogen tanks.

The use phase of the buses is dominated by the fuel consumption and all necessary steps for fuel supply. Due to the combustion of the diesel during their operation, conventional diesel buses generate air emissions which are harmful to climate and health. In the case of BEBs and FCBs which operate locally emission-free, environmental impacts are shifted to the provision of the energy source (electricity or hydrogen, respectively) and the required electrical components of the drivetrain (the battery and the fuel cell, respectively). For electric power and hydrogen supply, we considered the production, transportation and refuelling/charging including the necessary infrastructure (plants, pipelines, trailers, etc.). The only exception to this is hydrogen production by natural gas steam reforming. In this case, no meaningful allocation of the infrastructure was possible. For hydrogen supply, also the necessary compression to at least 350 bar at the refuelling station was considered.

Maintenance covers regular maintenance activities such as lubricant and tire changes and additionally the replacement of components (battery and/or fuel cell). The component replacement is considered by adding the proportional share of the environmental impact associated with the component, depending on the component's lifetime and the remaining time until the end of the bus lifetime. Repair and general expenses for workshop/depot or operation control were not considered. Credits for materials recovered from disposal or energy used in the bus recycling at the end of its life were not taken into account, in line with common practice in LCA in the automotive industry.

Life cycle inventory data (emissions and resource depletion) for the provision of materials and energy were taken from Managed LCA Content (MLC) from Sphera's life cycle assessment software LCA for Experts (formerly GaBi Databases) (Sphera, 1992-2023). Place of operation is throughout Europe, therefore, the impacts associated with electricity consumption were based on an European electricity mix for the generic approach in Part I. In Part II, a country-specific electricity mix was used except for hydrogen production via chlor-alkali electrolysis, where due to model limitations the EU grid mix had to be applied. The hydrogen consumption and other operational data were matched with performance assessment data from the operational bus monitoring.

As environmental impact category for climate change, the global warming potential according to Environmental Footprint 3.0 (European Commission, Joint Research Centre, 2019) was used, expressed in CO_2-equivalents (CO_2e). Nitrogen oxide (NO_x) and particulate matter (PM 2.5) emissions are considered as a proxy indicator for the impact on air quality in urban areas.

The bus specifications and operational conditions used for the assessments in Part I and Part II are detailed in the respective sections.

1.4 Noise

Noise emissions are of essential importance in city areas. Electric drives offer advantages in terms of noise emissions, which is particularly noticeable in areas with low traffic congestion. Accordingly, FCBs reduce the local noise pollution compared to diesel bus operation. The reduced noise emissions during operation are a benefit in addition to the locally emission-free operation of the e-buses. Noise emission measurements carried out by the Institute of Automotive Engineering (ika) of RWTH Aachen Technical University showed a reduction potential of the linear scaled loudness of the buses with electric drive train by approx. 2/3 in the operating modes arrival, departure, and accelerated passing (AG Innovative Antriebe Bus, 2016).

In contrast, a hydrogen refuelling station produces increased noise emissions compared to a diesel refuelling station, caused by the cooling units and the compressor. Sound insulation measures can reduce these emissions (Kupferschmid & Faltenbacher, 2018).

Noise emissions generally depend to a large extent on the local traffic and driving condition, but also on the local situation and noise propagation, and could not be quantified in the context of the current reports. Therefore, no results on the environmental performance regarding noise emissions are available, and no comparison between different drivetrain options or bus types, or estimation of external costs avoided by the reduction of noise emissions (see next Chapter) were possible.

1.5 External costs

External costs originate from impacts of social or economic activities not being fully compensated or accounted for (European Commission, 2019). In this report, we calculate the external costs of emissions associated with city bus operation. The environmental impacts considered are the same as for the LCA, namely emissions of greenhouse gases, NO_x and PM 2.5. Thus, the external costs comprise three cost types:

- Climate change avoidance costs based on the total GWP (including upstream and downstream processes of vehicles and hydrogen)
- Average damage costs of air pollution based on local NO_x emissions
- Average damage costs of air pollution based on local PM 2.5 emissions

For the three cost types, the Handbook on the external costs of transport (European Commission, 2019) provides the cost factors presented in Table 1-1 and Table 1-2. Different methodologies can be applied for the valuation of externalities, inter alia, the damage cost or avoidance cost approaches. We follow the methodology in the Handbook on the external costs of transport by using avoidance cost factors to calculate external costs of climate change and damage cost factors for air pollution costs (European Commission, 2019). For climate change avoidance costs, we use the central estimate in the short and medium run as cost factor. As average damage costs of air pollution, we consider the country-specific and landscape-specific conditions of the individual sites. To determine the total external costs for each scenario, the cost factors are multiplied by the respective emissions calculated.

Table 1-1: Climate change avoidance costs in €/t CO2 equivalents (European Commission, 2019)

Time horizon	Low	Central	High
Short and medium run (up to 2030)	60	100	189
Long run (from 2040 to 2060)	156	269	498

Table 1-2: Air pollution costs: average damage costs in €/kg (European Commission, 2019)

Country	NOx transport city	NOx rural transport	PM 2.5 transport metropole[2]	PM 2.5 transport city	PM 2.5 rural transport
France	27.2	16.2	407	131	87
Germany	36.8	21.6	448	144	93
Italy	25.4	15.1	409	132	79
Netherlands	26.5	15.3	458	148	101
Spain	8.5	5.1	348	112	46
United Kingdom	13.6	7.9	380	122	65
EU 28	21.3	12.6	381	123	70

1.6 Total Cost of Ownership

Total Cost of Ownership (TCO) analysis is an instrument for assessing the total costs of a product or service, considering not only the costs occurring in the initial investment phase, but over the entire life cycle of the product or service. We used TOC analysis to compare the life cycle costs of FCBs and BEBs. The TCO in this work comprises the costs of the vehicle, of the energy carrier including the necessary energy supply infrastructure, driver costs, maintenance costs, and finally credits for potential further use of components and infrastructure. Consistent with the LCA, the functional unit is also defined as city bus operation over its service lifetime of 12 years.

[2] More than 0.5 million inhabitants

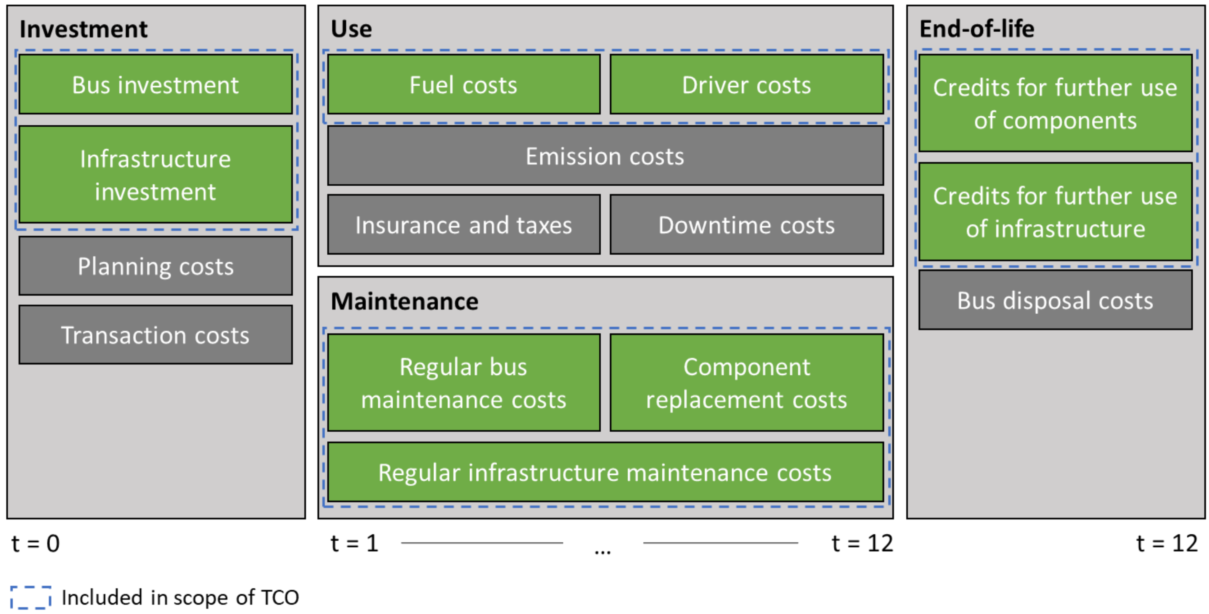

Figure 1-2: Scope of the TCO analysis

The bus investment is exclusively represented by the bus price and no further cost for the acquisition, grants or subsidies are considered. The investment of the refuelling or charging infrastructure is defined as lump sum incurring for construction or acquisition of the infrastructure excluding land costs. Further potential costs of the investment phase such as planning costs or transaction costs were not included in our scope.

Costs for fuel[3], drivers, and regular bus and infrastructure maintenance, were considered as annual costs over the lifetime of the bus. If available, data and information from the bus operators were used. Bus and infrastructure maintenance costs cover all costs of maintenance including parts and labour. Furthermore, the one-time incurring costs of component (battery and/or fuel cell) replacements were included in the scope as they occur in the respective year of operation.

Included elements of the end-of-life phase were credits for a potential further use of infrastructure and replaced components represented by their remaining value as "neg-

[3] For reasons of simplicity, fuel is used in this report as umbrella term comprising diesel as well as hydrogen and electricity.

ative costs". For determining the remaining value, a linear decrease in value was assumed over the expected lifetime of the infrastructure and the components. Under the assumption that all costs of a period occur at the end of the period and the bus service lifetime ends after 12 years, period 12 covers the annual costs of the use and maintenance phase in this period as well as all potential credits associated with the end-of-life. For the bus itself, neither a remaining value nor disposal costs were considered.

For the results, the total cost incurred during the bus lifetime are grouped in the following cost categories:

1. Bus (bus investment)
2. Bus maintenance (regular bus maintenance costs; component replacement costs; credits for further use of components)
3. Driver (driver costs)
4. Fuel (fuel costs)
5. Infrastructure (infrastructure investment, regular infrastructure maintenance, credits for further use of infrastructure)

All cost components related to infrastructure are allocated corresponding to the stated number of buses the infrastructure is designed for.

To make the payments in the different years of operation comparable, they are discounted to the base year (year of investment) according to the Net Present Value (NPV) method. The NPV is a widely used approach of dynamic cost calculation to allow for the economic comparison of different investment options.

The NPV represents the sum of the initial investment (I) and the present value of all future payments. The present value of future payments is determined by discounting the payments (P_t) occurring in the period under consideration (t) with the discount rate (i_t). By assuming a constant discount rate (i), the NPV can be calculated as follows:

$$NPV = I + \sum_{t=0}^{T} \frac{P_t}{(1+i)^t}$$

The calculation of the costs per drive technology depends on a number of parameters and assumptions. They can vary between different transport companies due to their specific boundary conditions, e.g., energy consumption of the vehicles due to the specifications of the bus network (e.g., average travel speed, topography, distances between stops, passenger capacity). Regarding various input variables of the cost calculation, assumptions had to be made due to the novelty of the technologies (e.g., service life of cost-intensive components such as the HV battery or the fuel cell). The bus specifications and operational conditions used for the assessments in Part I and Part II are detailed in the respective sections.

1.7 Project experience

When no specific data from the JIVE sites were available, we used data from former project experiences and literature to fill remaining data gaps.

1.7.1 Accompanying research programme on innovative drive systems and vehicles

This research project evaluated the introduction of zero-emission local transport buses in Germany. Next to practical feasibility and energy efficiency, the economic and ecologic viability of zero-emission local transport buses were assessed. The evaluation was based on data from more than 130 battery electric buses covering up to two years of operation (Faltenbacher, et al., 2022). This project includes a market overview of bus models with different drive technologies (Faltenbacher, et al., 2019).

1.7.2 Introduction of hydrogen buses in public transport. Vehicles, infrastructure and operational aspects

This document addresses bus fleet operators who are interested in the deployment of hydrogen-powered vehicles. Fundamental aspects of the use of hydrogen in transport were elaborated and presented regarding vehicles, infrastructure, operation and environmental impacts (Kupferschmid & Faltenbacher, 2018).

PART I

Environmental Impacts and External Cost Benefits of Fuel Cell Hydrogen Bus Systems

This part includes the contents of JIVE D3.22 and JIVE 2 D3.6

2 Environmental impacts avoided by FCBs

2.1 Approach and boundary conditions

This section presents a possible site-specific range of emissions avoided through the replacement of diesel buses by fuel cell buses. We followed the LCA approach, as described in section 1.4. As described, the assumed lifetime of the buses is 12 years. Due to the simplified approach, the results only represent an estimation of the avoided emissions. The underlying assumptions and data for each site are detailed in the following tables and sub sections.

The calculation of the GWP considered the bus production, use and end of life of diesel and fuel cell buses. Furthermore, NO_x and PM 2.5 emissions are of high relevance for air quality in urban spaces and predominantly considered when assessing transport related air pollution. Accordingly, in addition to the GWP, the locally generated driving emissions of NO_x and PM 2.5 were calculated as a measure for local air pollution. Further emissions, e.g., associated with bus or hydrogen production, were not considered for the assessment of air emissions.

In a first step, the analysis comprised the avoided emissions by the deployment of the FCBs in the two JIVE projects. For this purpose, we assumed that the FCBs operated in JIVE replaced former diesel buses.[4] In a second step, we approximated the emissions that could be avoided if all remaining diesel and hybrid buses were also replaced by FCBs.

Therefore, we took the current respective fleet size as basis and developed the following three cases of fleet composition for each site:

- Pure diesel bus fleet - fleets consists entirely of diesel buses
- Status quo - current fleet composition; fleet consists of diesel buses and the FCBs deployed in the JIVE projects

[4] We distinguished between 12 m and 18 m buses and counted Double Deck buses as 12 m buses, since their empty weight can be compared to solo buses.

- Pure FCB fleet - fleet consists entirely of FCBs

To create comparability between the overall fleet mileage, we divided the buses for each site in two groups: Group A with the current average diesel bus mileage according to the additional data collection, and Group B with the current average FCB mileage based on the JIVE performance assessment. This approach is displayed in Figure 2-1.

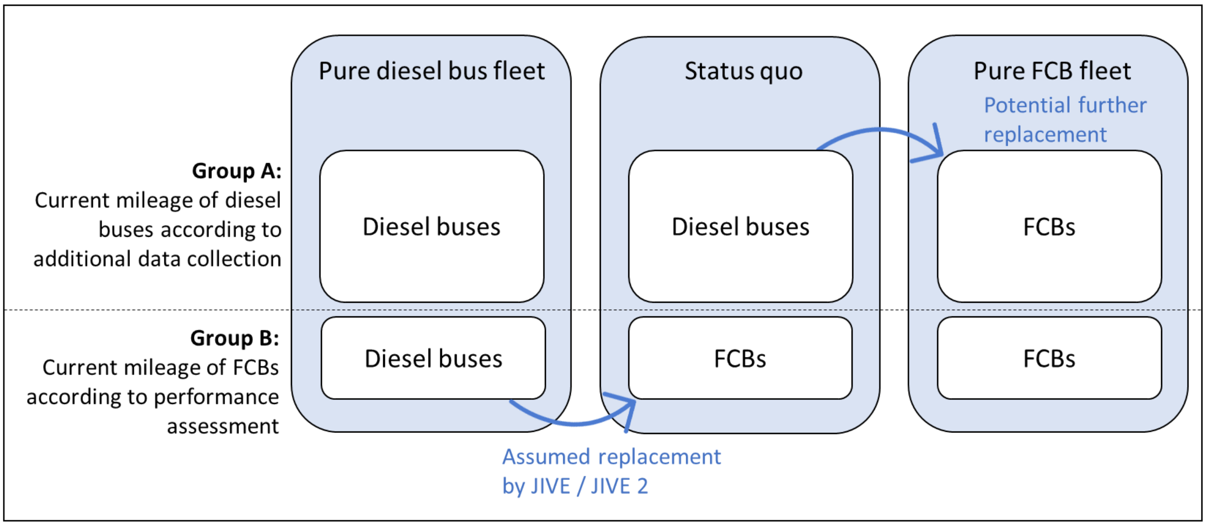

Figure 2-1: Three considered cases of fleet composition

The resulting respective mileage and fleet compositions are depicted in Table 2-1 and Table 2-2.

Table 2-1: Mileage based on performance assessment and additional data collection

Site	Mileage [km/a/bus]			
	Group A (based on current average mileage of diesel buses)		Group B (based on current average mileage of FCBs)	
	12 m	18 m	12 m	18 m
Site 1	47,476	-	49,272	-
Site 2	45,000	-	22,200	-
Site 3	49,405	78,022	26,484	-
Site 4	65,000	-	10,068	-
Site 5	34,525	65,561	18,912	-
Site 6	44,117	-	44,000	-
Site 7	51,000	-	36,822	-
Site 8	78,766	-	68,100	-
Site 9	104,000	-	44,000	-
Site 10	60,600	-	43,188	-
Site 11	45,703	45,703	-	38,508
Site 12	85,110	-	23,868	-
Site 13	25,000	-	18,240	-
Site 14	48,000	48,000	18,864	-

Table 2-2: Fleet size and composition per site for the three cases
Status quo based on information by bus operators; composition of pure diesel bus fleet and pure FCB fleet derived from replacement assumptions

Site	Pure diesel bus fleet		Status quo				Pure FCB fleet	
	# Diesel / Hybrid 12 m	# Diesel / Hybrid 18 m	# Diesel / Hybrid 12 m	# Diesel / Hybrid 18 m	# FCB 12 m	# FCB 18 m	# FCB 12 m	# FCB 18 m
Site 1	158 / -	- / -	133 / -	- / -	25	-	158	-
Site 2	37 / -	- / -	32 / -	- / -	5	-	37	-
Site 3	149 / -	16 / -	141 / -	16 / -	8	-	149	16
Site 4	1355 / -	- / -	1335 / -	- / -	20	-	1355	-
Site 5	208 / 47	34 / 12	196 / 47	34 / 12	12	-	255	46
Site 6	412 / -	- / -	392 / -	- / -	20	-	412	-
Site 7	229 / -	- / -	179 / -	- / -	50	-	229	-
Site 8	275 / -	- / -	255 / -	- / -	20	-	275	-
Site 9	79 / -	- / -	69 / -	- / -	10	-	79	-
Site 10	4154 / 3854	- / -	4134 / 3854	- / -	20	-	8008	-
Site 11	86 / -	14 / -	86 / -	2 / -	-	12	86	14
Site 12	95 / -	- / -	75 / -	- / -	20	-	95	-
Site 13	38 / -	- / -	33 / -	- / -	5	-	38	-
Site 14	110 / -	200 / -	90 / -	200 / -	20	-	110	200

2.1.1 Bus production

The production phase includes the raw material extraction, the production of components and the assembly of the bus. We used generic models for diesel and fuel cell buses to calculate the emissions associated with bus production, considering a 12 m and 18 m bus. For this simplified assessment, the existing diesel hybrid buses at two sites were assumed as conventional diesel buses.

The configurations for both bus types were based on the configuration of current bus models (Faltenbacher, et al., 2022). The specifications of the FCBs used for modelling are depicted in Table 2-3.

Table 2-3: FCB configuration based on Faltenbacher, et al. (2022)

Specification	12 m FCB	18 m FCB
Battery chemistry	LTO	LTO
Battery capacity [kWh]	36	54
FC power [kW]	70	100
Hydrogen storage [kg]	38	46
Battery life time [years]	6	6
FC life time [years]	6	6

2.1.2 Use phase

The use phase considers bus operation and bus maintenance. For the operation of the buses, the sites provided average information about diesel consumption that were collected within the framework of an additional data collection (see Table 2-4). For the hydrogen consumption of the FCBs, we used the site-specific values which have been gathered during the data monitoring of the JIVE projects. In case no site-specific value for hydrogen consumption could be gathered due to various reasons (buses not in operation, data collection issues etc.), the average consumption across all JIVE sites was used. For 12 m buses, this resulted in a specific hydrogen consumption of 7.2 kg H_2/100 km. For 18 m buses, the hydrogen consumption of FCBs at site 11 was taken, with a surcharge of 20 % to consider potential differences in operation and topography.

Table 2-4: Specific fuel consumption per site and bus technology
Diesel values provided by operators, hydrogen values according to JIVE data monitoring.
Light grey cells: Assumptions based on averages from the JIVE sites

Site	Diesel consumption [l/100 km]		Hydrogen consumption [kg H_2/100 km]	
	12 m	18 m	12 m	18 m
Site 1	32.67	-	6.6	-
Site 2	31.50	-	7.6	-
Site 3	60.71	83.03	6.3	10.3
Site 4	40.00	-	6.4	-
Site 5	42.00	42.70	8.6	10.3
Site 6	38.50	-	7.2	-
Site 7	38.10	-	8.7	-
Site 8	31.16	-	7.0	-
Site 9	26.30	-	9.0	-
Site 10	38.41	-	6.8	-
Site 11	39.50	54.00	7.2	8.6
Site 12	25.00	-	7.2	-
Site 13	38.22	-	8.4	-
Site 14	43.00	55.00	4.9	10.3

For the use phase also the maintenance of the buses was considered, covering tyre exchange and lubricants.

Diesel

The environmental impacts generated by the diesel supply are calculated with Sphera's MLC (Sphera, 1992-2023). For emissions generated by diesel combustion, the values in Table 2-5 are applied.

Table 2-5: Driving emissions of diesel buses with emission class Euro VI (Faltenbacher, et al., 2022)

Emissions during operation	12 m Diesel	18 m Diesel
NOx [g/km]	0.874	0.734
PM 2.5 [g/km]	0.0068	0.0077
CO_2 [g/km]	1,100	1,440

Hydrogen

The way of hydrogen generation is of high relevance for the environmental impact of the use phase. Since no complete information on the individual H_2 generation for all sites was available, three variants indicating the possible range of environmental impact related to the generation of hydrogen were used:

- H_2 generation by steam methane reforming
- H_2 generation by electrolysis with electricity from the current European grid mix (data refer to the European electricity grid mix in 2021)
- H_2 generation by electrolysis with electricity from wind

The steam methane reforming and the H_2 generation by electrolysis with electricity from the European grid serve as a worst case scenarios. The EU grid mix in these cases is also used for compression and dispensing. Electrolysis with electricity from wind power, which is also used for compression and dispensing, represents the best case with the lowest environmental effects. Since the hydrogen production is not always on-site, we assume a hydrogen transport at 200 bar over a distance of 50 km to the hydrogen refuelling station for all sites.

The environmental impacts from hydrogen supply are calculated with Sphera's MLC. (Sphera, 1992-2023). Figure 2-2 shows the greenhouse gas intensity of the three hydrogen production pathways considered in this study.

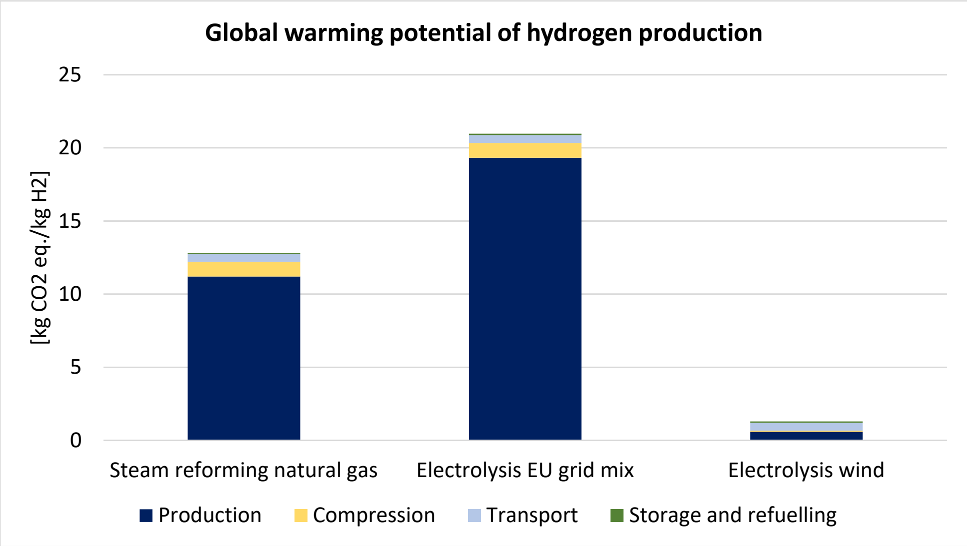

Figure 2-2: Global Warming Potential of hydrogen production pathways

The operation of the hydrogen buses is locally emission-free. Maintenance includes the battery and fuel cell replacement after 6 years as well as regular maintenance, meaning tyre exchange and lubricants.

2.1.3 End of life

The end of life of both vehicle types was calculated with Sphera's MLC (Sphera, 1992-2023). Analogue to bus production, we used generic models for the diesel buses as well as for the FCBs. In line with common LCA practice in the automotive industry, no credit for material or energy recovered from recycling were given.

2.2 Results

The results demonstrate the avoided emissions of total GWP, local NO_x emissions and local PM 2.5 emissions over the entire bus life cycle with an assumed lifetime of 12 years. The first figure displays the combined results for all JIVE sites, and the second for one exemplary site. The results for all other sites are given in tabular form as absolute and relative avoided emissions. As explained in Chapter 2.1, for all sites three cases are compared: A pure diesel bus fleet, a FCB fleet according to the JIVE projects replacing the corresponding number of diesel buses, and a pure FCB fleet. For each site the individual fleet size and mileage is taken into account (see Table 2-1 and Table 2-2).

2.2.1 Global warming potential

Under the current conditions in the European Union, hydrogen produced via electrolysis using the EU grid mix is associated with a high GWP due to the prevailing electricity generation from coal-fired power plants in several Member States (see Figure 2-2). As a consequence, the operation of fuel cell buses does not necessarily have a lower GWP than that of diesel buses. In these cases, the replacement of conventional power plants with renewable energy is of utmost importance for the reduction of CO_2-emissions by the deployment of locally zero-emission bus systems. Due to the high dependence on the national grid mix, we did not include this scenario in the figures to avoid possible misinterpretations.

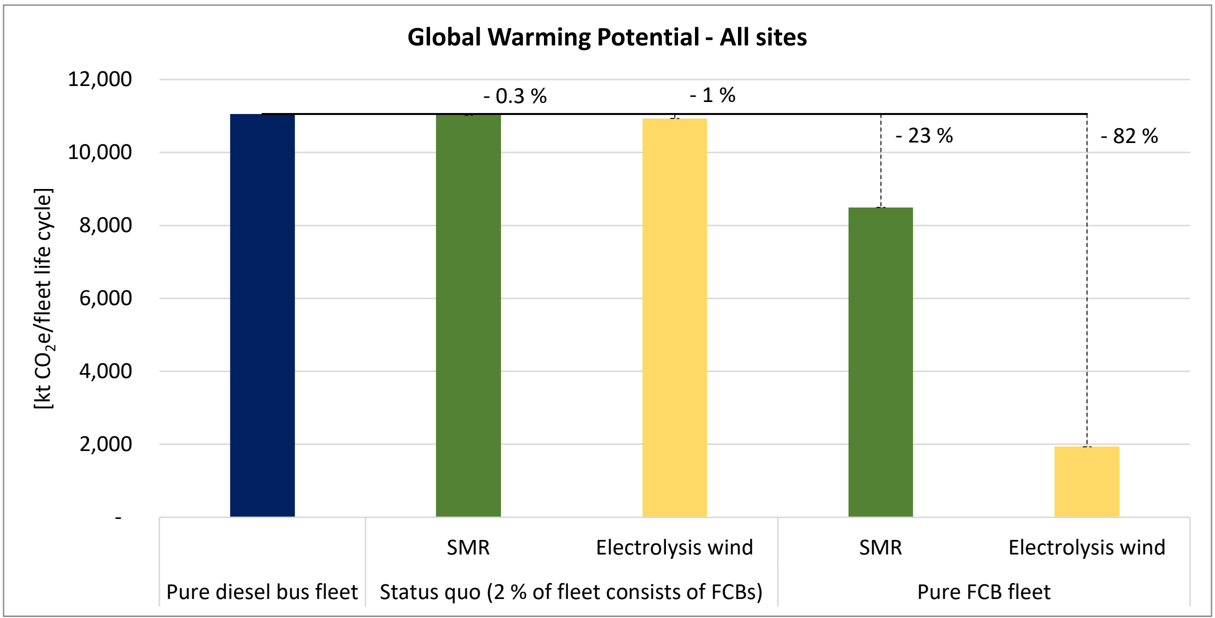

Figure 2-3: Global warming potential for diesel bus replacement by FCBs – All sites

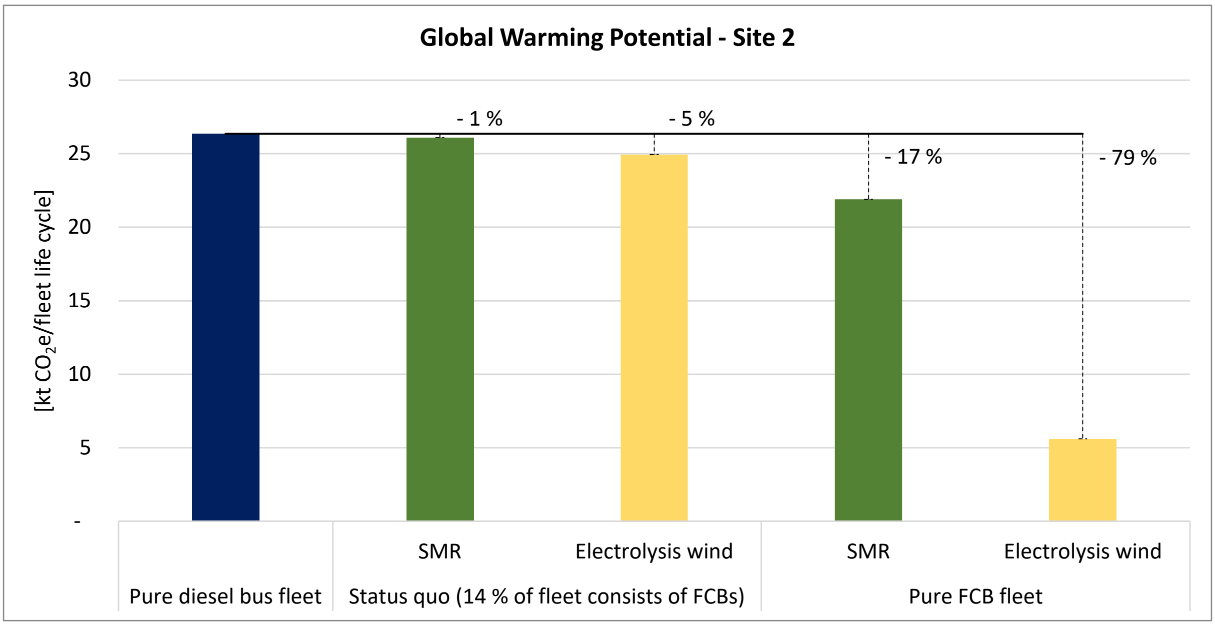

Figure 2-4: Global warming potential for diesel bus replacement by FCBs – Site 2

Table 2-6: Global warming potential for diesel bus replacement by FCBs – individual results for all sites (kt CO_2e/fleet life cycle and relative)
Light grey cells: Relative avoided emissions compared to the pure diesel bus fleet

Site	Pure diesel bus fleet	Status quo					Pure FCB fleet			
		Share of JIVE FCBs in fleet	SMR		Electrolysis Wind		SMR		Electrolysis Wind	
	Total GWP		Total GWP	Avoided emissions	Total GWP	Avoided emissions	Total GWP	Avoided emissions	Total GWP	Avoided emissions
Site 1	127.2	16%	121.5	-4%	110.3	-13%	92.7	-27%	23.8	-81%
Site 2	26.3	14%	26.1	-0.9%	24.9	-5%	21.9	-17%	5.6	-79%
Site 3	163.6	5%	162.3	-0.8%	160.4	-2%	107.3	-34%	27.0	-83%
Site 4	1475.0	1%	1474.4	-0.04%	1472.6	-0.2%	994.1	-33%	224.5	-85%
Site 5	234.4	4%	234.2	-0.1%	231.5	-1%	208.0	-11%	51.6	-78%
Site 6	315.6	5%	312.1	-1%	303.4	-4%	243.2	-23%	62.3	-80%
Site 7	188.8	22%	186.0	-1%	163.9	-13%	170.1	-10%	38.2	-80%
Site 8	346.9	7%	341.4	-2%	328.2	-5%	258.9	-25%	51.3	-85%
Site 9	119.4	13%	118.0	-1%	113.6	-5%	92.4	-23%	16.6	-86%
Site 10	7549.6	0.2%	7545.6	-0.1%	7537.5	-0.2%	5887.3	-22%	1327.9	-82%
Site 11	81.0	12%	78.6	-3%	73.1	-10%	55.9	-31%	15.7	-81%
Site 12	108.7	21%	107.5	-1%	102.7	-5%	85.6	-21%	17.3	-84%
Site 13	17.1	13%	16.5	-3%	15.9	-7%	10.8	-37%	4.6	-73%
Site 14	299.5	6%	299.3	-0.1%	294.6	-2%	264.3	-12%	68.2	-77%

2.2.2 Local nitrogen oxide emissions

Local NO_x emissions are independent on the hydrogen production method. Therefore, we do not consider the different H_2 production scenarios in the following. As the FCBs locally are emission-free, no local NO_x emissions are generated if we assume a pure FCB fleet.

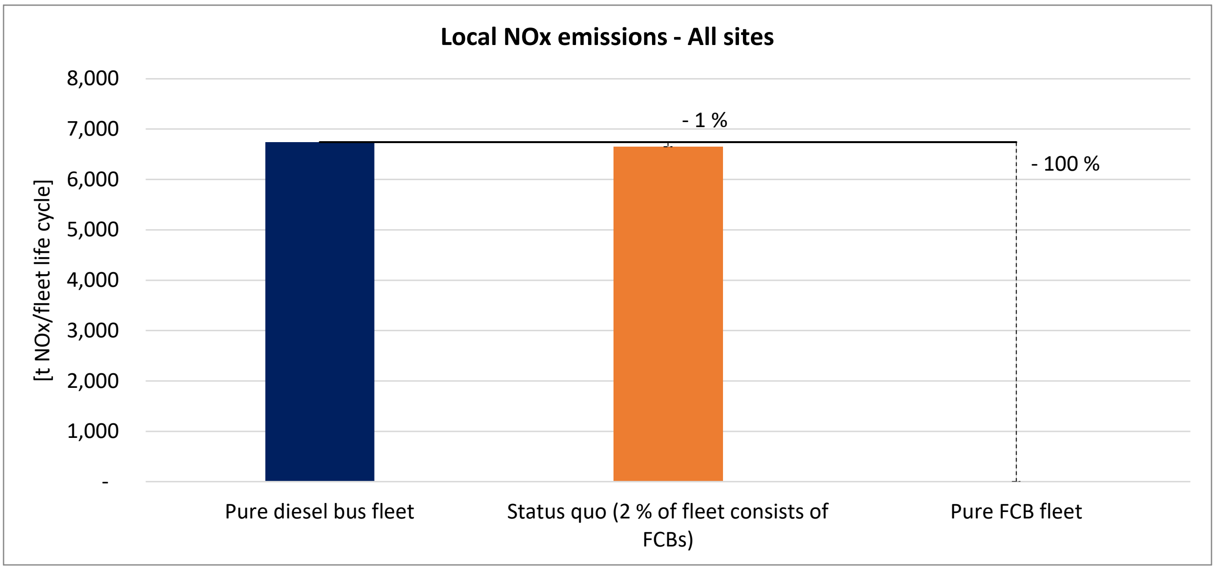

Figure 2-5: Local NO_x emissions – All sites

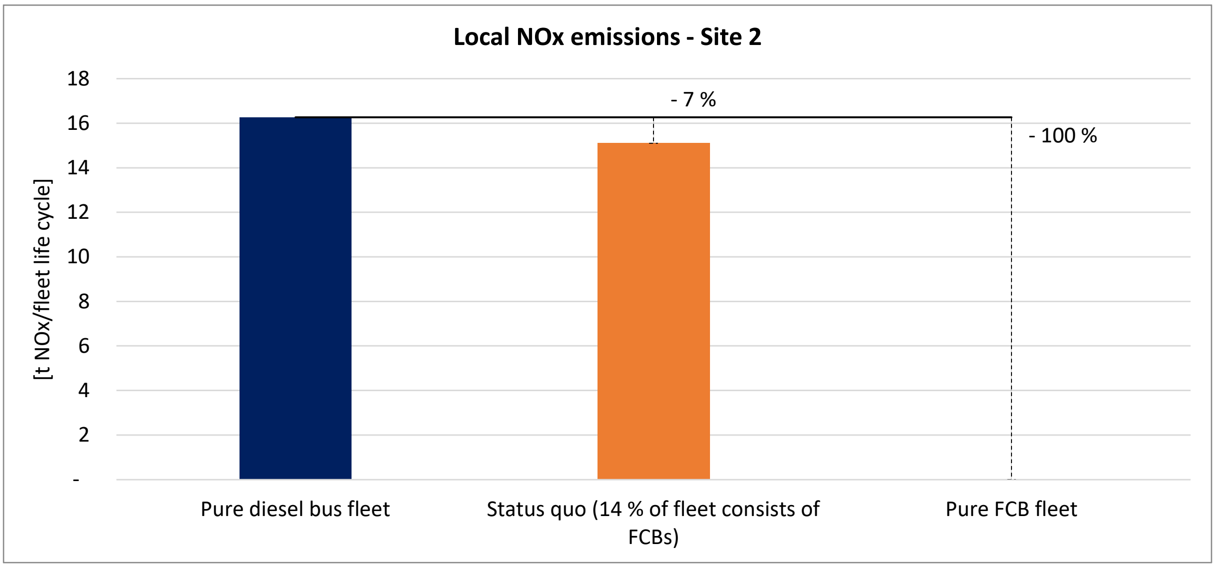

Figure 2-6: Local NO_x emissions – Site 2

Table 2-7: Local NOx emissions for diesel bus replacement by FCBs – individual results for all sites (t NOx/fleet life cycle and relative)
Light grey cells: Relative avoided emissions compared to the pure diesel bus fleet

Site	Pure diesel bus fleet	Status quo			Pure FCB fleet	
	Local NOx emissions	Share of FCBs in fleet	Local NOx emissions	Avoided emissions	Local NOx emissions	Avoided emissions
Site 1	79.1	16%	66.2	-16%	0	-100%
Site 2	16.3	14%	15.1	-7%	0	-100%
Site 3	86.3	5%	84.1	-2%	0	-100%
Site 4	912.2	1%	910.1	-0.2%	0	-100%
Site 5	126.6	4%	124.2	-2%	0	-100%
Site 6	190.6	5%	181.4	-5%	0	-100%
Site 7	115.1	22%	95.7	-17%	0	-100%
Site 8	224.9	7%	210.7	-6%	0	-100%
Site 9	79.9	13%	75.3	-6%	0	-100%
Site 10	4649.1	0.2%	4640.1	-0.2%	0	-100%
Site 11	46.1	12%	42.0	-12%	0	-100%
Site 12	72.0	21%	66.9	-7%	0	-100%
Site 13	9.6	13%	8.7	-10%	0	-100%
Site 14	133.8	6%	129.9	-2%	0	-100%

2.2.3 Local particulate matter emissions

Analogue to the local NO_x emission, local PM 2.5 emissions are also independent of the hydrogen production method. Hence, we again do not consider the three H_2 generation scenarios. Just as with NO_x emissions, no local PM 2.5 emissions are generated if we assume that the fleet consists entirely of FCBs.

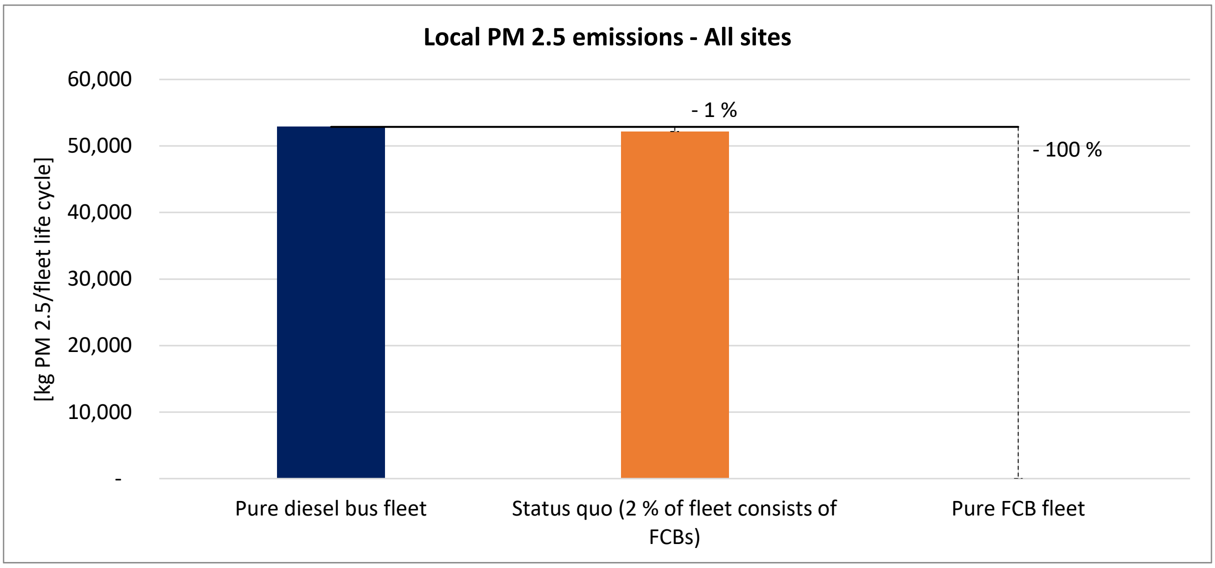

Figure 2-7: Local PM 2.5 emissions – All sites

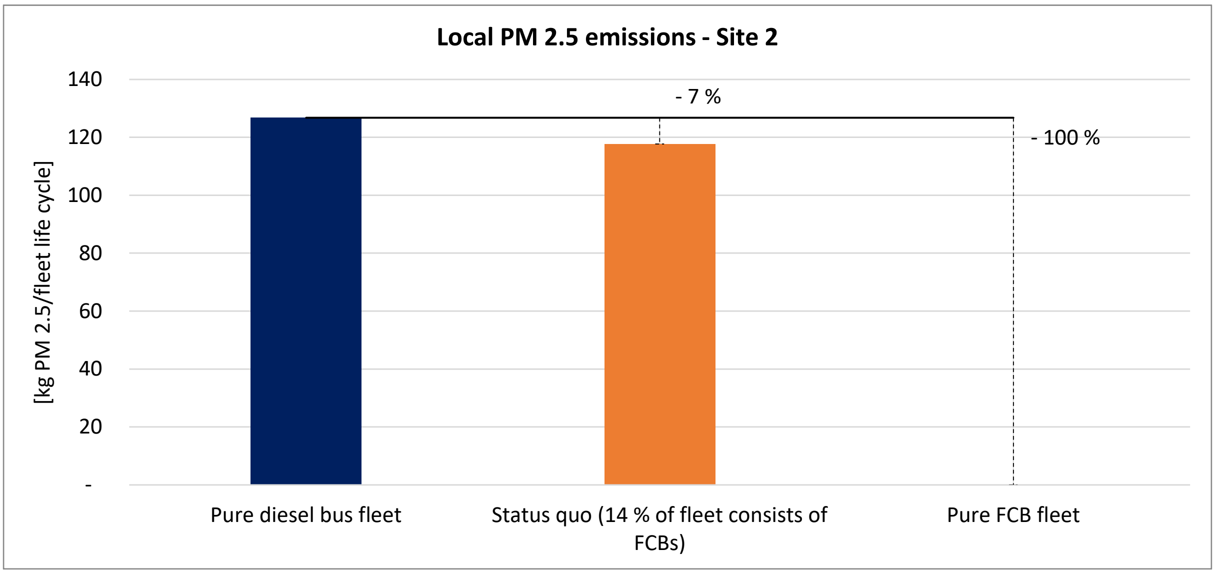

Figure 2-8: Local PM 2.5 emissions – Site 2

Table 2-8: Local PM 2.5 emissions for diesel bus replacement by FCBs – individual results for all sites (kg PM 2.5/fleet life cycle and relative) Light grey cells: Relative avoided emissions compared to the pure diesel bus fleet

Site	Pure diesel bus fleet	Status quo			Pure FCB fleet	
	Local NOx emissions	Share of FCBs in fleet	Local NOx emissions	Avoided emissions	Local NOx emissions	Avoided emissions
Site 1	616.7	16%	516.0	-16%	0	-100%
Site 2	126.7	14%	117.7	-7%	0	-100%
Site 3	702.5	5%	685.2	-2%	0	-100%
Site 4	7107.7	1%	7091.3	-0.2%	0	-100%
Site 5	1059.5	4%	1041.0	-2%	0	-100%
Site 6	1485.2	5%	1413.3	-5%	0	-100%
Site 7	896.5	22%	746.0	-17%	0	-100%
Site 8	1752.7	7%	1641.4	-6%	0	-100%
Site 9	622.4	13%	586.4	-6%	0	-100%
Site 10	36224.8	0.2%	36154.3	-0.2%	0	-100%
Site 11	372.6	12%	329.7	-12%	0	-100%
Site 12	560.6	21%	521.6	-7%	0	-100%
Site 13	74.9	13%	67.4	-10%	0	-100%
Site 14	1275.5	6%	1244.7	-2%	0	-100%

2.3 Discussion

With the replacement of diesel buses by FCBs, all local combustion related emissions are avoided. Because the FCBs operate locally emission free, no NO_x or PM 2.5 emissions are generated during their operation. The assumption of a pure FCB fleet thus results in the complete avoidance of local air pollution emissions.

The reduction in GWP strongly depends on the hydrogen production pathway and the electricity mix used. With the assumption of hydrogen from electrolysis using electricity from wind power at all JIVE sites, an overall GWP reduction of 82 % can be achieved. If all sites used hydrogen produced from steam reforming, this would leads to an overall GWP reduction of 17 %.

Within the JIVE projects only a small share of the bus fleets was replaced by FCBs, so even with hydrogen from electrolysis using electricity from wind power there is only a minor reduction in GWP compared to the diesel-only fleet. The absolute and relative avoided emissions differ for each site due to the consideration of site-specific conditions, e.g. number of buses, share of FCBs, mileage, and fuel consumption. For instance at site 10, the absolute emissions avoided are significant, but the relative difference is comparably low for all impact categories because of the large overall fleet size.

The presented results depict an approximation of the avoided emissions. For further convergence, detailed site-specific information would be necessary, inter alia, diesel emission classes for all vehicles and the specific electricity mix used for hydrogen production.

3 External costs avoided by FCBs

3.1 Approach

Based on the environmental impacts avoided as depicted in Chapter 2, this Chapter presents the related external costs avoided. As in Chapter 2, we distinguished the three cases of fleet composition:

- Pure diesel bus fleet - fleets consists entirely of diesel buses
- Status quo - current fleet composition; fleet consists of diesel buses and FCBs
- Pure FCB fleet - fleet consists entirely of FCBs

We also took into account the two hydrogen production scenarios described in Chapter 2.2: hydrogen via steam methane reforming and hydrogen via electrolysis using electricity from wind. To determine the total external costs, we used the approach described in Chapter 1.3, considering the avoidance costs of climate change and the damage costs for local NO_x and PM 2.5 emissions.

The calculation of the external costs is thus based on the results of Chapter 2, the environmental impacts of the different scenarios, as well as country-specific cost factors retrieved from the Handbook on external costs of transport. Therefore, within the site-specific approach, generic data and assumptions are included.

The external costs of noise were not included, because noise reduction could not be quantified within the scope of this report. Other important external cost categories like congestion and accidents were assumed to be equal for diesel and hydrogen buses.

3.2 Results

3.2.1 Overall quantification of external costs avoided by FCB

As in the previous chapter, the avoided external costs are presented for all JIVE sites combined and for one exemplary site, Site 2. The results for all other sites can be found in Table 3-1.

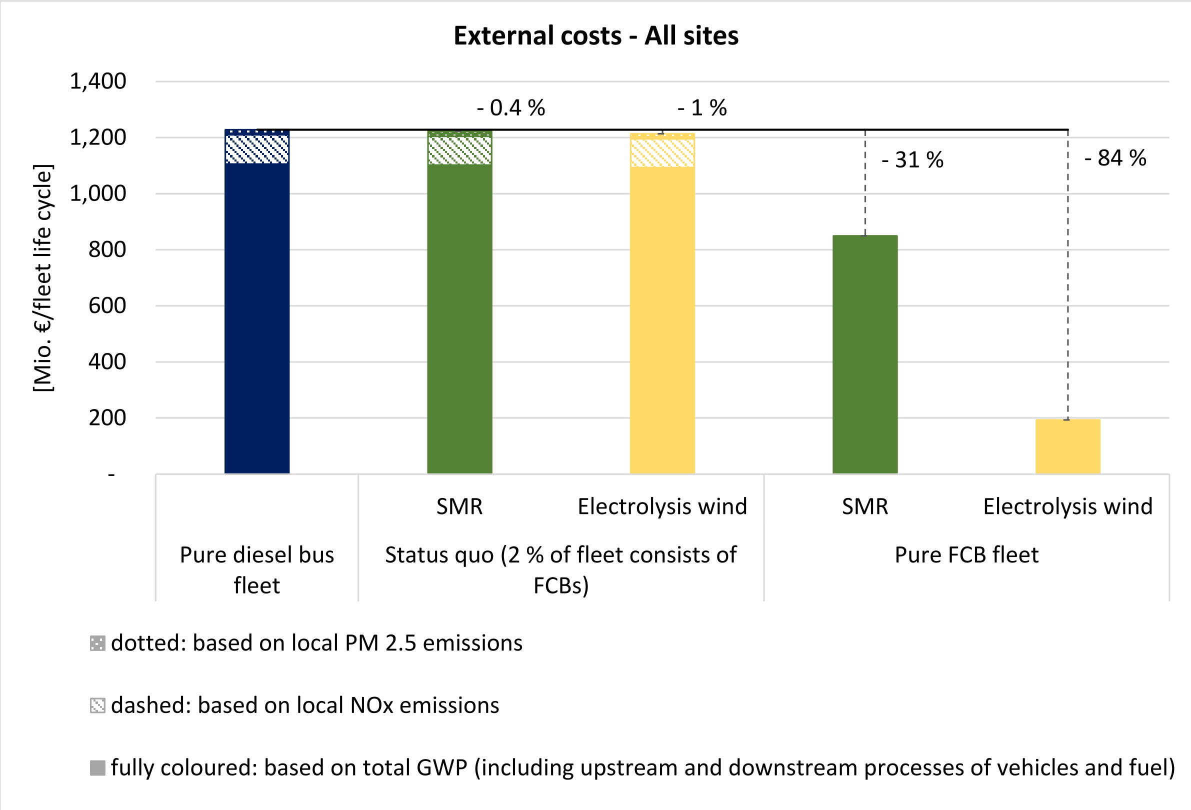

Figure 3-1: External costs – All sites

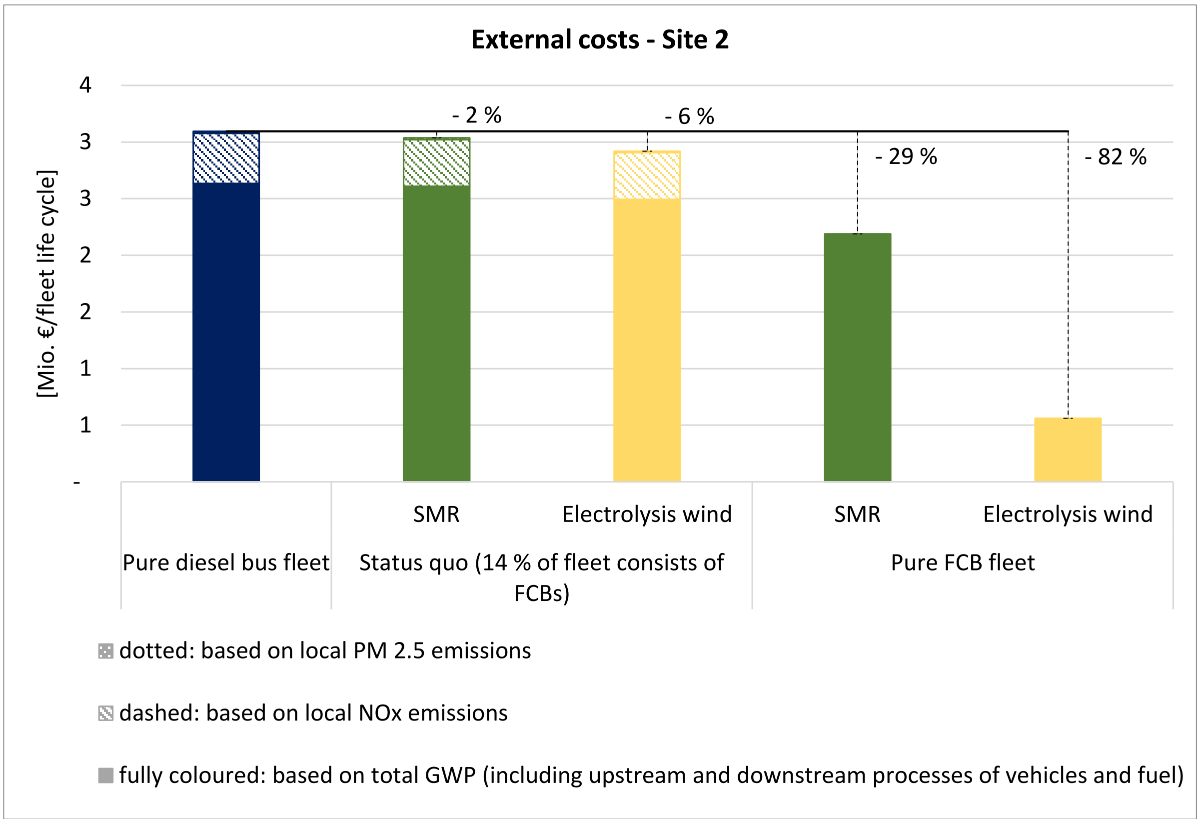

Figure 3-2: External costs – Site 2

Table 3-1: External costs for diesel bus replacement by FCBs – individual results for all sites (Mio. €/fleet life cycle)
Light grey cells: Relative avoided external costs compared to the pure diesel bus fleet

Site	Pure diesel bus fleet	Status quo					Pure FCB fleet			
		Share of FCBs in fleet	SMR		Electrolysis Wind		SMR		Electrolysis Wind	
	Total external costs		Total external costs	Avoided external costs	Total external costs	Avoided external costs	Total external costs	Avoided external costs	Total external costs	Avoided external costs
Site 1	13.9	16%	13.1	-5%	12.0	-14%	9.3	-33%	2.4	-83%
Site 2	3.1	14%	3.0	-2%	2.9	-6%	2.2	-29%	0.6	-82%
Site 3	17.3	5%	17.2	-0.9%	17.0	-2%	10.7	-38%	2.7	-84%
Site 4	162.6	1%	162.5	-0.06%	162.3	-0.2%	99.4	-39%	22.4	-86%
Site 5	26.8	4%	26.7	-0.3%	26.4	-1%	20.8	-22%	5.2	-81%
Site 6	34.3	5%	33.9	-1%	33.0	-4%	24.3	-29%	6.2	-82%
Site 7	23.5	22%	22.5	-4%	20.2	-14%	17.0	-28%	3.8	-84%
Site 8	40.9	7%	40.0	-2%	38.7	-6%	25.9	-37%	5.1	-87%
Site 9	14.2	13%	13.9	-2%	13.4	-5%	9.2	-35%	1.7	-88%
Site 10	832.0	0.2%	831.4	-0.1%	830.6	-0.2%	588.7	-29%	132.8	-84%
Site 11	9.4	12%	9.0	-4%	8.5	-10%	5.6	-40%	1.6	-83%
Site 12	12.9	21%	12.6	-2%	12.1	-6%	8.6	-33%	1.7	-87%
Site 13	2.0	13%	1.9	-4%	1.8	-7%	1.1	-46%	0.5	-77%
Site 14	35.1	6%	34.9	-0.5%	34.4	-2%	26.4	-25%	6.8	-81%

3.2.2 Average external costs per vehicle kilometre

Besides the overall quantification, the external costs per vehicle km associated with the operation of a FCB in comparison to the operation of a diesel bus were calculated. This allows local council administrations to quantify the associated external effects of operating FC buses instead of conventional diesel buses. For this purpose, we used the generic 12 m bus models and assumed an average mileage of 50,000 km/a over the lifetime of 12 years. For the fuel consumption, we used the average of all JIVE sites, resulting in a diesel consumption of 37.1 l/100 km and a hydrogen consumption of 7.2 kg H_2/100 km. For the average external costs, we used the external cost factors for city areas in the European Union given in Table 1-1 and Table 1-2. The resulting average external costs per vehicle km are depicted in Table 3-2.

Table 3-2: External costs for bus operation per vehicle kilometre in € ct/vehicle km
Composition of damage costs for local NO_x and PM 2.5 emissions as well as climate change avoidance cost based on total GWP (including upstream and downstream processes of vehicles and hydrogen)

External costs [€ ct/vehicle km]	12 m Diesel (Emission class VI)	12 m FCB	
		SMR	Electrolysis wind
Damage costs for local NOx emissions	1.9	-	-
Damage costs for local PM 2.5 emissions	0.1	-	-
Avoidance costs for total GWP	14.2	10.7	2.5
Total external costs	**16.2**	**10.7**	**2.5**

It should be noted that In the Handbook on the external costs of transport (European Commission, 2019), external costs per vehicle kilometre are also given for several vehicle types and emission classes. Despite both calculations are based on the same external cost factors, the calculated values presented here cannot be directly compared to these figures. Most important, the here presented values are specifically calculated based on the input and results of the LCA in Chapter 2, e.g. the assumed fuel consumption. Furthermore, the Handbook considers several other external cost categories like accidents or congestion, which were not in the scope of our analysis.

3.3 Discussion

The external costs are dominated by the costs for greenhouse gas emissions which account for more than 90 % of the total external costs. With the replacement of diesel buses by FCBs, NO_x and PM 2.5 emissions are completely avoided, and external costs are only related to CO_2e-emissions.

Due to the consideration of the GWP across all life cycle phases, the hydrogen production method has a significant impact on the avoided and potentially avoided external costs. In accordance with the results on avoided environmental impacts in Chapter 2, the H_2 production by electrolysis using electricity from wind power results in the lowest external costs. When the entire fleet is replaced, external costs can be reduced by 84 %. Related to the vehicle kilometre, this corresponds to a reduction from 16.2 € ct/km for a diesel bus to 2.5 € ct/km for an FCB.

As for the environmental assessment, individual results for the sites depend on the specific situation (number of buses, share of FCBs, etc.) and therefore show some significant variation.

PART II

Comparison of fuel cell with battery electric bus systems against operational, economic and environmental parameters

This part includes the contents of JIVE 2 D4.3

4 Approach and boundary conditions

The goal of Part II is to compare FCBs with BEBs with regard to their environmental, economic and operational performance under comparable operating conditions. In contrast to Part I, we did not use a generic approach. We rather based our analysis on specific data and information from two sites deploying both bus technologies in parallel (see Chapter 1.2). However, although the real data reflect bus configurations used for comparable purposes, there are notable differences in individual parameters (see Table 4-1) that clearly impact the ecological as well as economic assessment. One example is the different unladen weight of FCBs and BEBs. The different framework conditions of the sites (e.g., H_2 production path, mileage, configuration of the charging and refuelling infrastructure) also have a significant influence on the results.

Therefore, it has to be pointed out that the results only depict the situation at the two sites investigated, and do not allow any general statement about the advantageousness of one of the bus drivetrain technologies. Furthermore, the results of Part I and Part II are independent of each other and cannot be directly compared due to the different underlying methodological approach. For reasons of anonymization, the site numbers are also different for both parts, meaning site 1 in Part I is not the same site as site 1 in Part II.

If necessary, information and data gaps were filled with values from literature or previous projects, the results for the environmental and economic performance thus entail uncertainties. Therefore, we performed a sensitivity analysis to assess the robustness of our results. The following table presents the received information and data as well as the assumptions made for the LCA and TCO analysis in this Part II.

Table 4-1: Specifications and assumptions for comparison of FCBs and BEBs in regard to their environmental and economic performance.
Data delivered by bus operators except for values in light grey cells: Assumptions made based on values from literature and previous projects.

	Parameter	Site 1		Site 2	
		FCB	BEB	FCB	BEB
Bus specifications	Bus type	Double-deck	Double-deck	Solo	Solo
	Bus manufacturer	Wrightbus	Optare	Van Hool	Ebusco
	Bus model	Streetdeck FCEV	Metrodecker	A330 FC	2.2
	Bus length [m]	10.9	10.5	12	12
	Bus empty weight [kg]	12,050	11,180	13,755	12,850
	Hydrogen storage [kg]	27	-	38.5	-
	Battery type; capacity [kWh]	LTO; 27.4	LFP; 300	LTO; 24	LFP; 362
	Battery replacement after [a]	8	8	8	8
	FC power [kW]	85	-	83	-
	FC lifetime [h]	35,000	-	35,000	-
	FC replacement after [a]	-	-	10	-
Bus operation	Charging strategy	-	Depot	-	Depot
	Annual distance driven [km/a]	58,000	58,000	94,000	94,000
	Annual operating hours [h/a]	2,827	2,827	3,558	3,558
	Fuel consumption - vehicle [kg H_2/100km, kWh/100km]	6.4	133	6.7	110
	Efficiency charging infrastructure [%]	-	88 %	-	88 %
	Fuel consumption - effective [kg H_2/100km, kWh/100km]	6.4	151	6.7	125

	H_2 production method	Chlor-Alkali electrolysis	-	Alkaline electrolysis	-
	Electricity mix	Grid mix	Grid mix	100 % wind	100 % wind
	H_2 infrastructure	Delivered, compressed, trailer	-	Delivered, compressed, trailer	-
	H_2 transport distance [km]	320	-	316	-
Economic parameters	Bus price [€]	664,000	531,675	625,000	450,000
	Specific maintenance and repair cost [€/km]	0.88	0.88	0.88	0.88
	Battery cost [€/kWh]	400	250	400	250
	Cost degression – battery [% p.a.]	4	4	4	4
	Fuel cell cost [€/kW]	1,000	-	1,000	-
	Cost degression – fuel cell [% p.a.]	9	-	9	-
	Fuel price [€/kg H2, €/kWh]	6.8	0.18	7.0	0.21
	Driver cost [€/h]	17.5	17.5	25	25
	Additional driver hours [%]	10	10	10	10
	Annual increase in driver, fuel and maintenance cost [% p.a.]	2	2	2	2
	Infrastructure investment [€]	2,717,000	2,000,000	Included in H_2 price	2,000,000
	Annual infrastructure maintenance cost [€/year]	93,000	100,000	Included in H_2 price	100,000
	Number of buses infrastructure is designed for	40	60	20	60
	Infrastructure lifetime [a]	20	12	15[5]	12

[5] Included for completeness, but not relevant for the TCO because infrastructure costs are included in H_2 price.

Bus specification

At site 1, two double-deck models served as basis for comparison: the FCB model Wrightbus Streetdeck FCEV and the BEB model Optare Metrodecker. At site 2, the FCB model Van Hool A330 FC and the BEB model Ebusco 2.2 were considered as two solo 12 m bus models. The empty vehicle weight including battery ranges between 11,180 kg and 13,755 kg, with the BEBs having a lower weight at both sites. Both FCB models are equipped with an LTO battery, while the BEB models are furnished with an LFP battery. Battery replacements are assumed after 8 years according to average values found in literature and guarantees by manufacturers, e.g. (Ebusco Deutschland GmbH, n.d.). According to the bus operator at site 1, a fuel cell lifetime of 35,000 hours is expected. With the given annual operating hours, it was assumed that a fuel cell replacement is not required in this case. At site 2, no information on the expected fuel cell lifetime was available from the bus operator. Therefore, the same fuel cell lifetime as for site 1 is assumed, requiring a replacement after 10 years due to the higher number of yearly operating hours.

Bus operation

The BEBs at both sites are exclusively charged at the depot. According to the two bus operators, the charging sessions are not limited to overnight charging. One additional charging session during the day frequently occurs. BEBs and FCBs have not been deployed to the same extent at the sites. However, to allow comparison, the same mileage and operating hours were assumed for both technologies, resulting in 58,000 km/a for site 1 and 94,000 km/a for site 2. The fuel consumption at site 1 with 6.4 kg H_2/kWh and 133 kWh/100 km is the average value from a seven-month operating period of 20 FCBs and 34 BEBs. For site 2, the average vehicle hydrogen consumption of 6.7 kg H_2/100 km was retrieved from the JIVE data collection. The average vehicle electricity consumption of 110 kWh/100 km was stated by the bus operator without further information about the representativeness. To consider losses during the BEB charging process and therefore to determine the effective electricity consumption, an efficiency of the charging infrastructure of 88 % was assumed (Faltenbacher, et al., 2022). Efficiency losses during hydrogen upstream processes were included in the hydrogen supply, see Chapter 1.3.

At site 1, the hydrogen is generated as by-product of chlor-alkali electrolysis using the EU grid mix and then transported over 320 km at 200 bar via diesel trailer. The BEBs are charged with electricity from the national grid mix.

At site 2, the delivered hydrogen is produced via alkaline electrolysis with the use of electricity from 100 % wind power, that is also used to charge the BEBs. The hydrogen is transported as compressed H_2 via diesel trailer over a distance of 316 km. According to information by the operator, around 800 kg H_2 are transported with each delivery trip, a pressure of 500 bar is thus assumed.

Economic parameters

The indicated bus price is the price per vehicle for the transaction between the bus manufacturer and the bus buyer without the consideration of grants or subsidies. The stated bus prices vary between 450,000 € (BEB, site 2) and 664,000 € (FCB, site 1). At site 1, the specific costs of the self-performed FCB maintenance and repair including labour and parts was stated as around 0.88 €/km. Since no information about the maintenance costs was perceived for the three other bus models, this value was assumed to be equal for all bus models. For the potential component replacement, a current price of 400 €/kWh for a LTO battery and 250 €/kWh for a LFP battery was assumed, compare for example Burke and Miller (2020). A future annual cost degression of 4 % per year was expected. For the fuel cell, a current price of 1,000 €/kW (compare for example Faltenbacher, et al., 2022) with an annual future cost degression of 9 % per year was assumed, due to expected higher cost reductions resulting from expected economies of scale. Hydrogen prices stated by the operators represent fixed prices per year. For electricity, prices between 0.18 €/kWh (site 1) and 0.21 €/kWh (site

2) were indicated. The stated fuel prices reflect hydrogen and electricity prices as perceived in July/August 2022. An annual increase by 2 % is assumed in driver, fuel and maintenance costs.

The infrastructure investment and maintenance costs were allocated according to the number of buses the infrastructure had been designed for. For the FCBs at site 1, an infrastructure investment of 2,717,000 € was stated, with annual maintenance costs of 93,000 €/year, allocated to 40 buses. With a linear depreciation over the lifetime of 20 years, the remaining infrastructure value after the bus lifetime was credited. In contrast, at site 2 the infrastructure costs were included in the hydrogen price.

For the BEBs at site 2, an infrastructure investment of 2,000,000 € was stated with annual infrastructure maintenance costs of 100,000 €/year. The infrastructure had been designed for 60 buses. A contractual lifetime of 10 years was specified by the operator but with a technically longer possible lifetime. Therefore, an effective lifetime of 12 years and neither a replacement nor a remaining value was assumed. For the BEBs at site 1, no information was available, wherefore all infrastructure-related costs were adopted from site 2.

Driver cost rates include labour and social security contributions. For the calculation of the annual driver costs, these values were multiplied with the annual driver hours. These in turn were determined by taking the bus operating hours as basis plus an assumption of 10 % for the consideration of driver changes and breaks.

To calculate the NPV of payments, a discount rate of 4 % is assumed.

5 Environmental performance

For the comparison of FCBs and BEBs in terms of their environmental performance, we followed the LCA approach as described in Chapter 1.4 with the functional unit defined there as city bus operation over the service lifetime of 12 years. The assessment related to the operation of a single FCB versus a BEB under the specific operating conditions as detailed in Chapter 4. The environmental impact was limited to greenhouse gas emissions because FCBs and BEBs both operate locally emission free, so that NO_x and PM 2.5 emissions are not relevant for this comparison, For each site, the GWP associated with both bus technologies regarding the entire life cycle of bus production, fuel supply, bus maintenance including component replacements, and end-of-life was compared.

Because of the different approach, the results of this analysis cannot be compared to the values in Chapter 2.2.1.

5.1 Results

In the following, the results of the LCA for the operation of both vehicle types at the two sites are displayed and elaborated.

5.1.1 Site 1

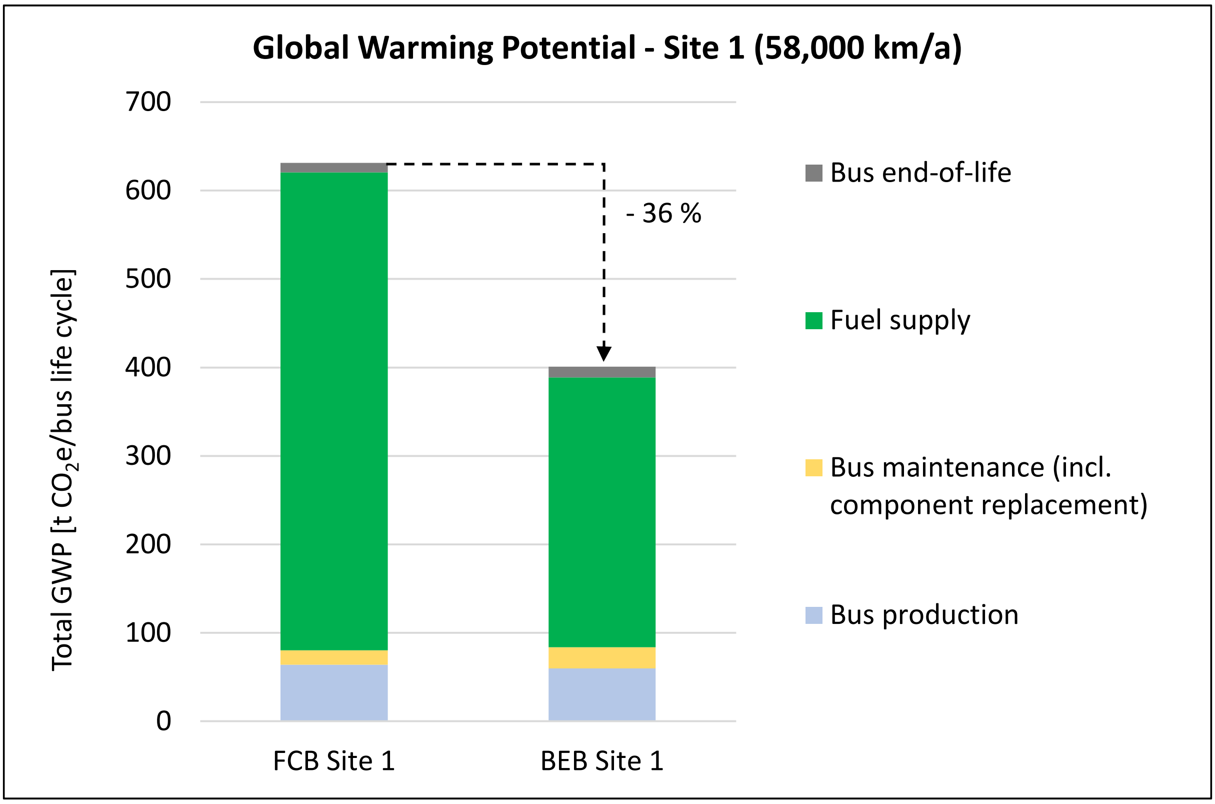

Figure 5-1: GWP for FCBs and BEBs at site 1 (Mileage: 58,000 km/a)

At site 1, the total GWP of the FCB equals 631.4 t CO_2e, while the GWP of the BEB amounts to 401.0 t CO_2e. This results in a lower GWP of the BEB at this site by 36 %.

The production phase of the FCB and the BEB at site 1 represents in both cases the life cycle phase with the second highest contribution to the GWP. For the FCB, the production phase has a share of 10 % of the GWP with 63.8 t CO_2e, while for the BEB, the phase has a share of 15 % with 59.9 t CO_2e. The GWP of production is thus 6 % lower for the BEB than for the FCB.

The GWP associated with the bus basis of the FCB is equal to 35.5 t CO_2e, while the GWP of the bus basis of the BEB amounts to 29.7 t CO_2e due to its lower empty bus weight. In turn, the GWP of the specific drivetrain components is higher for the BEB with 30.1 t CO_2e compared to 28.4 t CO_2e for the FCB due to the significantly higher capacity of the BEB battery.

This higher GWP of the BEB battery is also reflected in bus maintenance: While the GWP of regular maintenance such as tire changes is equally high for both technologies with 13.2 t CO_2e, the GWP related to the battery replacement is 10.8 t CO_2e for the BEB and 3.2 t CO_2e for the FCB. In this case, no fuel cell replacement is assumed according to the expected fuel cell lifetime and operating hours over the bus lifetime. Therefore, the total maintenance's GWP is 32 % lower for the FCB than for the BEB. Compared to the other life cycle stages for each bus technology, bus maintenance has a share of 3 % (FCB) and 6 % (BEB) and thus represents the life cycle phase with the second lowest contribution (after end of life, see below).

The fuel supply represents for both buses at this site the life cycle stage with the significantly highest contribution to the GWP with 86 % (FCB) and 76 % (BEB). The GWP associated with the hydrogen supply for the FCB equals 540.4 t CO_2e. This applies for the operation case of 58,000 km/year over 12 years and the hydrogen being produced as by-product of chlor-alkali-electrolysis and transported by diesel trailer at 200 bar over 320 km, and then further compressed to 440 bar at the HRS. In comparison, the GWP associated with the electricity supply for the BEB amounts to 304.8 t CO_2e and is therefore 44 % lower.

End-of-life represents for both bus technologies at site 1 the life cycle phase with the lowest share of the GWP. For the FCB, end-of-life accounts for 10.8 t CO_2e, equivalent to 2 % of the GWP, and for the BEB, end-of-life contributes 12.3 t CO_2e, equivalent to 3 % of the GWP. Therefore, the end-of-life GWP of the FCB is 12 % lower than the one of the BEB.

5.1.2 Site 2

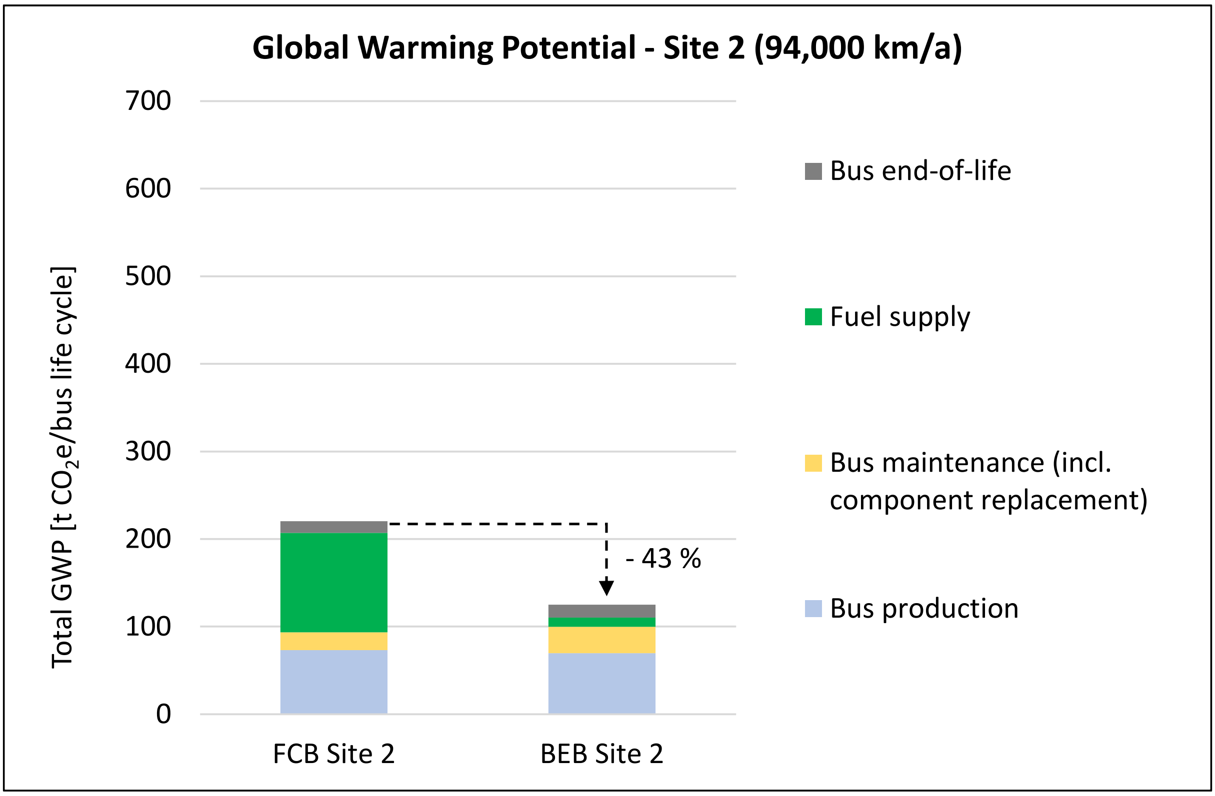

Figure 5-2: GWP for FCBs and BEBs at site 2 (Mileage: 94,000 km/a)

In total, the GWP associated with the FCB at site 2 equals 220.5 t CO_2e, while the GWP associated with the BEB at site 2 amounts to 125.1 t CO_2e, and thus around 43 % lower than the one of the FCB. Compared to Site 1, the significantly lower GWP for both bus types is noticeable. The high difference results primarily from the different electricity mixes and hydrogen production methods used during the use phase (see below).

For both buses, the production phase contributes a significant share of the GWP with 73.2 t CO_2e corresponding to 33 % (FCB), and 69.8 t CO_2e corresponding to 56 % (BEB), respectively. The GWP for production is therefore 5 % lower for the BEB than for the FCB. The GWP of the bus basis of the FCB amounts to 42.1 t CO_2e and exceeds that of the BEB with 34.8 t CO_2e, because also at site 2 the empty weight of the FCB model is higher than that of the BEB model. On the other hand, the GWP associated with the drivetrain specific components is higher for the BEB with 35.0 t CO_2e in comparison to the FCB with 31.0 t CO_2e, again due to the higher capacity of the BEB battery.

Analogue to site 1, the GWP of regular maintenance including lubricant and tire changes is equally high for both technologies, here with 16.9 t CO_2e due to the higher mileage requiring more frequent maintenance. The battery replacement for the BEB after 8 years amounts to 13.0 t CO_2e. The battery replacement after 8 years and the fuel cell replacement for the FCB after 10 years amounts to 4.3 t CO_2e. In total, this results in a 32 % lower GWP for maintenance for the FCB, contributing to around 9 % (FCB) and 24 % (BEB) to the total GWP, respectively.

For the operation case of 94,000 km/year and considering effective consumptions of 6.7 kg H_2/100 km and 125 kWh/100 km, the GWP of the fuel supply of the FCB is around ten times higher than the one of the BEB. With an electricity mix of 100 % wind power, the GWP associated with fuel supply of the BEB amounts to 10.6 t CO_2e over the entire bus life cycle. This equals a share of 8 % of the total GWP and represents the phase with the lowest contribution for the BEB. In contrast, with electricity from 100 % wind power used for hydrogen generation and a transport over 316 km by diesel trailer at assumed 500 bar, the GWP of the hydrogen supply amounts to 113.6 t CO_2e over the entire life cycle, representing the phase with the highest contribution to the total GWP with 52 %.

For the FCB at site 2, the end-of-life represents the life cycle phase with the lowest share of the GWP with 6 % and 13.4 t CO_2e. For the BEB, the GWP associated with the end-of-life accounts for 14.9 t CO_2e which equals 12 % of the GWP. Therefore, end-of-life represent the life cycle stage with the second lowest contribution to the GWP of the BEB. Comparing the two technologies, end-of-life GWP of the FCB is 10 % lower than of the BEB, again due to the higher battery capacity of the BEB.

5.2 Sensitivity analysis

A sensitivity analysis was conducted for several parameters to determine their impact on the results of the assessment of the GWP at the two sites. Using a ceteris paribus assumption, the following parameters were varied:

- No component replacements were assumed for BEBs as well as FCBs

- Hydrogen transport distance
- Specific hydrogen consumption of FCBs
- Specific electricity consumption of BEBs

In Figure 5-3 and Figure 5-4, the results are presented as rounded integer percentage difference between the GWP of the BEB and that of the FCB. The x-axis indicates the relative advantageousness of the BEB over the FCB in positive figures, with the black centre line indicating the initial results, i.e. the GWP of the BEB being 36 % (site 1) and 43 % (site 2) lower than that of the FCB. The blue horizontal bars show the change in advantageousness for the specified parameter variation, rounded to full percent.

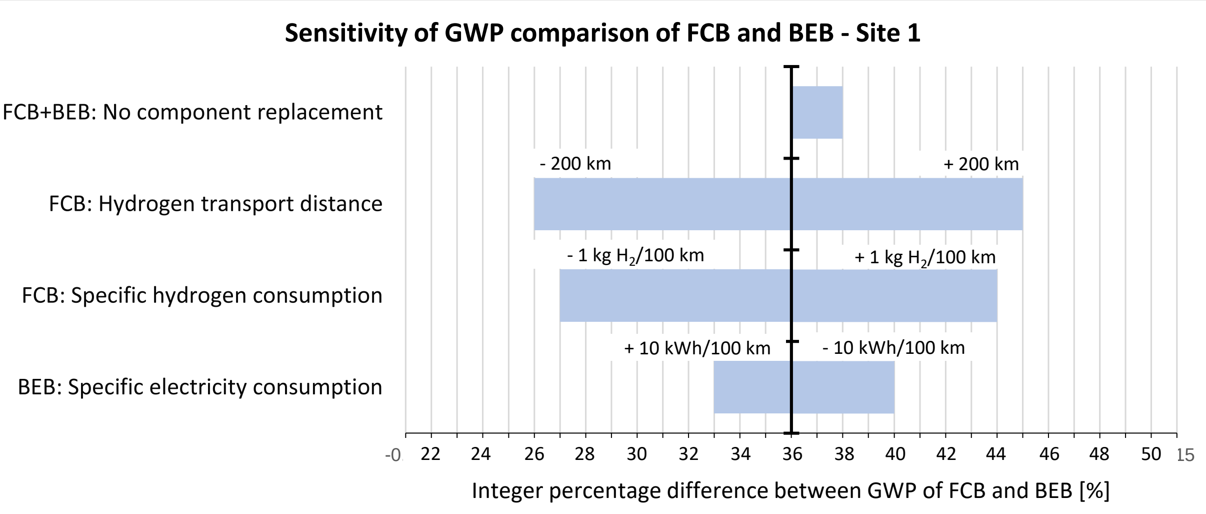

Figure 5-3: Sensitivity analysis of GWP comparison of FCB and BEB at site 1

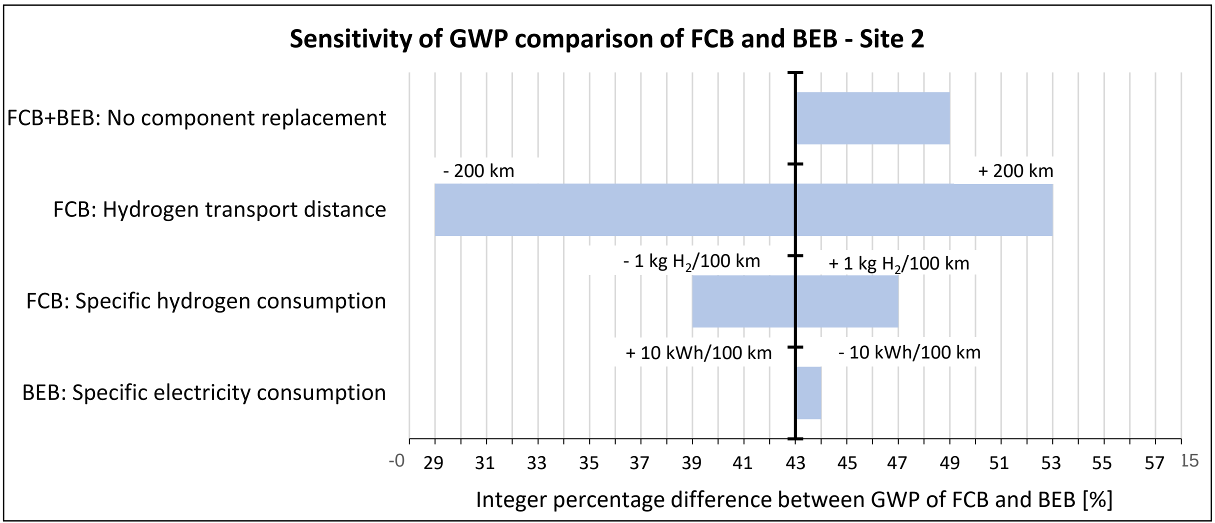

Figure 5-4: Sensitivity analysis of GWP comparison of FCB and BEB at site 2

We assumed for both bus technologies that battery and fuel cell replacements are not required. Due to the significant higher battery capacity of the BEBs, their GWP is proportionally more reduced, resulting in an increased difference of the GWP between the different drivetrains at both sites. For site 2, the variation is even higher because maintenance represents a higher share of the GWP.

The use phase represents the phase with the highest relevance for the comparison of the environmental impact of FCBs and BEBs. Therefore, the variation of the hydrogen transport distance as well as the specific hydrogen consumption results in a significant alteration of the relative difference between the GWP of the two bus technologies. At site 2, the GWP associated with the electricity consumption is already low in the initial calculations due to the use of electricity from 100 % wind power. Therefore, a variation of the electricity consumption does not show a visible effect on the overall results at this site.

5.3 Discussion

When considering the global warming potential as impact category, the LCA indicates environmental advantages of BEBs at both sites. Fuel supply is decisive for the climate impact, with hydrogen production and reconversion to electricity implying high efficiency losses compared to the direct use of electricity in BEBs. The resulting climate impact strongly depends on the origin of the electricity and hydrogen used. The results demonstrate that the use of renewable energy can significantly reduce the climate impact for both bus systems.

The sensitivity analysis shows that especially the variation of parameters related to the hydrogen supply chain can significantly change the relative difference between the GWP of both bus technologies. For the two sites investigated, the environmental advantageousness of the BEB remains stable for the assumed variations because of the additional energy consumption for hydrogen generation.

The presented results are highly dependent on the local conditions, specifications and assumptions made. Therefore, they are exclusively applicable to the considered cases and cannot be used for general statements.

6 Economic performance

The economic performance was evaluated with a TCO analysis as described in Chapter 1.3, considering bus and infrastructure procurement, use and maintenance, and potential credits at the end-of-life. The functional unit is defined as city bus operation over the service lifetime of 12 years.

6.1 Results

In the following, the results of the TCO analysis for the operation cases at both sites are displayed and explained. The TCO of FCBs and BEBs were compared for both sites considering bus procurement, maintenance, driver and fuel costs as well as infrastructure. TCO results are given as the Total Cost of Ownership for a single bus over its entire lifetime of 12 years, with the specific mileage as indicated by the site, and a share of infrastructure costs according to the FCB and BEB fleet size, respectively.

6.1.1 Site 1

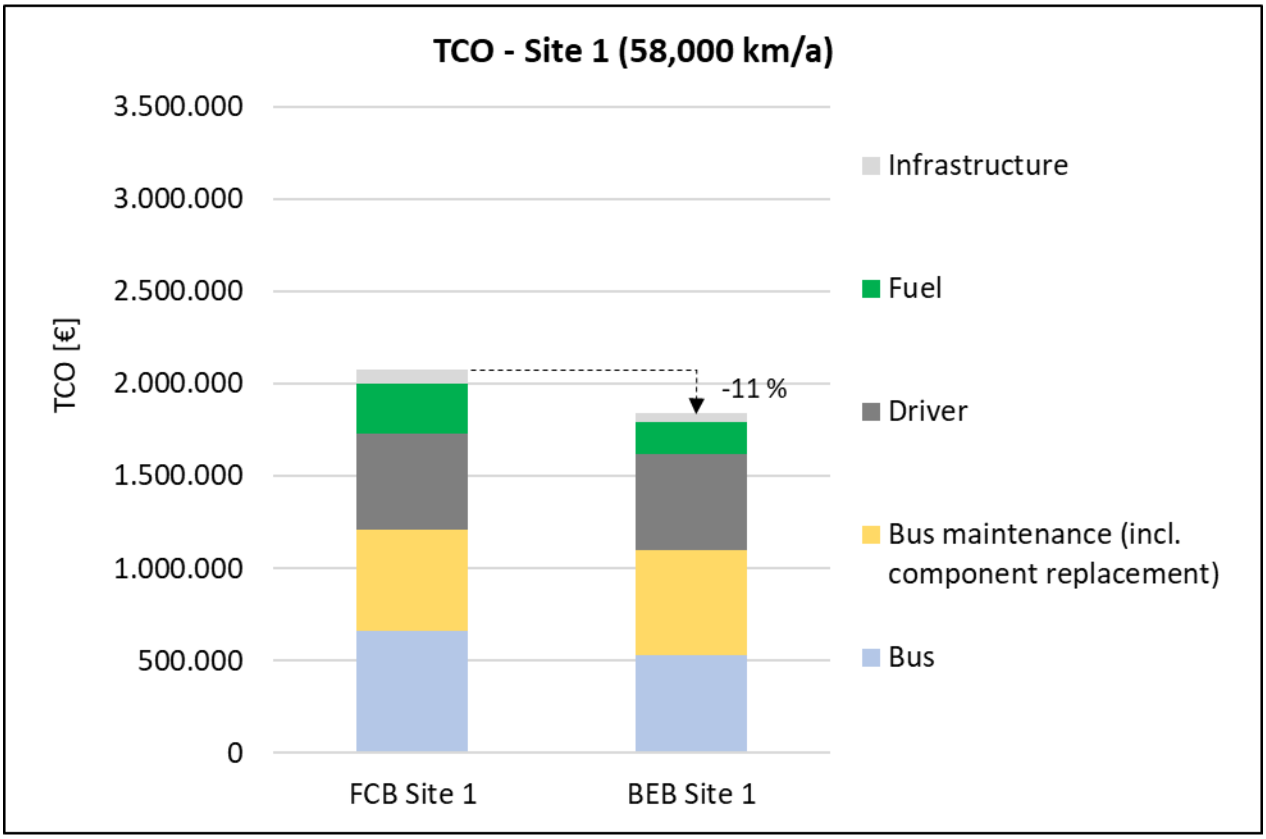

Figure 6-1: Results of the TCO analysis for FCBs and BEBs at site 1 (Mileage: 58,000 km/a)

At site 1, the TCO of the FCB amounts to around 2,074,000 € for the operation case of 58,000 km/year over 12 years. In comparison, the TCO of the BEB is around 1,853,000 € and thus 11 % lower. The bus investment occurs in t = 0 and is represented by the bus price without considering subsidies or grants. Here, the BEB price of around 532,000 € is 24 % lower than the FCB price of 664,000 €. For both example buses at this site, the bus investment contributes to a high share of the TCO with 32 % for the FCB and 29 % for the BEB.

Bus maintenance includes regular maintenance activities and potential battery and fuel cell replacements. The regular bus maintenance is assumed to be equal for both technologies and represents the major part of maintenance cost with around 541,000 € over the 12 years. Since no fuel cell replacement is assumed for the FCB at this site, the costs for the battery replacement add to the maintenance cost for both technologies, considering a potential further use after the bus lifetime by credits. Taking into account the significantly higher capacity of the BEB battery on the one hand, but the higher specific costs per kW for the FCB LTO battery on the other, this results in total maintenance costs for the BEB of around 566,000 €, and for the FCB of around 545,000 €. Therefore, the total maintenance costs of the FCB at site 1 are around 4 % lower than those of the BEB.

Driver costs are equal for both bus technologies but are included in the analysis due to their high share on the total costs. Under the site-specific operation conditions, driver costs sum up to around 524,000 €, representing a significant share of the TCO with 25 % (FCB) and 28 % (BEB), respectively.

Over the entire bus lifetime of 12 years, fuel costs are calculated to be 37 % lower for the BEB than for the FCB. For the FCB, hydrogen costs sum up to around 266,000 €, which represents 14 % of its TCO. For the BEB, electricity costs account for 167,000 € and thus 13 % of its TCO. In both cases, fuel costs represent therefore the cost category with the second lowest contribution to TCO.

Based on the data and assumptions for the charging and refuelling infrastructure, infrastructure costs including investment and maintenance over the bus life cycle are 27 % lower for the BEB than for the FCB, summing up to around 76,000 € for the FCB and to around 55,000 € for the BEB. For both technologies, the cost category therefore represents the one with the lowest contribution to TCO with 4 % (FCB) and 3 % (BEB), respectively.

6.1.2 Site 2

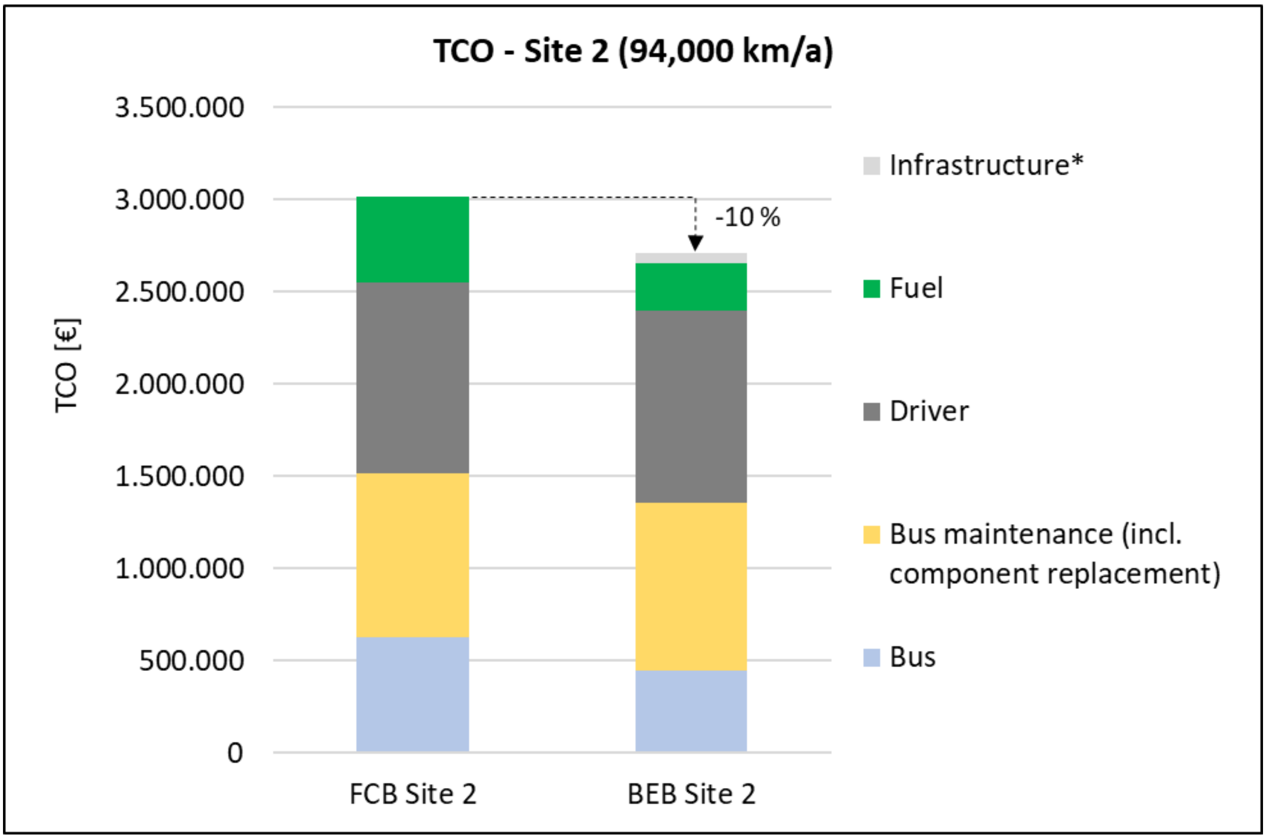

Figure 6-2: Results of the TCO analysis for FCBs and BEBs at site 2 (Mileage: 94,000 km/a)
* For FCBs, the hydrogen price includes the infrastructure costs

For the operation case of 94,000 km/year over 12 years at site 2, the TCO at this site adds up to around 3,031,000 € for the FCB and to around 2,272,000 € for the BEB, the TCO of the BEB therefore being 10 % lower than the one of the FCB. In this case, the bus price of the BEB equals 450,000 € and is 28 % lower than the price of the FCB with 625,000 €. The bus investment contributes a share of the total TCO of 21 % (FCB) and 17 % (BEB).

Again, the regular bus maintenance was assumed to be equal for both technologies with around 877,000 € over the bus lifetime. For the FCB, a fuel cell replacement after 10 years, and for both bus types, a battery replacement after 8 years were assumed. The component replacement accounts for additional 7,000 € (FCB) and 30,000 € (BEB) when the remaining value of the replaced components after the bus lifetime is deducted. In total, the maintenance costs of the FCB account for 29 % of the TCO and are 2 % lower than the maintenance costs of the BEB, which represents 34 % of its TCO.

At site 2, the driver costs are for both bus technologies the cost category with the highest share of the TCO: They sum up to 1,070,000 € over the bus lifetime of 12 years with 94,000 km/year. This results in a share of the TCO of 34 % (FCB) and 38 % (BEB), respectively.

For the FCB, the infrastructure costs are included in the hydrogen price. When fuel and infrastructure costs are summarized, they sum up to around 310,000 € (BEB) compared to 467,000 € (FCB). Therefore, the fuel supply and infrastructure costs of the BEB are 33 % lower than the hydrogen cost for the FCB. For the BEB, fuel and infrastructure costs together account for 10 % of the TCO, while for the FCB, fuel and infrastructure costs represent 15 % of the TCO.

6.2 Sensitivity analysis

Analogous to the sensitivity analysis for the LCA, a variation of several parameters took place to determine their impact on the results of the TCO analysis for FCBs and BEBs at the two sites. Using a ceteris paribus assumption, the following parameters were varied:

- No component replacements were assumed for BEBs as well as FCBs
- Bus price
- Hydrogen price

In Figure 6-3 and Figure 6-4, the results are presented as rounded integer percentage difference between the TCO of the FCB and the TCO of the BEB for both sites. The x-axis represents the initial results with the TCO of the BEB being 11 % (site 1) and 10 % (site 2) lower than the GWP of the example FCB. In case the rounded percentage difference equals the initial result, no bar is displayed.

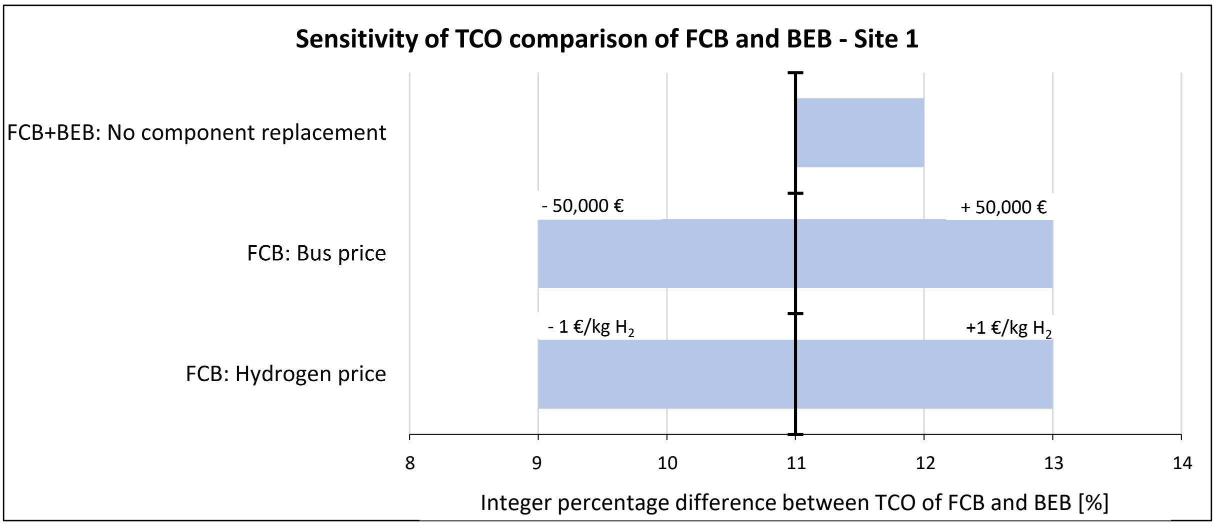

Figure 6-3: Sensitivity analysis of TCO comparison of FCB and BEB at site 1

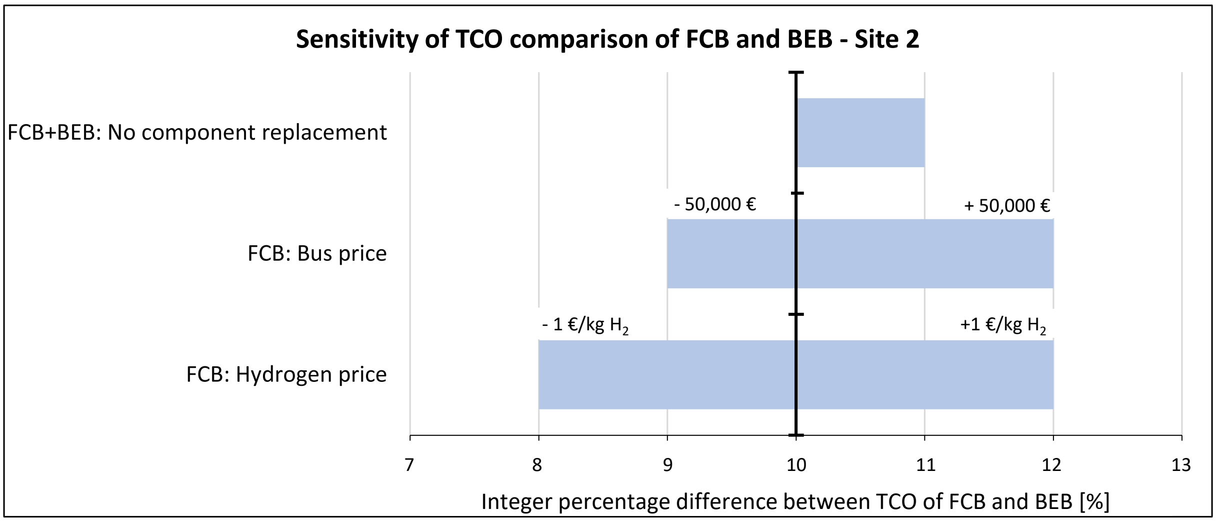

Figure 6-4: Sensitivity analysis of TCO comparison of FCB and BEB at site 2

Analogous to the sensitivity analysis for the LCA, we assumed that neither for the FCB nor the BEB, components need to be replaced. Due to the higher capacity of the BEB battery, this variation increases the percentage difference at both sites by 1 %. A variation of the FCB price by 50,000 € as well as of the hydrogen price by 1 €/kg H_2 reduces, respectively increases, the percentage difference at both sites up to 2 %.

6.3 Discussion

Based on the received information and data from the two sites, the results show advantages of the BEBs in term of their economic performance at both sites at the current conditions. The main causes are lower bus purchasing prices as well as lower fuel costs.

The sensitivity analysis thus shows the significant effects of the alteration of these parameters. However, the BEB stays advantageous for all variations. However, the relative advantageousness of the BEB is in the order of 10 % only, and it's not completely unlikely that a further reduction in bus or hydrogen price may reverse the situation. A such reduction seemed to be unlikely at the time of writing and was thus not considered.

As for the LCA, it needs to be noted that the performed TCO analyses depend on the local conditions. Accordingly, any conclusion is only valid in consideration of the assumptions made and may not be generalised.

7 Operational performance

In the following, FCBs and BEBs are compared in terms of their operational performance, including vehicle and infrastructure availability, range, refuelling vs. recharging time, space implications for infrastructure, and passenger capacity.

Not for all parameters concrete and comparable values were available for the sites. Values depend on multiple parameters, like recharging and refuelling concept, dimensioning of the infrastructure, or the distance (and thus time to shuttle) to the HRS. Operational performance generally cannot be expressed by a single value, and often specific advantages are associated with drawbacks in other aspects. Hence, operational performance is discussed qualitatively based on site information and information from previous projects to highlight conditions and preferences under which FCBs show advantages in comparison with BEBs.

7.1 Availability

Generally, availability serves as an indicator of the maturity of a technology.

7.1.1 Vehicle availability

One of the objectives of the JIVE projects has been to operate fuel cell buses with an average fleet availability of at least 90 %.

In JIVE, availability data was available for 11 sites operating in total 154 FCBs. Previous projects (Faltenbacher, et al., 2022) provided data from 18 transport companies which operated depot and opportunity charging BEBs. Figure 7-1 shows the comparison of fleet availability based on these two sets of data.[6]

[6] The BEB figures were obtained during a one-time query at the operators, while the JIVE data is based on the continuous performance assessment. Because of this difference, the comparability of the two datasets may be limited.

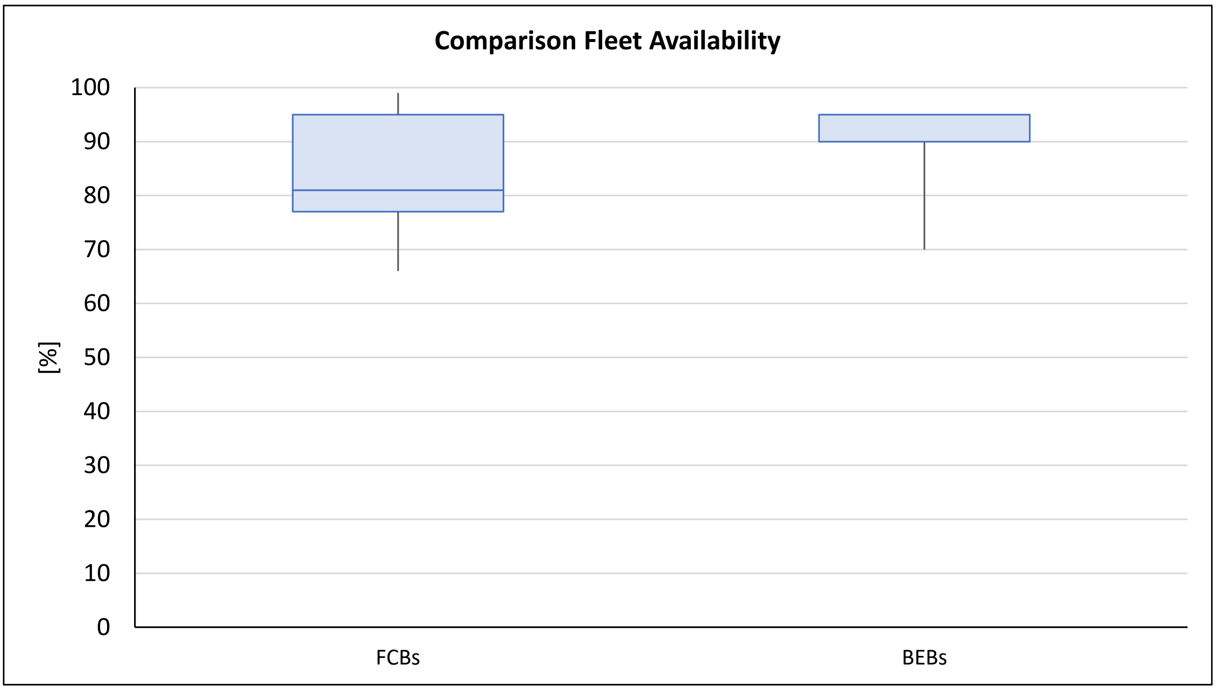

Figure 7-1: Comparison of fleet availability
Based on data from the JIVE projects and Faltenbacher, et al. (2022)

The median availability of the considered buses is 81 % for the FCBs and 90 % for the BEBs. However, the range of availability is quite similar for both technologies. The best performing FCB fleet even shows a higher availability than the best performing BEB. The FCBs generally show a wider variation in availability, while the availability of the BEBs mostly is in a comparably narrow range at high level. The high variation may be related to the fact that all FCBs are new bus models being the first time in regular service, so they display a comparably high number of teething issues. In contrast, the BEBs mostly are already further enhanced follow-up models or at least have had a longer service time, leading to a more stable operation with far less downtimes. Accordingly, it can be expected that the availability of the FCBs should increase with the further maturation of the technology.

Figure 7-2 shows the stated downtime reasons for FCBs, while Figure 7-3 shows the downtime reasons for BEBs.

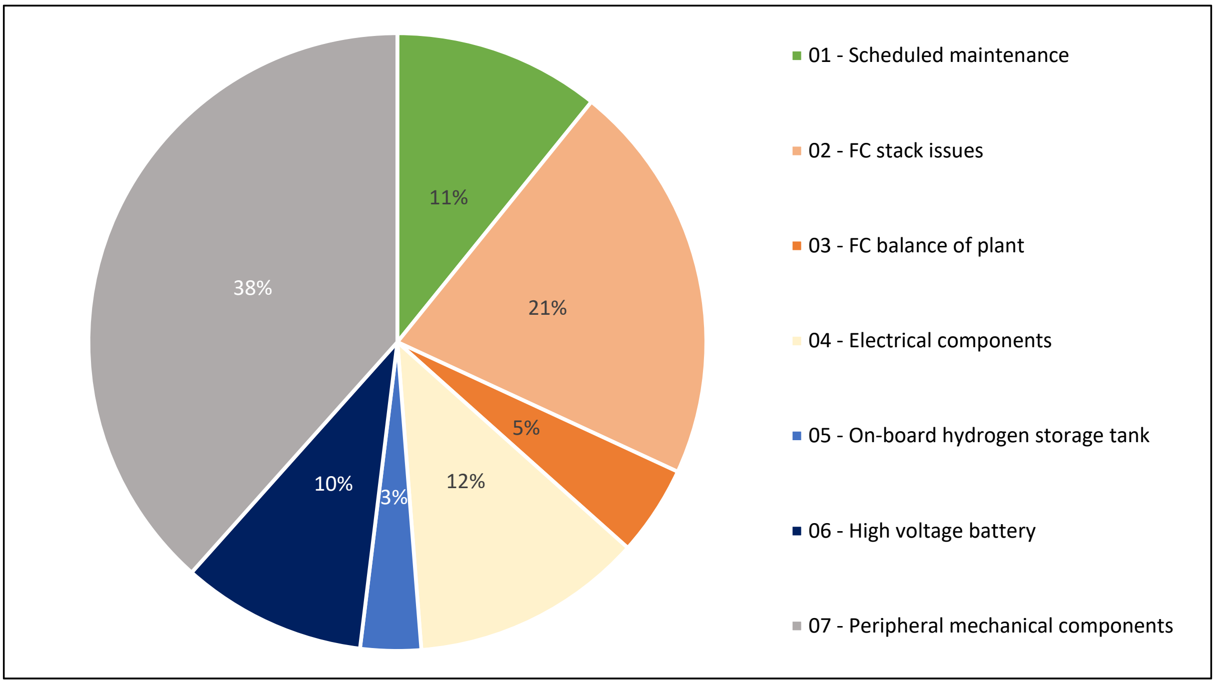

Figure 7-2: Downtime reasons FCBs
Based on data from the JIVE projects

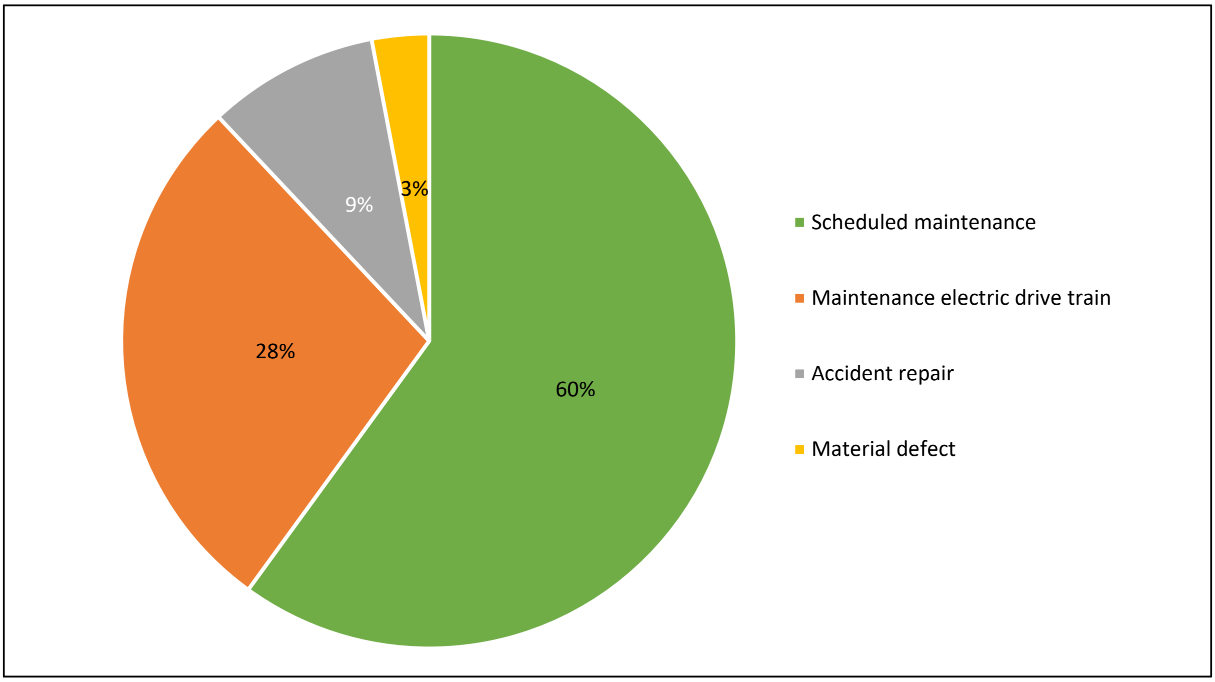

Figure 7-3: Downtime reasons BEBs
Based on data from Faltenbacher, et al. (2022)

For the FCBs, nearly 40 % of downtime is related to peripheral mechanical components which are not related to the drivetrain technology. These faults may thus be an indicator for teething issues of the newly developed FCBs, that may often occur with any new bus model, and that are supposed to decline significantly with further bus deployment and model development. Additionally, along with the increased experience and further advancement of the fuel cell technology, also the downtime related to the technology-related components (FC stack, FC balance of plant, hydrogen storage, HV battery) can be expected to decline substantially. It can be seen that for the BEBs, the electric drivetrain related maintenance has a share of 28 % on the entire downtime, what is a significantly lower technology related share than for FCBs but still a but still a considerable percentage.

It should be emphasized that despite the lower technological maturity of the FCBs, some models and fleets achieve an availability of up to 99 % which is equivalent to conventional diesel bus fleets.

7.1.2 Infrastructure availability

The basis for a reliable bus operation is a functioning fuel supply infrastructure. While the performance of the electricity supply is essential for battery electric buses, for fuel cell buses a continuous hydrogen supply has to be ensured. Based on data from JIVE and from Faltenbacher et al. (2022), Figure 7-2 shows a comparison of the availability of the hydrogen refuelling stations (HRS) and the charging infrastructure. The median availability for the HRS is 92 % while the one of the chargers is 98 %.

It has to noted that according to the definition established the HRS is also unavailable when there is no more hydrogen. It became apparent that a consistently stable supply chain was not given at all locations. In particular, the high electricity prices led in some places to the hydrogen production by electrolysis being reduced or even discontinued in order to directly market the electricity far more profitably. Also longer downtimes of the electrolyser unit finally led to a reduced HRS availability, as well as other disruptions of the supply chain, like a limitation in H_2 transport capacity due to missing trailers. Unfortunately, data did not allow quantitative statement on the different failure causes was possible.

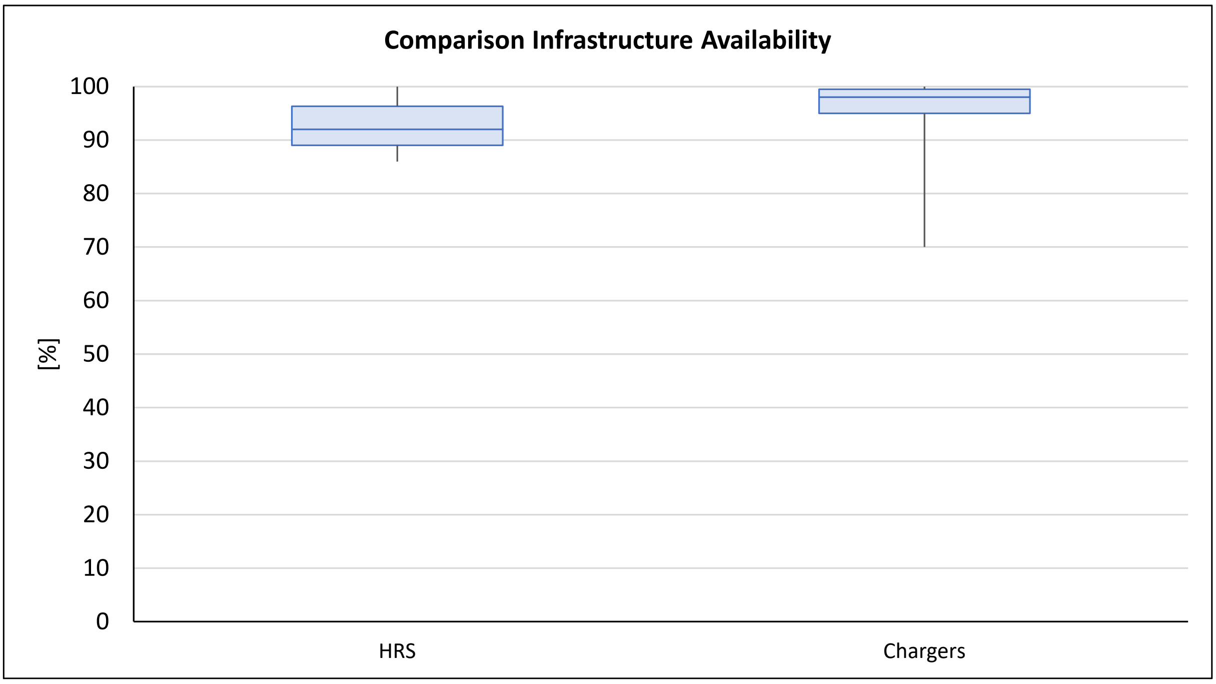

Figure 7-4: Comparison of infrastructure availability
Based on data from the JIVE projects and Faltenbacher, et al. (2022)

A high infrastructure availability is crucial for a reliable bus operation, as there is often little (or even no) redundancy for infrastructure. However, as for the buses, also the refuelling stations and, if applicable, the electrolysers are new technologies facing multiple teething issues. Accordingly, the availability target of 98 % for the hydrogen station units (and thus at the same level as the charging infrastructure) is expected to be achieved at the end of the JIVE projects.

7.2 Range

Meeting operator's range requirements is a crucial factor for alternative bus drivetrains to fully replace diesel buses. Two factors determine the range: the specific energy consumption, and the installed battery capacity or hydrogen storage, respectively. With regard to the energy demand, the selected heating concept plays a crucial role for electric buses. For example, if heating is purely electric in line with completely emission-free operation, the achievable range of BEBs on cold winter days can be reduced by up to 50 %, dropping far below the minimum range of 200 km required by the majority of operators. Energy consumption of the FC buses increases to a lesser extent at low temperatures, and they can provide an operating range of at least 300 km also in winter. (Faltenbacher, et al., 2022).

According to the JIVE performance assessment, the H_2 consumption of the FCBs is below 7 kg H_2/100 km at several sites. Even with a hydrogen tank capacity of 27 kg like for the FCB at site 1 (see Chapter 4), this results in a regular range of 350 km with one fill. A larger tank with a storage capacity of 38 kg H_2 (as it is the case for the bus model at site 2) easily allows a range of more than 500 km under normal operating conditions and thus in the range of diesel buses. Fuel cell buses therefore offer significant advantages for bus schedules with high range requirements.

This is also reflected in the information received from the two examined JIVE sites deploying both bus systems. At both sites, the BEBs are frequently charged twice per day with an intermediate charge at the depot, while the FCBs are usually refuelled once. Moreover, site 2 stated that the BEBs are mainly deployed for routes inside the city, while the FCBs are also utilized for longer distances outside the city.

One operator stated that according to internal calculations approx. 80 % of his routes would be achievable with a BEB on a 1-to-1 replacement, considering an upper limit of future BEB range capability of 260 km. Additionally, various duties within the schedule would far exceed the mean distance, so the maximum duty scheduled distance per route could be quite large in comparison to the average. This would only be possible to mitigated to a certain degree, e.g., by a good charging strategy. If this will not be possible and additional work and time has to be made within the schedule, this additional time, driver expense and perhaps extra buses would need to be considered. We know from other studies, e.g., Faltenbacher, et al. (2022), that 10-35 % additional buses are considered when replacing diesel buses with BEBs. This would significantly impact the ecological and the economic comparison and could even reverse the result in favour of the FCB, as we assumed a 1-on-1 replacement for this study. The operator further pointed out that for intermediate charging during the day, what could avoid the use of additional buses, electricity cost would be 2-3 fold more expensive, and that also had to be factored in.

7.3 Refuelling vs. recharging time

With regard to the time needed for refuelling/charging, FCBs show a significant advantage. The time for refuelling FCBs is only slightly longer compared to refuelling diesel buses. For battery buses, the time depends on the charging strategy (depot or opportunity charging) and the installed charging power. We received refuelling as well as charging time data for the period of July 2021 to June 2022 for site 1. The median value of the refuelling time for the FCBs was 4.7 minutes/refuelling session. The median for the charging time per day (including multiple charging sessions) for the FCBs was 7.2 h/day. This is longer than the nightly parking time of many buses at the depot, so that (depending on the trip length) intermediate charging during the day becomes mandatory.

However, the required operating range and the necessary charging strategy for BEBs are specific for each individual situation. Thus, while FCBs are recognised to have a higher reach and allow a more flexible operation, the possible deployment of BEBs has to be considered on a case-by-case basis.

7.4 Space requirement for infrastructure

The required space for a hydrogen refuelling infrastructure depends on the fleet size and thus the hydrogen demand, and the hydrogen supply concept (On-site electrolysis or trailer supply). Considering all components of an H_2 filling station (including compressor, storage tank, fuel pump, safety distances, on-site hydrogen production and/or parking spaces for trailer), a small fleet of 5-10 buses requires approximately 380-480 m² including trailer parking space in case hydrogen is delivered, and a fleet of 50 buses around 520-650 m² or 900-1,150 m² with an on-site electrolyser (Kupferschmid & Faltenbacher, 2018). However, the experience from the JIVE stations showed that also with on-site hydrogen production, additional space for trailer delivery is advisable as a fallback option in case of electrolyser failure.

For BEBs, the charging strategy is the key factor influencing the required space. Charging infrastructure for opportunity charging must be set up on or very near a line, commonly in the public space. Besides the space for the charging installation itself (charging point or pole with boom), enough space for the bus to park for several minutes to allow for recharge is required.

In addition to the required power supply in the range of 250 – 450 kW per charging point, a further charging point may be required at a terminal stop in order to ensure the smoothest possible operation. Even with opportunity charging, BEBs generally need to be recharged overnight at the depot, requiring the respective charging infrastructure. Even with a reduced charging power, the electricity demand for a whole BEB fleet may not be available at all depots. For depot charging, the space implications for charging points can differ depending on the local situation and charging equipment (e.g., manual connector, pantograph). Besides the charging points, additional space may be required due to safety reasons (ensuring escape routes between buses and charging equipment). E.g., charging points with a width of 0.5 m and the extra escape space of 0.8 m require an additional distance of 1.2 m between buses when parked, requiring significantly more space for overnight parking of the fleet.

7.5 Passenger capacity

The bus capacity is of high relevance for efficient schedule planning. The capacity of both FCBs and BEBs varies across different models. Considering for instance the two bus models at site 2, the 12 m FCB model has a nominal capacity of 125 passengers and the 12 m BEB model of 131 passengers. These capacities are at the upper end of the range when comparing them to the ones given for standard buses in the market overview by Faltenbacher et al. (2019). As a general conclusion it can be stated that the hydrogen (for FCBs) and electrical components (for both alternative drivetrains) do not limit the available passenger capacity. Passenger capacity is thus not a limiting factor when considering zero emission drivetrain options.

7.6 Discussion

In terms of operational performance, FCBs and BEBs both show individual strengths and advantages. It can be expected that with an increasing maturity of the fuel cell and hydrogen technology in the next years, the availability of FCBs will attain values comparable to those of other bus technologies. With respect to the lower complexity of electric drivetrains, many experts expect these to have an even higher availability and lower maintenance requirements than diesel vehicles in the long term.

The battery capacity of BEBs has increased significantly over the last years, allowing an extended range without additional opportunity charging. However, electric heating may reduce the range of BEBs by up to 50 % in winter months. While under favourable conditions opportunity charging may mitigate range limitations and fit into the time table, FCBs generally offer a considerable advantage in terms of operating range. In addition, FCBs can be used more flexibly as they are independent of any installed equipment on their operating route.

While in general FCBs are refuelled significantly faster than BEBs recharged, the experience from the JIVE projects also shows that it may not be possible to set up a hydrogen refuelling station directly at the depot. In this case, the additional time for shuttling between the depot (or the route) and the HRS must be taken into account.

Both alternative drivetrain options require considerable additional space, either for the HRS (and the electrolyser, if applicable), or for the charging installations. Which of the two drive technologies is the most feasible under the spatial conditions at an existing depot can only be determined by an individual assessment, taking into account the respective specific requirements.

All assessments in this report were made under the assumption of a 1-to-1 replacement of diesel buses with an alternative electric drivetrain option. If additional buses had to be considered for BEBs due their range limitations, this would significantly alter the ecological and the economic comparison and could reverse results with FCBs being far more advantageous.

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