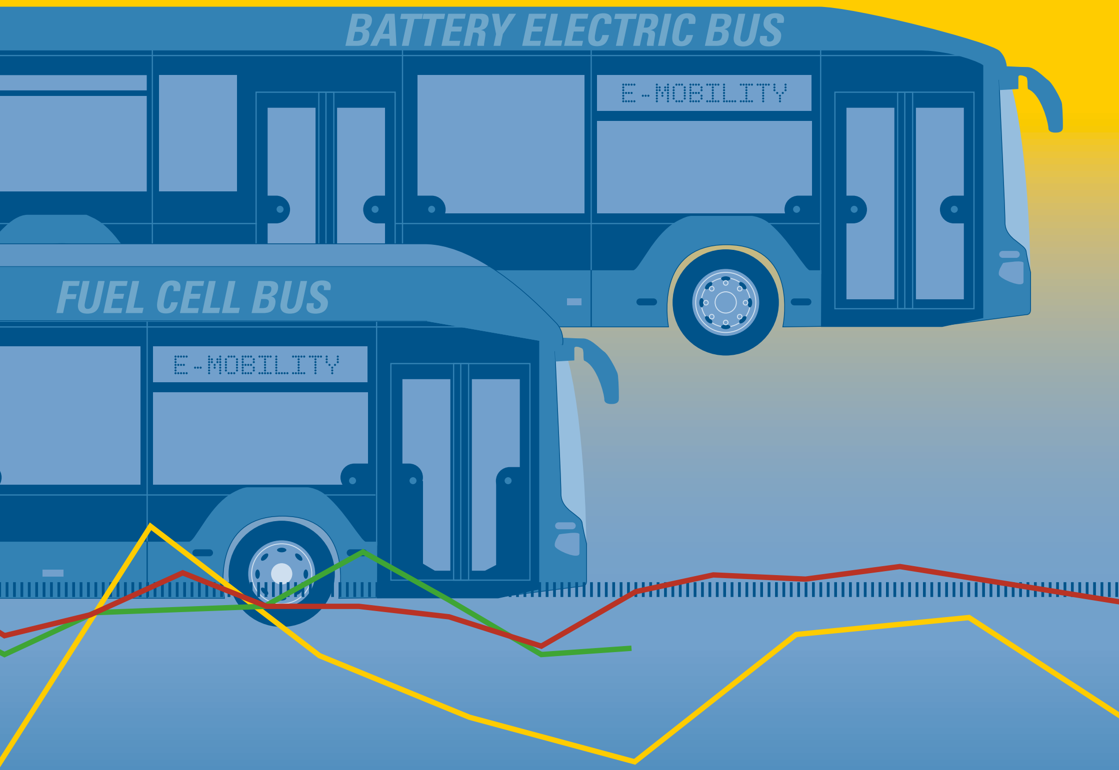


Final evaluation report

Accompanying research programme on innovative drive systems and vehicles

Innovative drive systems in road-based local public transport

Comissioned by:

Federal Ministry
for Digital
and Transport

Coordinated by:

NOW
NOW-GMBH.DE

Coordination Accompanying research
on zero emission buses:

sphera®

Executive Summary

Local public transport (LPT) is an indispensable component for ensuring individual mobility of the population. Therefore, it is important to make it more climate and environmentally friendly. The climate protection goals can only be met in the coming years by switching to emission-free, efficient and quiet buses with alternative drives. For example, emissions from local public transport are supposed to be cut in half by 2045 compared to 2019 levels. Accordingly, as part of the recently revised climate protection programme, the German Government is pursuing the specific goal of converting half of all city buses to electric drives by 2030. With the recently enforced Clean Vehicles Directive (CVD) and the Clean Vehicles Procurement Act (SaubFahrzeugBeschG), there is now – for the first time – a clear legal requirement for the proportionate procurement and operation of 'clean' or 'emission-free' buses. In Germany alone, the implementation of the CVD will result in a short-term market potential of approx. 2,000 clean or approx. 1,000 emission-free public transport buses per year by 2025. In the second stage of the CVD directive, this potential will increase to approx. 3,000 clean or approx. 1,500 emission-free buses by 2030. Overall, however, the market potential for locally emission-free city buses is estimated to be higher. This is mainly attributable to the fact that in order to achieve the aforementioned climate protection targets of the German government (50% emission-free city buses in the fleet by 2030) the share of emission free buses in new vehicle purchases needs to be even higher than the minimum quotas defined in the CVD.

Transport companies are facing two main challenges: the introduction and subsequent (partial) conversion to zero-emission buses with new types of drive components as well as the corresponding construction of the necessary energy supply infrastructure. To support the transformation, the Federal Government, the Federal States and the European Union have launched various funding programmes for market initiation and ramp-up. The Federal Ministry for Digital and Transport (BMDV) and the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) support the acquisition of electric bus systems including the vehicles and the necessary energy supply infrastructure. To provide additional support for market preparation and the market ramp-up for electromobility applications, the BMDV also funds research and development projects as well as the creation of electromobility concepts.

The BMDV initiated a programmatic accompanying research project (ARe for short) with the goal to compile the individual results of the funded projects for the introduction of zero-emission local transport buses. To establish a general overview, the accompanying research on buses compiles and evaluates the findings and experiences of the individual projects from the three funding areas of vehicle procurement, electromobility concepts, and research and development projects.

The accompanying research on buses pursues the ultimate goal of creating a better understanding, especially among transport companies and municipal authorities, of the technical and operational suitability of the individual zero-emission drive technologies within their own specific operating conditions. It also aims to shed light on the associated economic consequences.

A guide was developed to provide initial information on zero-emission bus systems. It was used as a base to develop an online decision-making tool that provides transport companies with indicative information based on the input data they provide on their specific operational processes. The guide and tool are available at http://www.ebustool.de.

A number of publications on various topics were also produced in addition to this final report. These include a funding project overview, an analysis of the e-mobility concepts with public transport relevance that were created with BMDV funding, and a legislation chart relevant to electromobility in public transport. Together with the detailed reports on individual evaluation criteria referenced in the various chapters of this report, these documents can be found in the 'Electromobility starter kit'[1] under the Local Public Transport (LPT) module. They provide a comprehensive range of information for transport companies and municipal authorities.

1 See https://www.durchstarterset-elektromobilität.de/OPNV/ (in German)

In this context, the working group 'Innovative drivetrains for buses' (WG Bus), initiated by the BMDV and BMUV in 2011, serves as a platform for direct exchange of information and experience between the various stakeholders. The goals of the WG Bus are:

- to compile results from the individual funding projects in a way that is independent from specific technologies,
- to network participating companies and organisations, to promote open communication among them, to increase knowledge
- to enable new stakeholders to enter the field of electromobility.
- to identify further fields of action and, if necessary, R&D requirements.

The steadily increasing number of participants in the WG Bus meetings documents the interest of the various stakeholders in the results.

The main results of the accompanying research on buses are presented below, separated into four evaluation categories: practical feasibility, energy efficiency, ecology and economic viability. The implementation of the accompanying research, and the elaboration of the results presented here were made possible by the willingness of the transport companies participating in the accompanying research to provide detailed operating data, as well as their practical experience to the ARe team under the leadership of Sphera Solutions. The ARe team would like to take this opportunity to thank these transport companies once again.

Practical feasibility and energy efficiency

Battery electric buses

The operational data of more than 130 buses from 8 different manufacturers are available for battery electric buses, in some cases over a period of more than two years. Of these, 117 are depot charging buses (112 solo buses (12 m), 5 articulated buses (18m)) and 14 are opportunity charging buses (4 midi-buses (<12 m), 9 solo buses, 1 articulated bus). The more extensive database compared to the last report of the WG Bus (2016) provides a more comprehensive and robust evaluation.

The deployed battery electric buses show an overall availability of approx. 87% in the period under consideration, with just under 87% for depot charging buses and 88% for opportunity charging buses. This represents a significant increase compared to the last status report of the WG Bus (from 2016), in which the depot charging buses had an availability of 72% and the opportunity charging buses an availability of 76%. To ensure smooth operations, a charging infrastructure with ideally 100% availability is needed. Currently, it is 96% on average.

If we compare the daily distance driven achieved so far with the range requirements of the transport companies, it becomes clear that this is currently one of the key challenges for the use of battery electric buses. Nearly 80% of the 30+ participating transport companies require a daily range of at least 200 km, while the remaining 20% consider a daily range of more than 350 km absolutely necessary.

The two relevant factors affecting range are the specific energy consumption of the bus per km and the battery capacity installed on the bus. The average installed battery capacity in solo vehicles with depot charging is just under 300 kWh. For opportunity charging buses it is 230 kWh. With regard to energy demand, the selected heating concept plays a crucial role. If heating is purely electric in line with completely emission-free operation, the achievable range is reduced by up to 50%, especially in cold winter months, and is thus far below the required range.

Various options are available to address this range gap. These include reducing energy consumption, increasing the storage capacity of the battery, examining the extent to which opportunity charging throughout the day, or alternatively the use of fuel cell buses, is possible, the use of a fuel-based auxiliary heating system using fuels from renewable energy sources, or adjusting the vehicle scheduling.

Source: BVG 2020

With regard to the resulting energy consumption, other additional energy demands must be considered besides the energy demand determined directly by the vehicle itself. These energy demands result from the requirement to regularly balance the battery by adjusting the charge level of the individual battery cells and the charge losses of the battery, and from the preconditioning of the vehicle as well as the conversion losses. In addition to the energy demand determined on the vehicle side, it is reasonable to expect a total additional charging energy demand in the order of 25 – 30%, related to the energy demand on the vehicle side.

The transport companies' assessment of the current technology readiness level of battery electric buses is predominantly positive. Based on initial operational experience, just under half of the transport companies consider the buses to be ready for series production (TRL 9) and another quarter consider them to be close to series production (TRL 8). The expectations of more than 90% of the transport companies that the battery electric buses should be ready for series production after one year are therefore not yet fully met. With regard to the charging infrastructure, just under 80% of the transport companies consider the battery electric bus system to be ready for, or close to, series production. The perception is similar when it comes to availability. The expectations stated by the transport companies at the beginning of the deployment with regard to availability were met in the vast majority of cases (75%). In operation, the battery electric buses achieve almost 90% availability. This value is only slightly below the availability of the diesel buses (93% on average). In general, it can be observed that the transport companies have high expectations of the battery electric bus technology, which are largely already met by the technology.

Fuel cell buses

Fuel cell buses were included in the accompanying research for the first time. Data from 45 fuel cell buses from two transport companies over a period of up to 16 months are available. However, the assessments of the fuel cell bus system are not yet fully reliable due to the still limited amount of data available.

The availability of the fuel cell buses is currently around 78% on average and thus still needs to be increased. The main downtime/failure causes are the fuel cell system and the conventional, non-drive-related mechanical components. With regard to refuelling station availability, initial data are currently available for one of the four refuelling stations used over a period of 15 months. The others are still in trial operation or have not yet been handed over to the transport companies. For this refuelling station, the overall availability is currently 93% in the period under consideration, with availability in the last 6 months reaching values above 97%.

The average consumption of the buses is about 9 kg H_2/100 km. Compared to the battery electric buses, the energy consumption of the FC buses increases to a lesser extent at low temperatures. In fact, the buses reach ranges of at least 300 km, even in the winter months, and thus fulfil expectations.

The currently still relatively low average daily distance driven clearly highlights the relevance of efficient operational integration of vehicle refuelling into the daily vehicle supply processes. A decentralised location of the hydrogen refuelling station can lead to considerable additional personnel expenses. One possible solution is to restructure the operational processes. The average refuelling time is 10 – 12 minutes which meets the operator's expectations. Consumption and range also meet operators' expectations.

The technology readiness level of the buses is currently rated by the transport companies in the range from 'prototype in field test' (TRL 7) to 'close to series production' (TRL 8), which largely corresponds to the expectations formulated at the beginning of the deployment. It is evident that the fuel cell buses have not yet reached the level of battery electric buses in terms of market maturity. However, considering the development status and the market ramp-up that is still to come, it meets the operators' expectations of the current technology. With regard to hydrogen refuelling stations, several refuelling station concepts were deliberately set up in one project, and these still have research status. In this respect, the expectations regarding the operational maturity with TRL 3 to 9 demonstrate a wider range compared to the FC buses. These expectations are largely fulfilled by the various refuelling stations.

Source: WSW mobil 2021

In conclusion, it can be said that the practical feasibility and operational maturity of electric buses has improved, but that there is still room for improvement. While the range of the battery electric bus is a key issue for further optimisation, the availability of the vehicles and the hydrogen refuelling stations must be increased in the FC bus system. There is further potential for optimisation here, especially with regard to the availability of spare parts.

Ecology

Due to the shift of environmental impacts from the actual bus operation to the provision of energy sources and vehicle manufacturing, it is necessary to consider the entire life cycle of the bus systems. The evaluation shows that the use of renewable energy sources is an indispensable prerequisite for realising relevant emission reduction potentials. For example, the use of electricity from wind and photovoltaics (PV) can achieve a reduction of 75–85% in greenhouse gases (GHG) and 50–75% in nitrogen oxide emissions (NOx). The highest emission reduction can be achieved with the use of purely electric heating concepts. If fuel-based heating concepts are used, the use of fuels from renewable energy sources that meet the requirements of the European Renewable Energy Directive II (RED II) offers an option to keep additional GHG emissions as low as possible.

Economic viability

The profitability analysis examined the battery electric bus with depot and opportunity charging as well as the FC bus and FC range extender (FC REX). The profitability analysis carried out to determine the total operating costs of the different e-bus systems to derive the total cost of ownership (TCO) calculation makes it clear that the use of e-buses is associated with additional costs in the short to medium term compared to diesel buses as the established reference technology. Without subsidies, these additional costs are 0.5–1.3 €/km or 16–38%. The additional vehicle requirement for the battery electric bus with depot charging, which depends on the vehicle scheduling, is a key factor for the additional costs. The H_2 supply costs play a significant role, especially for the FC bus and for the FC REX. On the other hand, a rising CO_2 price for fossil diesel can equally reduce the cost gap for all e-bus systems.

Currently, battery electric bus and fuel cell bus systems can only be used at close to diesel bus costs, or with additional costs in the range of < 15%, if subsidies are used and under certain conditions. The sensitivity analysis performed clearly illustrates that the additional costs of the individual drive technologies depend on various factors under the respective specific conditions of use. These factors include: operational (e.g. additional vehicle requirement), regulatory (e.g. reduction of the EEG levy [green power surcharge]) and economic (e.g. vehicle price, energy procurement costs).

As a result, indications can be provided regarding the economic effects on future budget and departmental planning for local public bus transport for the examined e-bus systems.

Outlook

In order to achieve the desired goal of converting bus-based public transport as much as possible to alternative drive systems to contribute to climate and environmental protection, it is necessary to stabilise and further intensify the already initiated market ramp-up for locally emission-free buses. It requires continued sustainable reinforcement of the innovative resourcefulness of the stakeholders on a broad front with regard to further technical development and the ongoing optimisation of operational processes and infrastructure.

In the short term, the framework conditions must be adapted to remove regulatory hurdles, simplify lengthy planning and approval processes and ensure investment security. If companies want to switch to alternatively powered vehicles today, they must have long-term assurance that the basis of their profitability analysis will not be impaired by short-term changes in the subsidy scheme and unclear exemptions from statutory levies (e.g. EEG levy) during the term of the project. It is important to constructively support the development of a self-sustaining market that has already begun.

Accordingly, various options for action have been developed to further support the ramp-up of low-emission drive technologies. It is not only a matter of designing the legal requirements in a way that is conducive to the desired market ramp-up, but also of ensuring and further improving acceptance of alternative drive technologies among transport companies and their customers. An overview of the developed options for action is divided into three areas of intervention:

´- **Promotion** to reduce cost differences, to gain insight, and to prepare and ramp up the market: Creation of financial incentives for the procurement of emission-free bus systems (vehicles and infrastructure), studies/concepts, R&D projects on components and their integration into the overall system

- **Environment, regulations & processes:** Setting targets for the use of buses in local public transport (e.g. the CVD requirements as a minimum target or more ambitious targets regarding climate and environmental protection), consideration of emission costs (e.g. CO_2 price),
  - Control of procurement processes via legal and regulatory requirements (e.g. CVD),
  - Simplification and acceleration of the funding application processes for the procurement of vehicles and energy supply infrastructure, consideration of required lead times for the award of transport contracts (at least 24 months lead time required for funding, planning, procurement, delivery/construction and commissioning),
  - Supplementing the currently provided funding to further support the incipient market ramp-up
  - Extension of the term of concessions/service contracts (extended amortisation periods),
  - Adjustment of energy supply regulations (e.g. operator of a public charging infrastructure becomes electricity supplier with all resulting consequences)

- **Knowledge transfer and acceptance:** Accumulation and dissemination of knowledge regarding alternative drive technologies and infrastructure systems of electric bus systems (e.g. with regard to their comfort features, their environmental impacts) in order to secure or increase acceptance of the technologies among transport companies, public authorities and passengers

With regard to the continuous development of key components, various expansion concepts result from the operational requirements and the necessity to be able to use very expensive components (such as high-voltage batteries) for as long as possible. These approaches are primarily aimed at minimising the energy demand and monitoring batteries in order to increase ranges and extend the useful life of batteries. Other development topics include assembly space, weight and production costs. For fuel cell buses, an additional target criterion is the stabilisation of the fuel cell, i.e. the avoidance of highly dynamic changes in performance, which in turn will increase its service life. There are also so-called range assurance functions (RAF), which initiate appropriate measures to reduce energy consumption in the event of a foreseeable failure to achieve a planned vehicle schedule.

No conclusive forecast can currently be made with regard to the market potential of the available emission-free drives. As the analyses show, almost 20% of the vehicle operational shifts by the transport companies are longer than 300 km. Although fuel cell buses can already meet this requirement today, they still have higher system costs (incl. H_2 supply) than battery electric buses, which cannot currently meet this range. It is therefore still necessary to promote battery and fuel cell buses in a way that is open to all technologies. With regard to the subsidies, it must also be considered that, in addition to the climate protection goal, they are intended to support the market ramp-up until a self-sustaining market has developed, which is why the various subsidy providers have formulated the goal of reducing the subsidy intensity in the future. This means that the providers of zero-emission buses and the associated charging infrastructure will be able to realise cost reductions on the required scale in the medium to long term.

Ultimately, zero-emission drive technologies can make different contributions to the desired sector coupling as part of the energy transition. For example, the batteries of buses, as mobile electrochemical storage units (or as stationary units in their 'second life'), represent a short-term storage option for fluctuating generation of renewable energies. Technically, this is already possible today, but there are still a number of regulatory hurdles to overcome. For fuel cell buses, the transformation of volatile renewable energy into hydrogen leads to a temporal decoupling of electricity procurement for hydrogen electrolysis and refuelling of the buses. By using electricity quantities that are absorbed by large hydrogen production plants (e.g. during windy periods), the overall efficiency of a renewable energy-oriented energy system can thus also be increased. However, the combined efficiency losses of the individual fuel cell buses and H_2 generation are higher than those of the battery electric bus.

1 Introduction

1.1. Initial situation – general conditions and political context

The German government's goal is to make the transport sector more energy-efficient and more climate and environmentally friendly. One of the essential prerequisites for achieving this goal is the conversion of transport to renewable energies in combination with low-emission drive technologies. As part of the recently revised climate protection programme, the German Government has formulated the specific goal of converting half of all city buses to electric drives by 2030. Electromobility is thus a critical factor in achieving the goal of the energy transition. Various funding programmes and demonstration projects have contributed significantly to the development of electromobility in Germany since 2009. Within the framework of the current funding programmes, the market ramp-up of alternative drive systems is now increasingly being promoted alongside traditional research and development projects.

As a central component of the transport system, local public transport (LPT) already transports roughly 10 billion passengers per year in Germany, both in conurbations and in rural areas. Measured in terms of transported passengers, its vehicles consume less energy, require less space in road traffic and thus save important resources compared to personal motorised transport. However, due to their high mileage and predominant diesel drive technologies, buses are also emitters of pollutants such as nitrogen oxides and noise, especially in densely populated urban areas. In the recent past, and still today, non-compliance with pollutant limits and noise pollution through road or ambient noise is a pressing environmental problem in a number of German cities. Therefore, the transport companies are currently faced with the task of realising the changeover from diesel buses to a climate and environmentally friendly local public transport system with alternatively powered buses. Finally, since August 2021, the current Clean Vehicles Directive (CVD) of the European Commission has mandated the introduction of buses with alternative drives in new procurements or contracts, at least on a pro rata basis[2].

2 More information on the European Commission's Clean Vehicles Directive and its implementation can be found in the next section.

Local public transport plays a particularly important role in the transport and energy transition. Electrification of the drive train is currently the most intensively pursued alternative for innovative drive systems for local transport buses. There are essentially three options, all of which have an electric drive and can accordingly be grouped under the generic term 'electric bus' or 'e-bus'

- Battery electric buses (BEV bus, also referred to synonymously as battery electric bus in the report)
- Hydrogen-powered fuel cell buses (FC bus)
- Trolleybuses
- Hybrid trolleybuses (HOBus, combination of battery and trolleybus)

Such a fundamental change in drive technology, involving electric drives instead of the established, mostly diesel-powered internal combustion engine, represents a considerable challenge for transport companies and requires a holistic approach. In addition to the selection of the most suitable drive technology and vehicle configuration, it also includes the energy supply type and a new operations organisation.

The suitability of the various available innovative drive systems is largely determined by the respective operational and technical parameters as well as the costs. Considerable technical and economic optimisation potential for the key components of the electric buses (such as batteries and fuel cells) and the necessary infrastructure (such as charging stations and electrolysers for H_2 production) is still expected in the coming years. The transport companies are therefore faced with a whole series of uncertainties when they are transitioning to low-emission or zero-emission local public transport.

In order to support the transport companies in the transformation, there are various funding initiatives at European, federal and state level[3] – and they are already proving to be very effective. While a few years ago the use of electric buses for local public transport mostly took place in isolated cases as test operations within the framework of funded research and demonstration projects, the number of e-buses in regular operation is now increasing. According to the KBA, more than 1,000 e-buses were already in use in July 2021 in Germany[4].

The Federal Ministry for Digital and Transport (BMDV) is currently funding the following elements through the Electromobility Funding Guideline, which runs until 2025:

- Procurement of battery electric vehicles and the charging infrastructure required for their operation,
- Municipal and commercial electromobility concepts,
- Research and development projects.[5]

The National Innovation Programme Hydrogen and Fuel Cell Technology of the German Government (NIP II) funds the procurement of vehicles and the associated refuelling infrastructure as well as research and development projects (R&D) in line with the funding priority. R&D projects on other alternative drive systems (e.g. hybrid trolleybuses) are funded as part of the Federal Government's Mobility and Fuel Strategy (MKS); therefore, generally speaking, there is open technology support for the market ramp-up of alternative drive systems for local transport buses.

Legislative drivers

The aforementioned requirements regarding air quality and noise reduction in inner cities and the social efforts to reduce greenhouse gas emissions to protect the climate, as stipulated in the Paris[6] Climate Agreement, are the main drivers for the use of electric buses or so-called zero-emission vehicles in local public transport.

The Clean Vehicles Procurement Act (Saubere-Fahrzeuge-BeschaffungsGesetz – SaubFahrzeugBeschG)[7] regulates the implementation of the European Clean Vehicles Directive (CVD)[8] in Germany and is currently considered the most relevant driver for the spread of electric buses.

3 An overview of the various funding programmes at EU, federal and country level can be found in the funding overview at https://www.durchstarter-set-elektromobilität.de/OPNV/ (in German)

4 NOW GmbH based on KBA: Evaluation of KBA figures, July 2021. 895 battery electric buses, 81 trolleybuses, 51 fuel cell buses. https://www.now-gmbh.de/wp-content/uploads/2021/08/KBA-Report-07-2021.pdf, last accessed on 13/08/2021

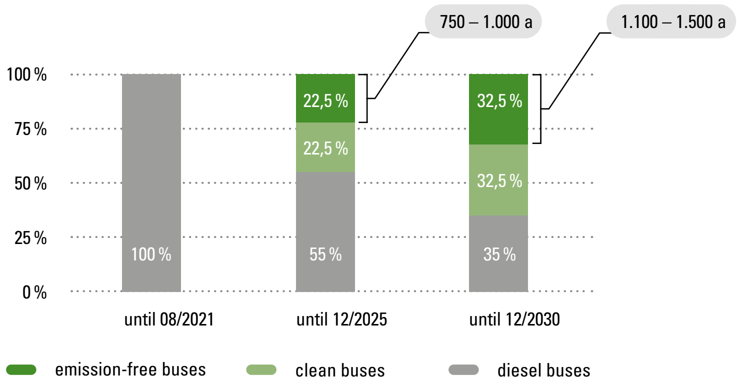
5 NOW GmbH: Electromobility funding programme, https://www.now-gmbh.de/foerderung/foerderprogramme/elektromobilitat/, last accessed on 13/08/2021

6 United Nations Framework Convention on Climate Change (UNFCCC): Paris Agreement, 2015, https://unfccc.int/sites/default/files/english_paris_agreement.pdf, retrieved on 08/06/2021 at 4.40 p.m.

7 Federal Government: Act implementing Directive (EU) 2019/1161 of 20 June 2019 amending Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles and amending public procurement legislation (Clean Vehicles Procurement Act – SaubFahrzeugBeschG), published in the Federal Law Gazette on 14 June 2021.

8 European Commission: Directive (EU) 2019/1161 of the European Parliament and of the Council of 20 June 2019 amending Directive 2009/33/EC on the promotion of clean and energy efficient road transport vehicles (Clean Vehicles Directive [CVD]), 2019, https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX-:32019L1161&from=EN, retrieved on 08/06/2021 at 4.45 p.m.

FIGURE 1 **Quota system according to EU Clean Vehicles Directive or Clean Vehicles Procurement Act (SaubFahrzeugBeschG) since 2/8/2021**



Since August 2nd 2021, the Clean Vehicles Procurement Act has stipulated binding quotas for the procurement of new 'clean and emission-free' buses for local public transport. It stipulates that in the period from August 2nd 2021 to December 31st 2025, at least 45% of the new buses to be procured or of the vehicles used for passenger transport within the scope of newly awarded service contracts must use alternative or 'clean' drive concepts, half of which must be emission-free (see Figure 1). According to the law, 'clean' drive concepts include alternative fuels such as GtL, CNG, LNG or biofuels, or diesel plug-in hybrids. At least 22.5% of the new buses to be procured or used in newly designated bus routes must be emission-free. For the purposes of the CVD, zero-emission buses are electrically powered buses (battery, FC or trolley buses) and buses with H_2 combustion engines.

This will probably result in a procurement requirement of up to approx. 1,000 zero-emission buses per year in Germany in the 1st period until end of 2025[9]. Further potential drivers for the increasing use of e-buses result from the implementation of the Renewable Energy Directive II (RED II) and the amendment of the Renewable Energy Sources Act 2021 (EEG 2021). The EEG 2021 provides for a reduction of the EEG levy for transport companies to 20% for the electrical energy consumption related to driving operations (min. 100 MWh annual consumption per transport company) starting in 2022, resulting in a relief for transport companies of more than 5 ct/kWh. With the 'Ordinance establishing further provisions for expansion of the greenhouse gas reduction quota'[10] for the implementation of RED II, on the other

9 From 1 January 2026, the quota of clean buses will rise to at least 65%, so that by then at least 32.5% of the new buses in use will have to be emission-free. Expressed in units, this results in an estimated demand for up to 1,500 zero-emission buses per year.

10 See Bundesanzeiger Verlag published in November 2021 (in German) hand, the electrical energy consumption is counted at three times its energy content for the fulfilment of the set greenhouse gas reduction quota. This creates an incentive, at least in principle, for distributors of fossil fuels (obligated parties as defined in § 37 BImSchG) to offer transport companies attractive conditions for the purchase of traction current. This way, fossil fuel distributors ensure that it is credited against their own GHG reduction quota.

An overview and further information on the political parameters at the different political levels can be found in chapter 2.1.3.

1.2. Contents of the accompanying research on buses

Support programmatic research by the Federal Ministry for Transport

The BMDV initiated an accompanying research programme in connection with the implementation of the Electromobility Funding Guideline with the goal to combine the individual results of the projects funded under the various funding programmes mentioned in chapter 1.1 to support market preparation and activation for electromobility applications. The accompanying research bundles and evaluates the project results from the three funding areas of vehicle procurement, electromobility concepts and R&D projects. It also facilitates networking and as part of the semi-annually WG Bus meetings a lively exchange takes place between the participating companies and organisations in order to deepen knowledge and allow new stakeholders to enter the field of electromobility. The long-term goal is to convert the existing fleet to alternative drives. The results are made available to the broader public via the 'electromobility starter kit' and are passed on directly to the relevant stakeholders in the various subject areas as well as municipal stakeholders. Furthermore, the programme accompanying research offers companies the opportunity to classify their own fleet deployment based on the technical and economic potential as well as the environmental impact in the overall context of the vehicles promoted in the programme. The programme's accompanying research is managed by the programme coordinator NOW (National Organisation Hydrogen and Fuel Cell Technology).

In order to support the market ramp-up of electromobility, four key subject areas have been identified as the pillars of the ongoing programme accompanying research:

- Innovative drives and vehicles
- General conditions/market
- Networked mobility
- Infrastructure.

The accompanying research on buses

The vehicle category city bus is the focus of the subject area of innovative drives and vehicles. In autumn 2018, the Federal Ministry for Transport commissioned a consortium[11] led by Sphera to perform the accompanying research on innovative drives in road-based local public transport. The programme was known as Accompanying Research on Buses (ARe Bus). The accompanying research continues previous accompanying research activities on partially electrified buses, such as diesel hybrid buses and full electric buses, namely battery electric buses within the setting of the R&D project EFBEL (FKZ 03EM0603) funded by Federal Ministry for Digital and Transport (BMDV, formerly BMVI) and other projects funded by the BMDV/ BMVI under the leadership of Sphera (formerly thinkstep). Several partners of the current ARe Bus consortium also worked on these previous projects.

11 The consortium conducting the accompanying research into innovative drives for buses is coordinated by Sphera Solutions. Other partners include VCDB, hySOLUTIONS, Fraunhofer IVI, SEK Consulting, and IVV Aachen.

In accordance with the BMDV's specifications, the accompanying research on buses pursues the following overarching goals:

- Detailed analysis and evaluation of the funded e-bus systems, consisting of buses with electric drive and the associated charging and refuelling infrastructure, taking into consideration the respective operating conditions.
- Information development, and provision of decision-making tools based on the results of the evaluation. This could take the form of a guide and an interactive, computer-based tool for transport companies and public transport authorities to support the selection of the appropriate e-bus system, taking into consideration the specific local application context.

The results of the supporting programme of research on buses are presented in this final report.

The evaluation of the e-buses was based on the in-depth analysis of the operational requirements (see chapter 2.1), the operational maturity of the vehicles and supporting infrastructure achieved during the study period (Q1 2019 to Q2 2021) (see chapter 2.2), and the energy efficiency (see chapter 2.3). A life-cycle based environmental and economic assessment of the deployed e-bus systems was also carried out (see chapters 2.4 and 2.5). The technology assessment is supplemented by information and results from seven R&D projects on various e-bus topics as well as 13 e-mobility concept studies. Within the e-mobility concept studies local bus-based public transport was either the main focus of the conducted study or was at least considered as a sub-sector within the study.

The established diesel internal combustion engine is used as the reference drivetrain technology for the performance assessment within the individual evaluation categories. Table 1 lists the evaluation categories and criteria used for the performance assessment. In order to assess the practical feasibility and operational maturity of the buses, the operational data collected during the monitoring period is assessed according to the selected evaluation criteria, such as distance travelled, availability, operational maturity level and energy consumption, including the energy efficiency of the energy supply infrastructure.

As much as reasonably possible, a comparison is also made with the requirements and expectations formulated by the transport companies, both prior to operations as well as during operations, for the applied technology as a target/actual comparison. Examples include the operational range and maturity assessment of the technology.

TABLE 1 **Evaluation categories and criteria within each category used to assess the performance of drive systems within the accompanying research**

Evaluation categories	Evaluation criteria
Practicality and readiness	Daily use (distance travelled, range)
	Availability of vehicles
	Availability of charging infrastructure
	Readiness for use / Technology Readiness Level (TRL)
Efficiency	Vehicle energy consumption
	Influence of climatic conditions
	Energy consumption of charging infrastructure
Ecology and climate protection	Reduction of CO_2
	Reduction of NOx and Fparticulate matter / PM
	Sensitivity analysis
Economic efficiency	Life cycle costs (total cost of ownership, TCO)
	Sensitivity analysis

The technical evaluation is followed by an examination of the ecological effects as well as the economic viability of the e-buses over their life cycle compared to conventional diesel buses.

Based on the results of the technical/operational, ecological and economic evaluation, a guideline was prepared and a decision tool was developed, both of which are briefly presented in chapter 2.6.

Working Group 'Innovative drivetrains for buses'

The results are made available to the stakeholders, among others, within the framework of the Working Group 'Innovative drivetrains for buses' (WG Bus). The WG Bus was jointly initiated by the Federal Ministry for Transport and the Federal Ministry for the Environment in 2012. Since then, it has served as a platform for the exchange of ideas and experience between transport companies, manufacturers, research institutions and the funding federal ministries. It links all the projects funded by the BMDV with the e-bus projects funded by the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV). The 34 BMDV projects in 33 transport companies included more than 380 electric buses, and the BMUV projects included 65 transport companies and almost 1,500 e-buses (see Figure 2) . All the projects funded by the BMUV are battery electric buses.

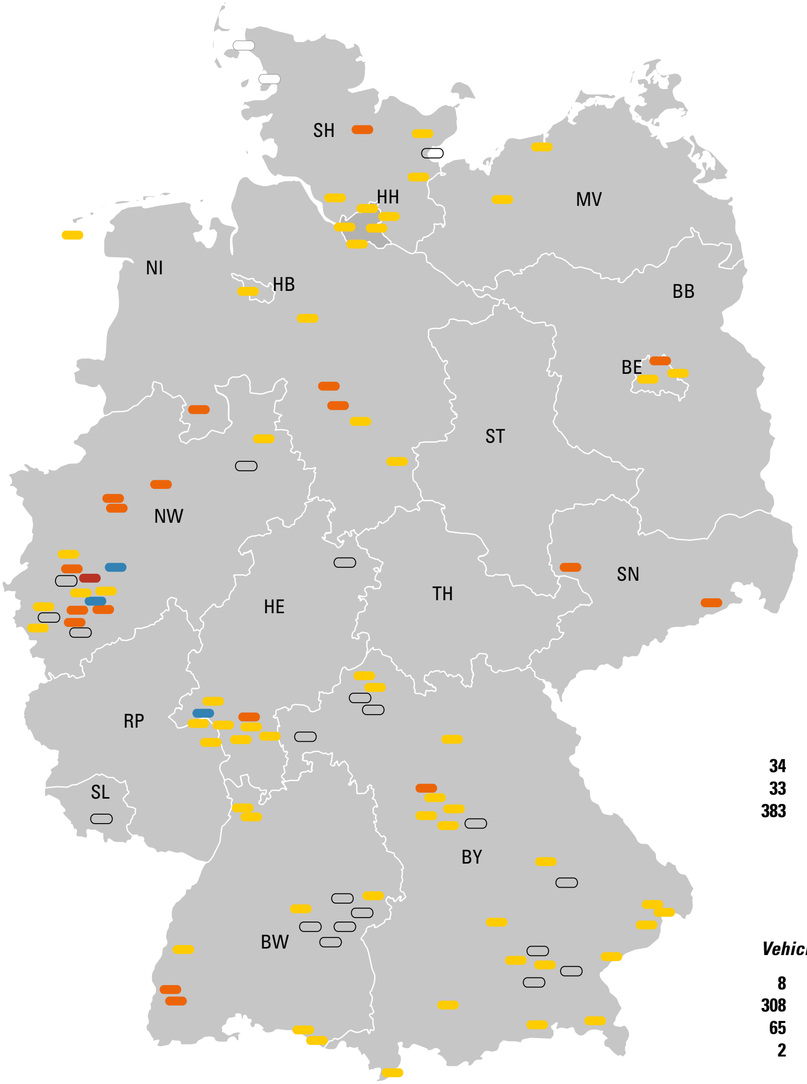
The items on the overview map of BMDV-funded projects are coloured according to the type of drive system deployed and the information available. More detailed information on the individual projects, including the projects funded by the BMUV, can be found in the 2021 project overview brochure [12].

12 The 2021 project overview brochure can be found on the Electromobility starter kit at https://www.durchstarterset-elektromobilität.de/OPNV/

Source: Hamburger Hochbahn 2021

Source: Regionalverkehr Köln GmbH 2021

FIGURE 2 **Overview of BMDV-funded e-bus projects**



34	Projects
33	Operator
383	Total buses

Vehicle size

8	Midi buses
308	Solo buses
65	Articulated buses
2	not specified

Drive technologies/information stand

- BEV depot charging
- BEV opportunity charging (additionally overnight depot charging)
- BEV battery overhead line
- H_2/FC
- Currently no further information available

Charging/fueling concept

266	Depot charger
25	Opportunity charger
20	Overhead line
70	Hydrogen

1.3. Analysed Technologies

Vehicles

According to the CVD, a vehicle is considered an 'emission-free vehicle' if the emissions during operation of the vehicle are less than 1 g CO_2/kWh. This includes vehicles that are powered by electrical energy (the term 'electricity' is also used in this report for the sake of simplicity) or hydrogen. Table 2 provides an overview of the zero-emission drive types for local transport buses considered in the programme accompanying research. Battery electric buses (BEV bus) use an electric motor, which is either installed as a central motor, as a motor close to the wheel (with gear stage) or as a wheel hub motor. The electrical energy for the electric motor is supplied either from that stored in a battery or supplied via an overhead line. A distinction must be made between power supply during travel via the overhead line for trolleybuses, or power supply during the charging process. Another distinction can be made between conductive (cable-connected) and inductive (charging plate with coil) power supply. In order for trolleybuses to be able to travel on routes without overhead lines, they have an additional power source on board. In the past, this was usually a diesel-powered auxiliary generator, which was not designed for regular operation, but primarily functioned as a minimum power supply for the vehicle to bridge sections without overhead lines, e.g. in the depot[13]. However, this function is now taken over by a high-voltage battery storage system. Trolleybuses equipped with high-voltage batteries are called hybrid trolleybuses. Depending on the installed battery capacity, they can also cover several km without overhead lines. The larger capacity now also enables fully-fledged driving operation on longer sections without overhead lines.

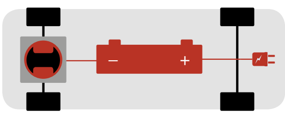
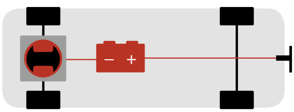
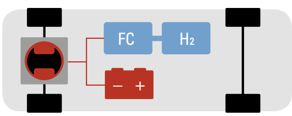
13 The term 'depot' is used uniformly throughout the report to refer to depot charging.

The hydrogen stored on board of fuel cell buses (FC bus) is converted into electricity in a fuel cell. The bus is refuelled with hydrogen via a specialised hydrogen refueller. Commonly this is compressed hydrogen and typically takes less than ten minutes, depending on the tank size and configuration of the refuelling station. Fuel cell buses are also usually equipped with a high-voltage battery. It functions as a buffer storage for recuperation of braking energy and for additional power supply for the drive, e.g. during start-up. It is designed according to demand with a significantly lower capacity compared to a battery electric bus and frequently does not have an external recharging option.

Due to the conversion losses, the energy efficiency of hydrogen-powered vehicles is lower than BEV vehicles. However, they have clear advantages in terms of refuelling time and range.

Moreover, there are two other hydrogen-powered drive concepts that are currently under development – the fuel cell range extender (FC REX) and the hydrogen combustion engine. Even though they are not yet widely available for use by transport companies, they should be mentioned here for the sake of completeness. The FC REX combines the battery electric bus with a large HV battery and external recharging as well as a fuel cell with H_2 storage for cruising range extension. Accordingly, this drive concept requires both a charging and an H_2 storage and refuelling infrastructure. The H_2 combustion engine offers synergies with the established natural gas internal combustion engine technology. It represents a relatively more cost-effective alternative to the FC bus, since most of the 'conventional' drivetrain components of the conventional combustion engine can be used. However, its efficiency is lower than the fuel cell and still requires exhaust gas after-treatment, especially with regard to reducing nitrogen oxide emissions.

TABLE 2 **Overview of monitored technologies**

		Principle	Photo	Maturity
Electricity	BEV		Vestische Straßenbahnen GmbH 	Series
Electricity	Trolley bus		Stadtwerke Solingen GmbH 	Series
Hydrogen	FC bus		Stuttgarter Straßenbahnen AG 	(small) series

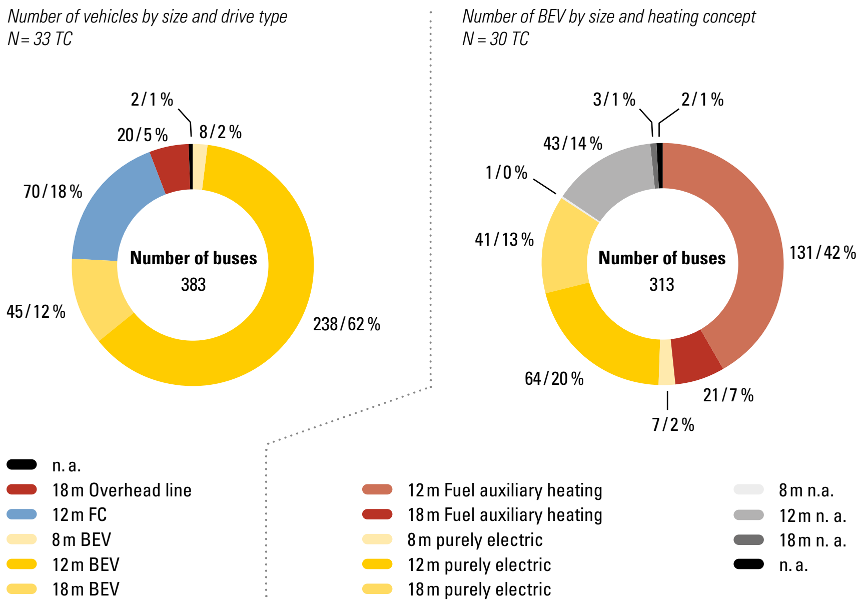
Overview of the subsidised buses by bus size and heating concept

There is a total of 70 subsidised fuel cell buses operated by 2 transport companies of which all are 12-metre buses. There are 20 subsidised trolleybuses which are all 18-metre buses and operated by one transport company. The 313 battery electric buses (incl. trolleybuses) operated by 31 transport companies make up the largest share of the buses funded by the BMDV. They mainly comprise 12 m buses (238), but also 18 m (45) and 8 m (8) buses. The length of another two subsidised buses is not yet known, as the project is currently suspended.

The expected energy consumption of battery electric buses is determined by the selected heating and air conditioning concept. As shown in Figure 3, almost 50% of the buses (152) are heated via a combustion auxiliary heating system, and another 36% (112) are heated purely electrically. For about 15% of the buses (49) it is not yet known which heating concept will be selected. The influence of the heating concept on the electrical energy demand is examined in more detail in chapter 2.3.2.

14 N stands for the number of transport companies

FIGURE 3 **Breakdown of subsidised buses by drive type and bus size, BEV by heating concept and bus size [14]**



Market overview/availability

The market research conducted as part of the accompanying research shows that there is already an established market for the 12 m and 18 m battery electric buses. Three manufacturers have currently been identified for the 12 m fuel cell bus, whereas no 18 m fuel cell bus is currently available on the market. According to the manufacturers, this vehicle category is announced for 2023/24. The FC REX concept is currently not offered commercially by any manufacturer. Trolleybus technology is offered by a small number of established manufacturers in both the 12 m and 18 m segments.

Energy supply infrastructure

Battery electric buses

There are two different concepts for the energy supply (i.e. recharging) of the battery electric buses. One variant is the recharging of the vehicles during breaks in the depot. This preferably is done overnight, but recharging can also take place during the day e.g. during a break. This concept is called depot charging.

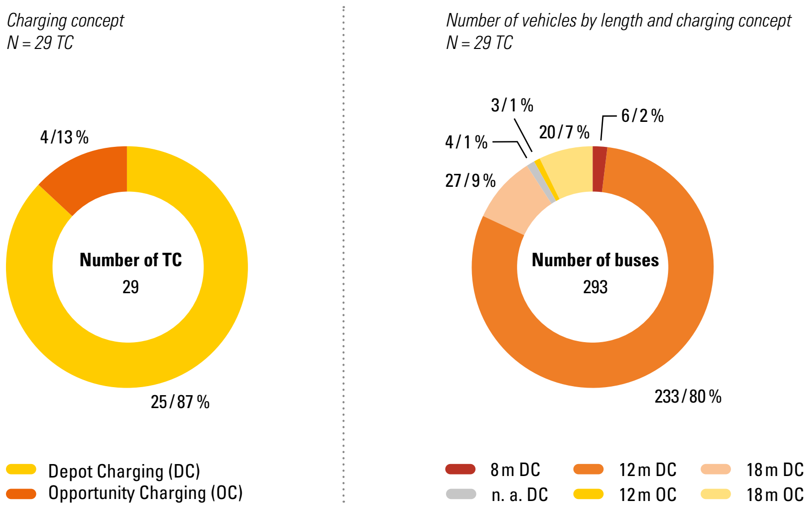
In the second variant, the bus is given a 'top up' charge at regular intervals during operation and is called opportunity charging. The recharging of the high-voltage battery normally takes place on the route, e.g. at terminal stops or turning points during the scheduled turnaround times or driver breaks. These two concepts give the operator some flexibility to select the best possible way to integrate the charging process into the bus fleet operations.

Battery electric buses designed as depot charging buses usually have the largest battery capacity, and the battery technology is usually only capable of limited fast charging. Depending on the battery technology used, this means that the batteries in this type of vehicle concept can commonly only tolerate a charging power compatible with its stated capacity. For example, an NMC battery with a battery capacity of 250 kWh will normally be charged with a maximum of 250 kW to guarantee its service life. The ratio between charging power and storage capacity is expressed as charge rate (C), i.e. the charge rate for depot charging buses is usually ≤ 1. Power transmission to the vehicle is mostly transferred via a charging cable with a plug or, alternatively, via a current collector (pantograph), which is either fixed to the charging infrastructure or mounted on the vehicle roof. In order to avoid peak loads, which should be kept to a minimum due to peak load dependent grid fees, it is advisable to provide a charging management system, especially if a large number of battery electric buses are likely to be used. These systems control the individual charging power as well as the time of the charging of the individual buses.

With opportunity charging, the battery electric buses normally have lower battery capacities, as recharging takes place several times a day, preferably during the turnaround time or the longer scheduled rest times. Since the objective is to transfer as much energy as possible during this time, high charging powers of up to 450 kW are used here. The combination of generally low battery capacity and high charging power can result in charging rates that are sometimes significantly higher than 1. In this case, an alternative battery technology based on lithium titanium oxide (LTO) is used. This battery technology is designed for high charging rates of up to 6 C or in some cases even higher. Due to the high charging power applied, the power transmission is usually done using a pantograph. The charging infrastructure for opportunity charging buses must be set up accordingly on or very near a line, commonly in the public space. The installation of the charging infrastructure in the public space can be quite demanding. In addition to the required power supply in the range of 250 – 450 kW per charging point, a second charging point may also need to be provided at a terminal stop in order to ensure the smoothest possible operation. The reason for this is to avoid negative effects in the event of delays or a technical malfunction at one of the charging points. The second charging point should be accessible whether or not the first charging point is in use, and this should be considered for the space requirements. Furthermore, the opportunity charging bus concept should be designed in such a way that reliable operation can take place despite any operational disruptions that may occur, e.g. due to failure or inaccessibility of a charging point at one of the end points.

Source: Rhein-Neckar-Verkehr 2020

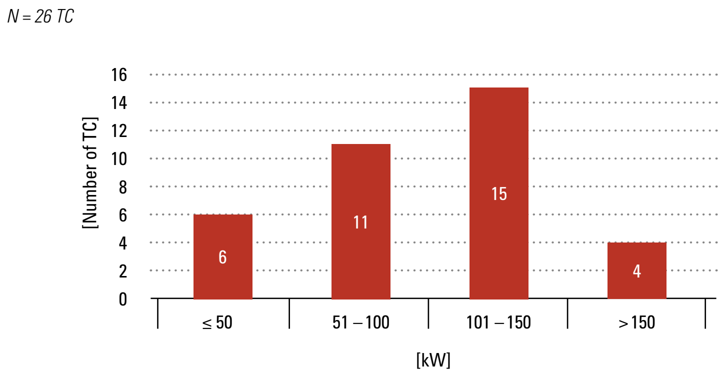
FIGURE 4 **Charging concept – battery electric buses**



Of the projects funded by the BMDV, 87% of the transport companies have opted for depot charging, whereas 13% use opportunity charging (see Figure 4). In terms of the number of vehicles, 267 buses or more than 90% use depot charging. For the 12 m buses alone, it is more than 97%. For the 18 m buses, 25 buses (60%) are charged by depot charging and 17 buses (40%) by opportunity charging. The 8 m buses are charged exclusively by opportunity charging, and the charging concept of 2 buses is not yet known due to the project status.

With regard to the maximum installed charging capacity, around one third of the transport companies have installed at least two different charging capacities at the charging points. 53% of the installed capacities are greater than 100 kW. As expected, outputs of more than 150 kW are installed by transport companies that use opportunity charging on the route (see Figure 5).

FIGURE 5 **Installed charging power – battery electric buses**



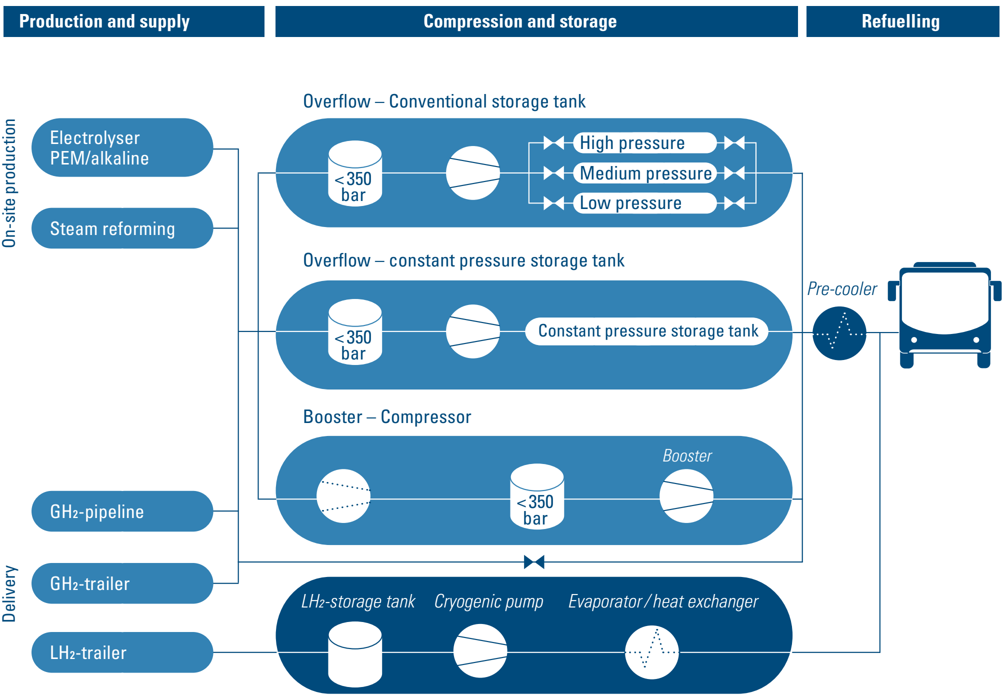
Overhead line

Trolleybuses obtain their power via an overhead line via a pantograph (current collector) to supply the required electrical energy both while driving and when stationary. If the vehicle is equipped with an HV battery as an energy storage device, additional electrical energy is taken up during the trip and when it is stationary in order to charge the HV battery (so-called dynamic charging) in addition to the electrical energy required for operation of the vehicle. This leads to an increase in the power consumption and may necessitate existing infrastructure systems being upgraded for this increased energy consumption. It may be necessary for the power consumption must be limited, e.g. when the vehicle is at a standstill, in order to avoid local thermal loads on the pantograph or the overhead line. Alternatively, the stationary recharging can be carried out via a stationary charging station designed for this purpose at the terminal stop using the pantographs of the trolleybus designed for this purpose, as is the case in Solingen, for example.

Hydrogen infrastructure

The energy supply infrastructure of fuel cell buses has many similarities to that required for natural gas vehicles. In order to have sufficient energy available in the vehicle, the hydrogen must be compressed to a high pressure due to its low volumetric energy density. During the refuelling process, a sufficient pressure difference between the refuelling station (up to 500 bar) and the bus (350 bar final pressure) is required for the hydrogen to flow into the vehicle's tank at sufficient speed to give a reduced refuelling time. Figure 6 shows the basic structure of a hydrogen refuelling station infrastructure with supply, compression & storage and refuelling.

FIGURE 6 **Principle sketch of a hydrogen filling station including delivery, compression, storage and refueling (Kupferschmid & Faltenbacher)**



There are various supply concepts for the provision of hydrogen, which require a decision on a case-by-case basis. When hydrogen is delivered by lorry, it is either transported in gaseous form at 200 – 300 bar or in liquid form if there is a greater demand. If there is a hydrogen production plant in the immediate vicinity, it is possible to use a pipeline connection. Hydrogen can also be produced on site by means of an electrolyser.

The H_2 supply concept currently preferred by transport companies envisages supplying a refuelling station at the company depot via gaseous compressed CH_2 [CGH_2] trailers with pressure levels of 200 – 300 bar. In the future up to 700 bar. In this case, the CGH_2 trailers are brought by lorry from the H_2 supplier in an exchange process, also known as the swap process, which means that at least two trailer parking spaces must be provided. In the long term, it is desirable to supply depot refuelling stations via an H_2 gas pipeline network, as this reduces the logistical and operational effort as well as the transport-related costs and environmental impacts. In Germany, the establishment of a widespread H_2 network will probably take some time. However the establishment of local H_2 networks, so-called H_2 microgrids, is already being planned or prepared at various locations in Germany. They offer the opportunity to gather initial experience and thus create 'best-practice' examples.

If there are public H_2 refuelling stations suitable for the refuelling of buses in the immediate vicinity of the depot or the route, they could also be used, either as a back-up or initially with a small number of vehicles as the main supply if no depot refuelling station is available. From an operational point of view, however, it makes sense to set up a dedicated H_2 refuelling station, as operational aspects (such as redundancy, refuelling capacity, initial filling of unpressurised H_2 tanks after maintenance, etc.) can be specifically adapted to the requirements of the transport company. Due to the planning, approval and investment costs associated with the construction of an H_2 refuelling station, it is advisable to plan it for a minimum fleet size (e.g. at least 10 vehicles).

Due to the nature of hydrogen, which forms an explosive mixture with air in certain mixing ratios, certain structural measures and safety distances must be observed for the design of the refuelling station. Further details can be found in VdTÜV bulletin 514.

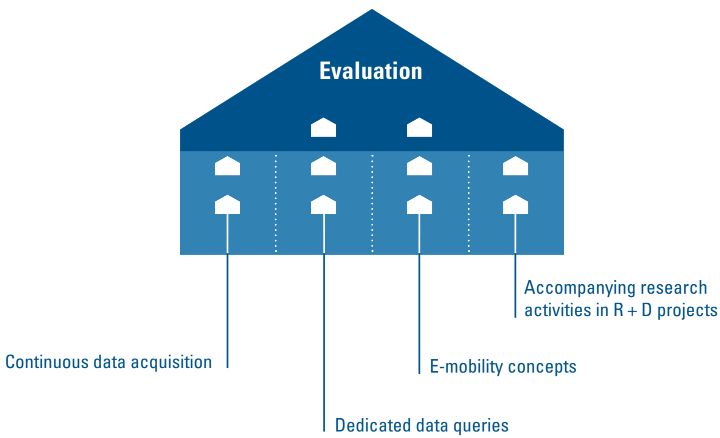
Market overview/availability

With regard to the energy supply infrastructure, the results of the market research performed show a broad spectrum of suppliers of charging, overhead line and hydrogen tank infrastructure. This applies to individual components of the infrastructure and to complete suppliers of turnkey infrastructure solutions. Therefore, there is already good overall availability of the various energy supply technologies.

1.4. Data basis of the accompanying research on buses

The data basis for the evaluation activities within the accompanying research on buses is based on four pillars (see Figure 7). They are, specifically, the continuous long-term collection of operational data (see chapter 2.2ff), the dedicated collection of information in the form of surveys, the e-mobility concepts related to local public transport, and the individual accompanying research activities in the R&D projects.

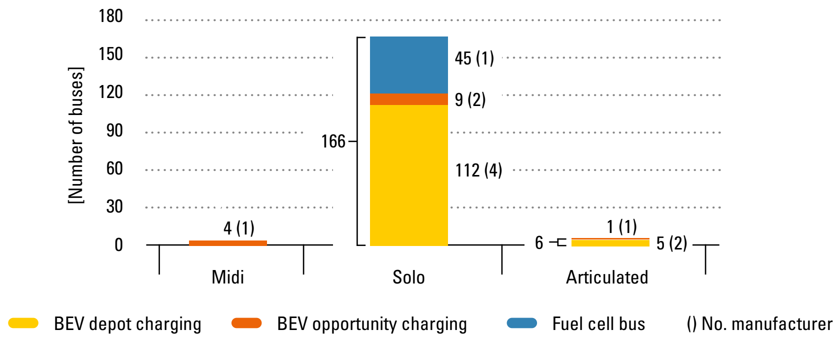
FIGURE 7 **Data basis of the evaluation activities in the accompanying research on buses**



From the continuous operational data collection, which covers the period from February 2019 through April 2021, data is available for up to 236 local buses from 19 transport companies. Of these, 131 are battery electric buses, 45 are fuel cell vehicles (see Figure 8) and 60 are conventional diesel buses.

The continuous operational data collection is based on the minimum data set as published by NOW, the German Dialogue Institute (DDI) and the Engineering Group for Transport and Process Development (IVV) in 2016. The data collection was carried out by means of data loggers or done manually by the transport companies. The data loggers were either data loggers supplied by the bus manufacturer or from third-party suppliers. The collected operational data was entered and evaluated in Sphera's web-based software SoFi. This data is used to evaluate the operating experience and performance in terms of progress monitoring over the observation period of this report.

FIGURE 8 **E-buses monitored by vehicle size and drive technology**



The data presented in chapter 2 of this final report correspond to the status of the data available at June 2021. These data are supplemented by reference values of diesel buses to enable a comparison with the reference technology of local public transport. This methodological approach has proven itself in previous activities and is continuously optimised.

Other sources of data and information for the evaluation activities in the ARe Bus were dedicated surveys of the funded transport companies on specific questions and topics relevant to the accompanying research. One example of this is the survey of operator requirements, including expectations regarding the technology readiness level, range, etc. at the beginning of the ARe Bus in Q4 2018. The subsequent survey of the transport companies regarding the level of fulfilment of the original expectations dates was carried out in the summer of 2021. It also includes an analysis of the data and results of the e-mobility concepts related to local public transport, which were also funded by the BMDV. The results of the R&D projects funded within the framework of the funding guidelines for electromobility and the mobility and fuel strategy of the Federal Government form the fourth pillar of the data basis.

Source: Berliner Verkehrsbetriebe, 2021

Source: WSW Mobil GmbH, 2021

2 Results

The results of the accompanying research on buses cover the evaluation categories mentioned in chapter 1.2: practical feasibility (chapter 2.2), energy efficiency (chapter 2.3), ecology (chapter 2.4) and economic efficiency (chapter 2.5). The guideline created within the framework of the accompanying research and the associated e-bus tool to support system selection is presented (chapter 2.6).

First, the requirements of the transport companies for buses with electric drives are presented, demonstrating how the successful integration into the operation can be conceptualised (chapter 2.1).

2.1. Requirements

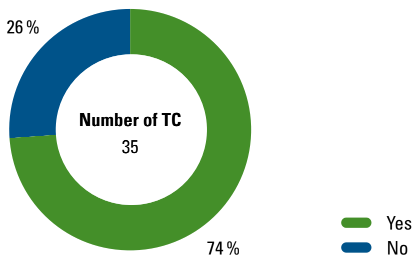
2.1.1. Operator requirements

The requirements for the introduction and operation of e-buses are both user-specific and dependent on the drive system. The transport companies funded by the BMDV were surveyed at the beginning of the accompanying research with regard to their requirements for e-bus operation. The operator requirements were assigned to the following four areas:

- I) Technical requirements
- II) Operational requirements
- III) Economic requirements
- IV) Ecological requirements.

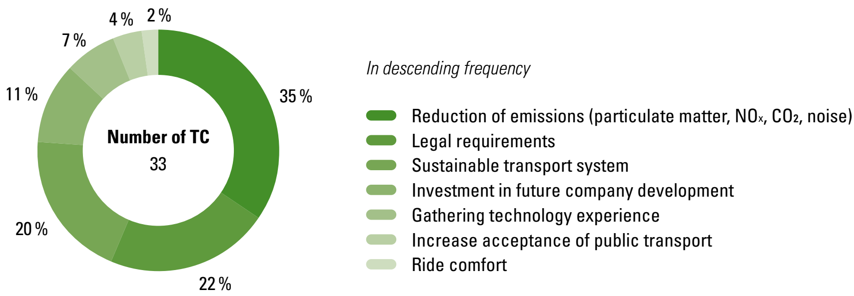
The feedback responses received from the transport companies were part of the 'operator requirements' survey form, which was sent to them with the minimum data set (MDS).

FIGURE 9 **Experience/prior knowledge in the field of electromobility**



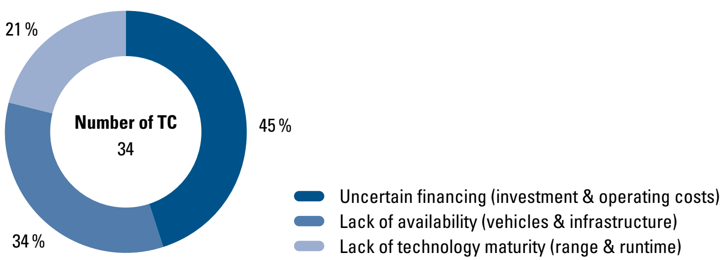
The motivation of the transport companies for the conversion to electromobility is mainly the general reduction of emissions (35%), which is closely followed by responding to the legal requirements that now exist (22%). The conversion to electromobility is seen as an investment in a sustainable transport system, which should also secure the future development of the company. Gaining experience with the technology and increasing the acceptance and comfort of local public transport for the customer are further motivating factors for the transport companies.

FIGURE 10 **Motivation for electromobility**



The transport companies increasingly cited uncertainties regarding the financing of investment & operating costs (45%) as a difficulty in implementing electromobility projects in the bus sector. A lack of availability of vehicles or the necessary infrastructure for procurement was also cited (34%). A lack of technology maturity (21%), concerning range and charging time among other things, also poses a challenge to the transport companies in the conversion.

FIGURE 11 **Obstacles to the conversion to electromobility**



The result is an evaluation of relevant technical, operational, economic and ecological requirements for the introduction of e-buses.

Further information can be found in the detailed report on operator requirements, which is available in the 'Electromobility starter kit'.

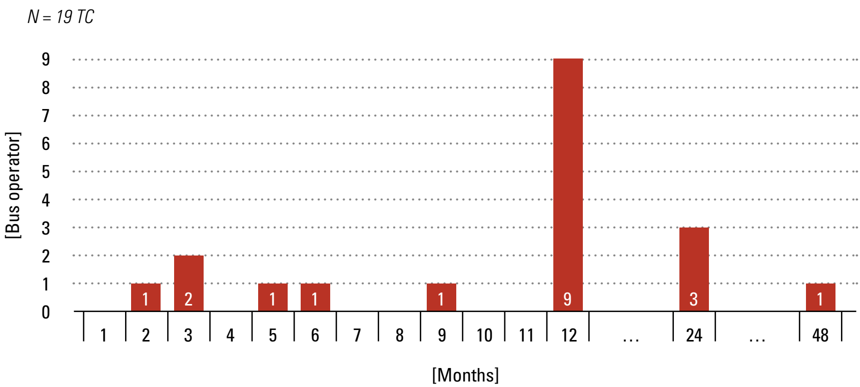
2.1.2. Planning periods

One objective of the accompanying research was the determination of the approximate timeframes for the individual project and implementation steps, starting from the basic decision-making process for introduction of e-buses, up to the implementation planning, and the actual commissioning of the new technology, consisting of vehicles and the associated charging and refuelling infrastructure.

Decision-making for the introduction of e-buses

Feedback from 19 transport companies gave a range of 2 to 48 months for the decision-making process for the introduction of electromobility in the bus fleet (see Figure 12). The duration is primarily determined by the political decision-making processes and the internal preconditions for the introduction of e-buses. For the majority of transport companies (39%), the decision-making process took about 12 months. For roughly 30% the duration was less than 12 months and for about 20% it was longer.

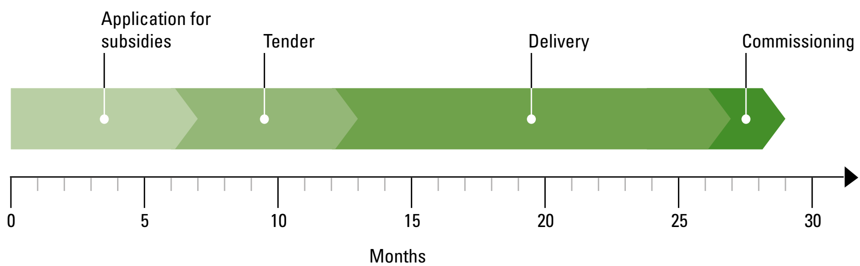
FIGURE 12 **Duration of the decision for electromobility**



Implementation timeline

Once the decision has been made to introduce electromobility, the next step is implementation. Depending on whether a company intends to take advantage of subsidies and whether an appropriate subsidy call is currently open, about (3–) 6 months should be estimated for the application and approval of subsidies. For the call for tenders, approx. (4 –) 6 months should be allowed from the preparation of the specifications to the awarding of the contract. If the contract value is above the relevant German public procurement thresholds (currently €428,000), a Europe-wide call for tenders is required, which can tend to take longer, sometimes up to 8 months. Accordingly, a period in the order of 9 – 14 months should be considered for the complete procurement including application for funding and tendering. Once the procurement has been awarded, the delivery time determines the remaining duration until commissioning. Currently, delivery times for buses are between 9 and 14 months, depending on the supplier. A delivery time of one year is considered realistic, although delays in delivery are not unusual right now. An additional 2 weeks to 2 months must be planned for the actual commissioning. Depending on the acceptance regime of the transport company, this results in an implementation period of 18 – 28 months; however, this is only a guideline that was based on the implementation projects analysed so far for the introduction of e-buses. Of course, the actual timeframes are highly dependent on the local conditions as well as the delivery time of the selected supplier.

FIGURE 13 **Implementation timeline**

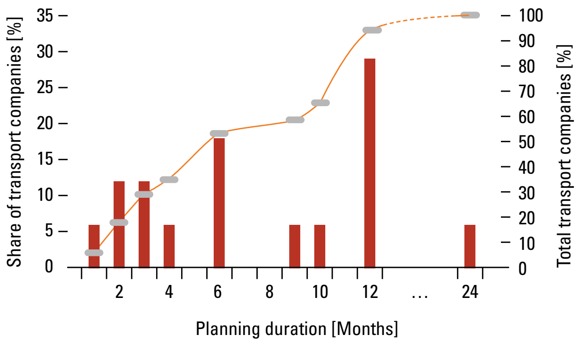


The basic planning and implementation of the charging and refuelling infrastructure fits into the time frame outlined above, although the phases are somewhat different in terms of content.

Detailed planning must be carried out for the construction of the energy supply infrastructure taking local conditions into consideration. Depending on the number and design of the planned charging points, the time required for this step can take up to 24 months (see Figure 14), as indicated by the survey of transport companies. Unless there are very special requirements, either due to local conditions or the need to supply a very large number of vehicles at once, a planning period of 6 – 12) months seems appropriate.

FIGURE 14 **Planning time for the installation infrastructure for battery electric buses**

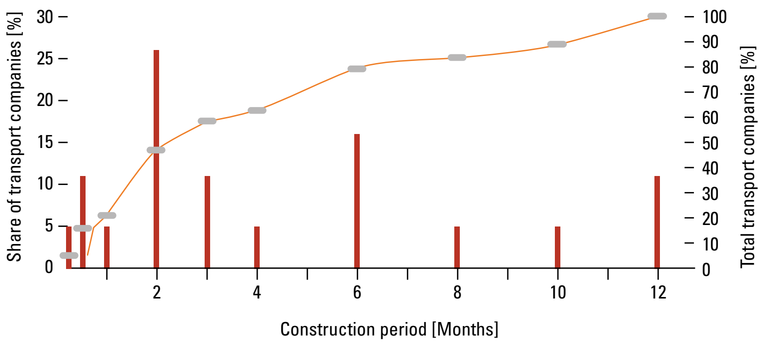
N = 17 TC



The same applies to the installation of the infrastructure. Almost half of the transport companies (47%) stated that they needed between 2 to 6 months for the installation. Larger installations may require up to 12 months.

FIGURE 15 **Duration for the installation of battery electric bus infrastructure**

N = 19 TC



Overall, the total time observed for planning and installation ranges from a few months to 2.5 years. An initial guideline value is 12 – 18 months, where the grid connection is a significant factor influencing the implementation duration, especially of the charging infrastructure (see chapter 2.5.2). If a more extensive grid upgrade is required, the duration for the installation of the charging infrastructure can quickly extend by a year or even longer. Therefore, it is recommended to contact the grid operator early in the planning process for the introduction of e-buses in order to clarify the power availability. A grid upgrade may be required, for which the necessary timeframe must be determined.

18 – 24 months should be planned for an H_2 refuelling infrastructure, since a more extensive approval process needs to be undertaken and, in most cases, the local approval authorities currently have little or no experience with the approval of H_2 refuelling infrastructure.

As a general rule, the planning and procurement of the energy supply infrastructure can take place in parallel with the procurement of the vehicles. However, attention must be paid to coordinating the vehicle and charging or refuelling procurement and installation. This is to facilitate any requirement regarding interfaces or communication between vehicles and the energy supply infrastructure (see chapter 4.2 on infrastructure standardisation) during construction and commissioning. It is also important to evaluate the performance of the respective infrastructure in operations with the vehicles (e.g. energy storage capacities and energy throughput capabilities on board the buses and on the energy infrastructure side).

2.1.3. Political parameters

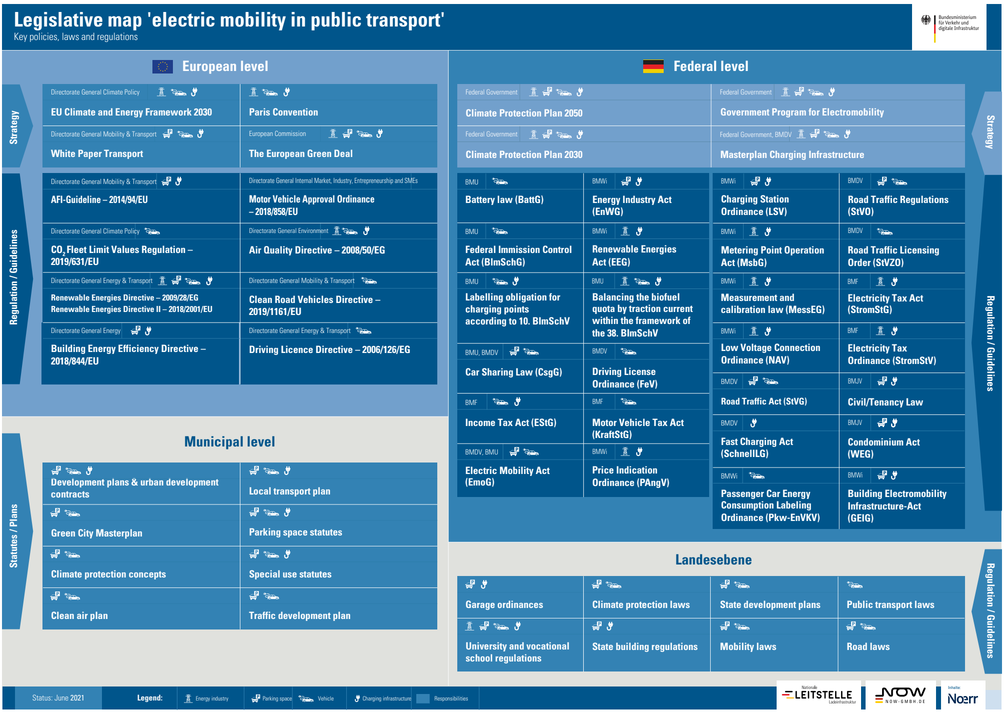
The evaluation of the political parameters relevant to local public transport electrification made it possible to identify political influencing factors on the market ramp-up at European, federal, state and municipal level.

The objectives and contents of the respective strategies, ordinances, laws, directives, statutes, plans and other parameters were evaluated qualitatively in connection with the planned implementation period. This made it possible to identify long-term development trends for the spread of electromobility in local public transport. Instruments that have a short-term and direct impact on the introduction of electric buses were also identified.

Legislative Map 'electromobility in local public transport'

The main results of the evaluation were presented in the form of a legislative map called 'electromobility in local public transport', and an accompanying brochure with further information on the individual strategies, laws and regulations. They are available for download in the Electromobility starter kit at https://www.durchstarter-set-elektromobilität.de/OPNV/ (in German).

FIGURE 16 **Legislative Map 'electromobility in local public transport'**



The main results for the various policy levels are summarised below.

European level

Strategies

At the European level, limiting global warming to a maximum of 2 °C is the overarching goal. The reduction of greenhouse gas emissions in the transport sector by at least 40% by 2030 to a maximum of 60% by 2050 compared to the reference year 1990 is stated as a goal in several strategies.

The years 2030 and 2050 are targeted as concrete time horizons for achieving the goals. These targets provide planning reliability to navigate adaptation processes for the introduction of electric buses in the context of European mid to long term policy.

Within the framework of the European hydrogen strategy, there is a strong push for electrolysis capacity expansion for the production of renewable hydrogen. Short-, medium- and long-term timeframes (2020, 2024 and 2030 – 2050) are defined for this objective.

Regulations / Directives

In summary, the regulations/directives at European level contain the following objectives and contents:

- Development of infrastructures for alternative fuels
- Definition of requirements for CO_2 emission performance
- Determination of minimum tax rates as well as tax exemptions for energy
- Determination of the share of renewable energies
- Establishment of specific pollutant limits
- Setting minimum targets for the share of clean or zero-emission heavy duty vehicles (M3) in public procurement
- Setting binding national annual targets for the reduction of greenhouse gas emissions.

With regard to the target achievement periods, the focus was on the years 2020, 2025, 2030. Accordingly, significant impacts can be expected in the above-mentioned areas in both the short and medium term.

Federal German level

At the German Federal level, the following goals and contents of political instruments were identified:

- Reduction of greenhouse gases in the transport sector by at least 65% by 2030
- Strategy for the expansion of electromobility
- Establishment of a needs-based refuelling infrastructure to supply vehicles with hydrogen
- Increasing the share of renewable energies in gross electricity consumption
- Shaping the market ramp-up and development of demand for fuel cell technologies, e.g. by setting progressive reduction of investment subsidies
- Implementation of the Clean Vehicles Directive (CVD) to support the introduction of zero-emission vehicles in municipal transport
- Feasibility studies to accompany the use of electric buses
- Promotion of flagship projects
- Setting cost reduction targets for fuel cell buses and hydrogen infrastructure components, e.g. by defining maximum eligible costs of FC buses
- Regulation of specifications regarding the construction and operation of charging and refuelling infrastructure
- Reform of state determined electricity price components, in particular EEG reduction or exemption for use in battery electric buses or for use in the production of green hydrogen
- Promotion, funding and further development of technologies for electricity generation from renewable energies
- Tax relief for local public transport companies
- Ensuring environmentally friendly disposal of spent batteries.

Source: Vestische Straßenbahnen GmbH

State level

The following objectives and contents of the analysed strategies and laws and regulations were identified at the national level:

- Achieving climate protection goals in the transport sector
- Promotion/funding of electromobility and related infrastructure in local public transport
- Establishment & operation of charging infrastructure
- Establishment of a hydrogen refuelling station infrastructure (refuelling stations and electrolysis plants), e.g. for fuel cell buses
- Review of existing guidelines for procurement and awarding of contracts with regard to their applicability to hydrogen and fuel cell technology.

Municipal level

At the municipal level, the following goals and contents of the analysed strategies and statutes and plans were identified:

- Improvement of air quality
- Achievement of climate protection goals
- Reduction of traffic-related pollutant emissions
- Creation of targets for the electrification of local public transport
- Acquisition and testing of electric buses
- Promotion of electromobility/emission-free vehicles
- Harmonisation of special road use regulations with regard to the installation of charging infrastructure.

In summary, short-, medium- and long-term political parameters and objectives could be identified at all levels investigated that will have a fundamental impact on the electrification of road-based local public transport.

2.1.4. Electromobility concepts

Objectives

The electromobility concepts funded by the BMDV within the framework of the Electromobility Funding Guideline of 5 December 2017[15], which deals with the overall systemic integration of electromobility in municipal and regional sustainability initiatives or concepts, are evaluated with regard to their effectiveness, feasibility and sustainability. The focus is on concepts that highlight the conversion of local public transport to the use of e-buses.

15 See https://www.ptj.de/lw_resource/datapool/systemfiles/cbox/5119/live/lw_file/frl_elektromobilitaet_bmvi_2017.pdf

The concept evaluation primarily focuses on the following aspects:

- Evaluation of the technology application and the effects of the respective technology on the infrastructure in the depot or on the route
- Presentation of the status quo of electrification in local public transport and the regional framework conditions. Timeframes for the conversion and resulting derivations for the market ramp-up of buses with alternative drives in local public transport.

In order to derive possible clusters, all analysis results are compared. Commonalities of the cities in which the same technology was recommended will be shown.

The concept evaluations will be used to generate general statements on motivating factors and obstacles in the transition from diesel-based inner-city public transport to electrically powered buses. The complete system, consisting of vehicles, charging infrastructure, energy supply and instruments for operational control and monitoring, must be considered. Fuel cell buses with the associated H_2 tank and refuelling infrastructure were not considered in the context of the e-mobility concepts examined, as they were not the subject of funding. The respective requirement profiles of the transport companies and users and the operational and technical parameters, which have a decisive impact on selecting the suitable system concept, must also be taken into account.

Based on the findings of this study, a model structure for feasibility studies will be created, which is intended to support transport companies and public transport authorities in the design of future conversion concepts.

Procedure

The subject of the study are the electromobility concepts with a local public transport connection that were approved within the context of the Electromobility Funding Guideline of the BMDV15. After the first three funding calls, a total of 129 municipal electromobility concepts were funded, of which 21 concepts are linked to a local public transport.

The concepts are divided into those with a focus on local public transport and those in which local public transport only covers a part of the concept. The focus of the study is on the concepts that exclusively highlight the conversion of local public transport to electromobility (focus on local public transport). The concepts with local public transport as a sub-area only consider it as a section in an intermodal route chain. From this, findings on possible connection points with local public transport and the functional interfaces between the considered sub-areas of the transport systems are derived. In order to create synergies with the accompanying research conducted by the BMDV, the findings of the accompanying research 'Networked Mobility' will also be highlighted.

In order to collect detailed information, survey criteria are defined, which are used for the evaluation and comparison of the concepts to be investigated. The survey criteria will be combined in a standardised survey form, which will be used as a basis for the concept analysis.

The evaluation of the analysis results and consequently the comparative assessment of the electromobility concepts is ultimately carried out using indicators that are derived directly from the survey criteria. In conclusion, a statement can be made regarding the possibilities and obstacles for the conversion of local public transport to electromobility.

Motivating factors

The main motives for the conversion of the bus fleet to zero-emission drive technologies are the lower environmental impact, the positive publicity and an associated image gain, reduced operating costs, the increasing range of bus types and energy supply systems ready for series production, and the financial support promised by the Federal and State Governments for the introduction of electric bus systems.

Low environmental impact
The positive ecological effects expected from electric bus operation are a key factor in the activities of transport companies and municipalities. In addition to their own ecological awareness and desire to make a contribution to improving the quality of life, the conversion of regular bus services to e-buses is also aimed at meeting the legal requirements for reducing emissions in city centres.

Image gain
By converting bus operations to emission-free drive technologies, local public transport acts as a role model within society. Environmentally conscious behaviour is viewed positively by the general public and helps support the positive image of transport companies and public transport authorities.

Low operating costs
The transport companies expect significant cost benefits in operating costs compared to the diesel bus reference system. The elimination of maintenance-intensive vehicle components, in particular the simplified drive train, lower maintenance and servicing requirements and correspondingly lower costs are expected. As a result of the higher efficiency in the drivetrain and battery recuperation capability of e-buses, higher energy efficiency and thus lower energy costs per kilometre are assumed.

Variety of series production-ready bus types and energy supply systems
The gradual improvement in the operational availability of e-buses and the development and commercial availability of an ever-increasing variety of technological solutions in the field of electric drive and energy supply systems, some of which are ready for series production, transport companies see the possibility of adequately mapping their own operations. Thus, they are increasingly tackling the challenge of developing and gradually implementing an operating concept that is suitable for them.

Financial support
The financial support promised by the Federal and State Governments for the procurement of e-buses, as well as the existing possibility of reducing the EEG surcharge or its planned elimination by the new federal government from 2023 (see chapter 2.5.2) for electricity for e-bus charging, motivates transport companies and municipalities to investigate the conversion to emission-free drive technologies for their operations.

Obstacles and challenges

The following aspects are seen as fundamental barriers to the conversion of the bus fleet to e-bus operation which are partly in contrast to the motivating factors listed above reflecting the varying perceptions and conclusion drawn on market readiness, costs etc. in the analysed concept studies:

- the complex structure of stakeholders in local public transport
- the high planning costs and the possibly high operational adaptation requirements associated with e-bus operation
- the still limited supply of marketable products
- the additional costs compared to diesel buses
- the great uncertainty regarding the provision of subsidies
- uncertainty about the actual operating income of e-bus operation.

Complex structure of stakeholders in local public transport
Fundamental decisions about changes in drive technology related to the provision of public transport services from diesel-based to alternatively powered local public transport requires consideration of many opinions and perspectives. The reason for this is the complex structure of stakeholders consisting of the public transport authority, the transport company, possibly subcontractors, public interest groups and often the transport association.

High planning costs and high need for operational adjustments
Stakeholders expect enormous efforts to be required in the concept study, project planning and implementation phases. An optimal deployment and operating concept must be developed for the specific application, accounting for operational, technical, economic and ecological parameters. The decision-making process, and ultimately the determination of the appropriate technology, require extensive knowledge and is therefore considered to be demanding. The necessary operational adaptation associated with e-bus operation represents another challenge. Only limited ranges can be achieved with the currently available technologies. In order to adequately replace diesel-based bus operation, operational and technical adaptations are required, which are believed to be too elaborate and not economically feasible.

Low supply of marketable products
While some funding recipients, who are motivated to switch to emission-free drive technologies due to the variety of bus types and energy supply systems that are ready for series production, other funding recipients do not yet see the possibility of meeting their specific needs and operational requirements with the products available on the market. Market entry of market-leading European diesel bus manufacturers was expected at the time the studies were conducted (2019 – 2020).

High additional costs
The higher investment requirement for vehicles and charging infrastructure compared to the conventional bus system is seen as the general challenge. Even with the inclusion of funding opportunities, there are some considerable additional costs that cannot be offset by the lower operating costs.

Uncertainty regarding actual operating income
The general uncertainties regarding the actual operating cost savings as a result of no reliable empirical values being currently available, prevent some of the funding recipients from defining implementation steps and starting the conversion.

Uncertainty regarding the provision of funding
As the implementation is largely dependent on funding, the stakeholders are striving to make the best possible use of existing funding opportunities. The electric bus system is complex with partly unknown components, e.g. the charging infrastructure. Consequently, some stakeholders are not in a position to accurately define all eligible system components and align them with the funding programme. If a complete system conversion is supposed to take place, the stakeholders are uncertain about taking the first step, as the project can only be evaluated economically dependent on a binding availability of funding, and the required funding cannot be guaranteed at the beginning of the system conversion.

Furthermore:
In general, it can be stated that the barriers to entry for the electrification of the bus fleet are higher for transport companies without a metro or tram network than for transport companies currently with this technology. Transport companies that already operate electric rail transport can draw on existing infrastructures and systems, for example in terms of workshop equipment, training requirements, etc.

The factors identified influencing the behaviour of the stakeholders are both motivating and inhibiting. For example, the availability of subsidies induces the stakeholders to dedicate themselves to the complex topic of e-bus introduction and to actively pursue the system conversion step by step. On the other hand, uncertainties regarding the actual granting of the subsidies, which are awarded in a competitive process, represent an obstacle.

Further information can be found in the brochure on the evaluation of electromobility concepts with reference to local public transport, which is available in the 'Electromobility starter kit' (in German).

2.2. Practical feasibility and operational maturity

2.2.1. Distance driven

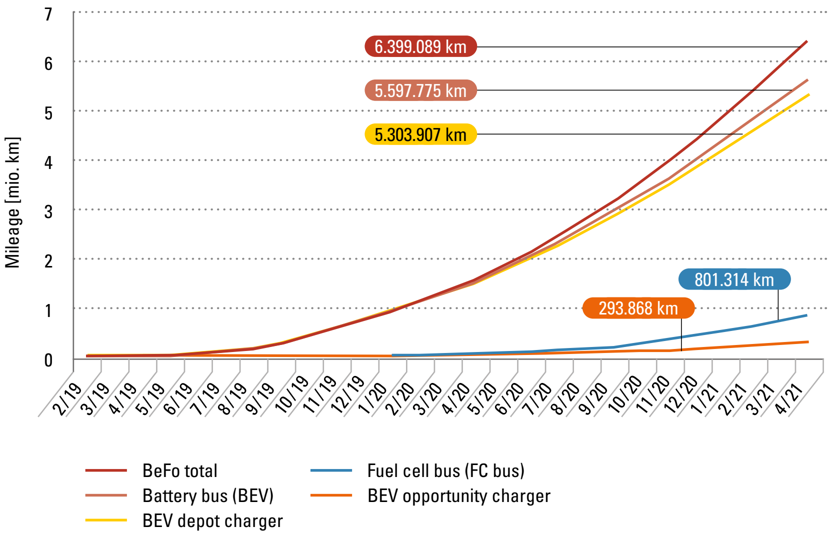
A total of 19 transport companies provided operating data for their battery and fuel cell vehicles as part of the accompanying research on buses. In the period from February 2019 to April 2021 (27 months), data from a total of up to 176 buses (131 BEV, 45 FC) with a cumulative distance driven of almost 6.5 million kilometres (BEV + FC) were recorded (see Figure 17). Depending on the transport company, the operational data is available on a daily basis or per trip, whereby a trip is defined for the purposes of the accompanying research as ignition on/off and a minimum trip length of 10 km. In addition to the BEV and FC buses, data was also collected for a total of up to 60 diesel reference buses in 2019 and up to 14 diesel buses in 2020, which had a cumulative distance driven of just under 3.4 million kilometres between February 2019 and December 2020.

For the battery electric buses, an extensive data basis is available due to the observation period lasting more than two years (commissioning of depot charging buses in February 2019, commissioning of opportunity charging buses in April 2019) and the number of recorded vehicles. Compared to the previous accompanying research from 2013 to 2016, the data basis has increased by a factor of approximately 8 with regard to the number of vehicles and by a factor of approximately 27 with regard to the distance driven.

For the fuel cell buses, which are included in the accompanying research for the first time, the distance driven is correspondingly lower due to the lower number of vehicles and the later time of commissioning (commissioning of the first 10 buses in

January 2020). Since November 2020, 45 FC buses have been in operation and the distance driven as of April 2021 is approximately 850,000 km. In the course of 2021, another 25 buses funded by the BMDV are planned to be put into operation, so that a further steady increase in distance driven is foreseeable. These additional vehicles will reinforce the fleets of the two transport companies that already operate the 45 FC buses.

FIGURE 17 **Total distance driven and distance driven by drive technology***



*** Quantity**
127 BEV
(∅ 72 | 3 – 121 / mon.)
45 BZ (∅ 26 |
5 – 45 / mon.)
Period
2/2019 – 4/2021

For the BEV as well as the FC buses, a positive trend in terms of distance driven and availability of the buses was observed during the study period (see following chapter 2.2.2), which can be attributed to a positive learning curve with the newly introduced technology. The longer the buses are operated, the more experience and confidence transport companies gain. This has a positive impact on the whole operation, from charging and refuelling to deployment planning and daily use.

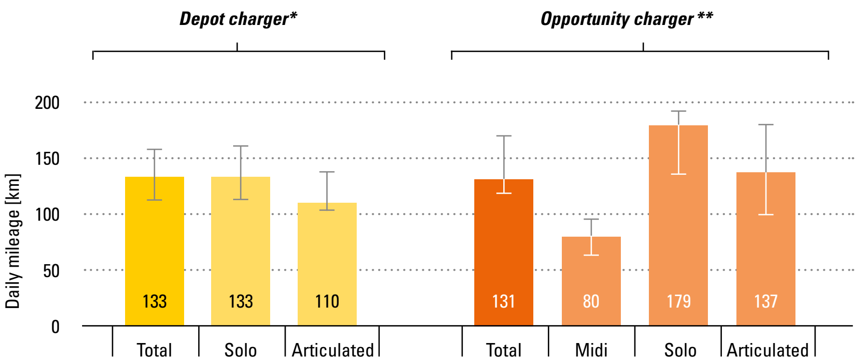
In the examination described below, the use of battery electric buses is based on daily and monthly distance driven as well as monthly operating days and compared with the requirements of the transport companies.

Battery electric buses

The evaluation of the operating data of the battery electric buses distinguishes between depot and opportunity charging buses, which are further divided into midi, solo and articulated buses. With depot charging, the buses are charged at the depot, whereas with opportunity charging, the buses are recharged on the route. With opportunity charging, however, the buses are usually also fully charged overnight in the depot.

Figure 18 shows the average daily distance driven by the battery electric buses. The collected data refers at most to the entire period of the accompanying research from February 2019 to April 2021.

FIGURE 18 **Average daily distance driven by the battery electric buses per bus**



*** Number of depot chargers**
Solo (Ø 64 | 3 – 103 / mon. | 11 TC)
Articulated (Ø 4 | 3 – 5 / mon. | 2 TC)
*** Period of depot chargers**
Solo (2 / 19 – 4 / 21)
Articulated (7 / 20 – 4 / 21)

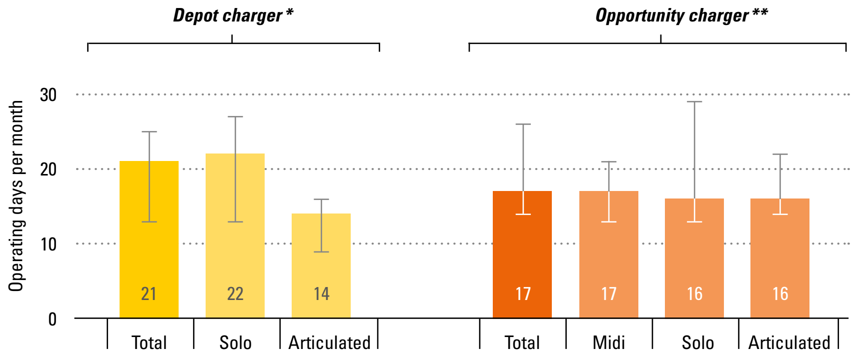
**** Number of opportunity chargers**
Midi (Ø 4 | 2 – 4 / mon. | 1 TC)
Solo (Ø 3 | 1 – 8 / mon. | 3 TC)
Articulated (Ø 1 | 1 / mon. | 1 TC)
**** Period of opportunity chargers**
Midi (7 / 19 – 4 / 21)
Solo (4 / 19 – 4 / 21)
Articulated (12 / 20 – 4 / 21)

For the depot charging buses, the average daily distance driven was 133 km. This average value is made up of operating data from up to 103 solo buses (Feb. 19 – Apr. 21) with an average distance driven of 133 km and up to 5 articulated buses (Jul. 20 – Apr. 21) with an average distance driven of 110 km. The installed battery capacity of the solo buses is approx. 290 kWh and that of the articulated buses approx. 410 kWh. One of the two transport companies that operates articulated buses also states an availability of the buses of only 60 – 70% and a TRL of 7, which explains the lower average distance driven by the articulated buses compared to the solo buses. However, due to the significantly lower number of buses as well as the shorter observation period of the articulated buses, the overall average of the depot charging buses is not noticeably affected. A comparison with the accompanying research from 2013 to 2016 cannot be made, as only operating data for 4 midi-buses with depot charging were recorded at that time and the bus size has a decisive influence on the range.

The opportunity charging buses achieved an average daily distance driven of 131 km, which is made up of the distances driven by midi, solo and articulated buses. Here, too, there are differences in terms of the number of buses and the timeframes for which data are available (see Figure 18). Despite the high distance driven by the solo buses (179 km), which represent the most buses with up to 8 buses as well as the longest observation period (Apr. 19 – Apr. 21) of this group, the overall average is only 131 km. This is mainly due to the distance driven by the midi-buses (80 km). This relatively low distance driven is due to the significantly lower installed battery capacity of the midi-buses (96 kWh) compared to the solo (127 – 396 kWh depending on the TC) and to the articulated buses (475 kWh). The distance driven by the one articulated bus (137 km) is similar to the depot charging buses not affecting the of overall daily distance driven by opportunity charging buses since data is only available for one bus for 4 months.

Apart from the opportunity charging midi-buses, the principle-based advantage of opportunity charging buses becomes apparent. They can achieve higher daily distances driven, as recharging usually takes place on the line, i.e. without returning to the depot and usually with higher charging power (150 – 450 kW). This is particularly noticeable for the solo buses, where the average daily distance driven is 179 km. For the articulated buses, the data situation is currently still very limited and does not currently allow any reliable statements to be made. For the sake of completeness, they are listed in Figure 18. Compared to the previous accompanying research, there has been a significant increase in the average daily distance driven by the solo buses, which is now approx. 20% higher (+ 30 km) and is also based on a broader data basis that now covers 2 years of operation.

FIGURE 19 **Average monthly operating days of battery buses per bus**



*** Number of depot chargers**
Solo (Ø 64 | 3 – 103 / mon. | 11 TC)
Articulated (Ø 4 | 3 – 5 / mon. | 2 TC)
*** Period of depot chargers**
Solo (2 / 19 – 4 / 21)
Articulated (7 / 20 – 4 / 21)

**** Number of opportunity chargers**
Midi (Ø 4 | 2 – 4 / mon. | 1 TC)
Solo (Ø 3 | 1 – 8 / mon. | 3 TC)
Articulated (Ø 1 | 1 / mon. | 1 TC)
**** Period of opportunity chargers**
Midi (7 / 19 – 4 / 21)
Solo (4 / 19 – 4 / 21)
Articulated (12 / 20 – 4 / 21)

Figure 19 shows that the depot charging buses were in operation on a monthly average of 21 days, while the opportunity charging buses were only in operation on 17 days.

The solo buses of the depot charging group run on an average of 22 operating days per month. As with the daily distance driven, the number of articulated buses (14 operating days) in depot charging buses is not particularly significant due to their small number and the limited period with available data for the average number of operating days. The depot charging articulated buses over the individual months showed, these buses are exclusively in operation between 7 and a maximum of 18 operating days per month. The average value of 14 operating days is therefore not based on individual outliers, but extends over the entire period under consideration. A comparison of the information provided by the two transport companies which provided data on the average availability and the TRL of the articulated buses shows that the availability of one transport company is only 60 – 70%. The TRL is rated at 7 by one transport company and 8 by the second, which explains the low number of operating days. The number of operating days of the depot charging buses has increased by about 16 – 20% compared to the previous monitoring research (18 operating days).

The average number of operating days per month for the opportunity charging buses is 17 for all bus sizes. The average operating days per bus size are evenly distributed between midi (17 operating days), solo (16 operating days) and articulated buses (16 operating days). The striking feature of the solo opportunity charging buses is the wide range, from a minimum of 13 to a maximum of 29 operating days (see Figure 19). In two transport companies, the buses were able to be used on 29 days in individual months, although this is not yet the norm. The low number of operating days can be somewhat explained by the information provided by the transport companies regarding the availability and the TRL of all bus sizes. One transport company states the TRL of the buses as only 3 – 4 and that of the charging infrastructure as 7. Another TC gives a value of 8 for both the TRL of the buses and the charging infrastructure, but the availability of the buses and the CIS is only listed as approx. 73% and 70% respectively. The remaining 3 TCs are satisfied with the availability of the buses and the CIS (each > 90%) and state a TRL of 8 – 9 for buses and CIS. The average number of operating days has not changed compared to the previous accompanying research.

Figure 20 and Figure 21 provide further insight into the number of operating days of depot and opportunity charging buses and how this measure evolved over time. Both depot charging buses (N = 13 TCs) and opportunity charging buses (N = 4 TCs) show a positive trend across all bus sizes, which indicates, among other things, a growing confidence of TCs in the technology. The exception is the articulated buses with depot charging, which may be due to the low number of buses (3 – 5 buses per month) of only two TCs, and because these buses are among the first vehicles of this size to be delivered. The fairly typical start-up difficulties with the introduction of a new type of vehicle are also evident here. The slight slump in solo buses with depot charging in mid-2019 is due to the fact that at that time only a small number of vehicles (3 – 14 BEV buses) were in use – first at one, and then two TC. Furthermore, the majority of the buses were from one manufacturer that retrofitted the vehicles during this period, which resulted in a discernible decrease in days in service during this period. As the number of TCs and buses increases over time, the spikes are also significantly dampened. With an average of 21 operating days per month, the average is a good 3 days above the findings of the previous accompanying research, where the average was 18 operating days per month.

FIGURE 20 **Monthly operating days of the depot charging buses over the period under consideration**

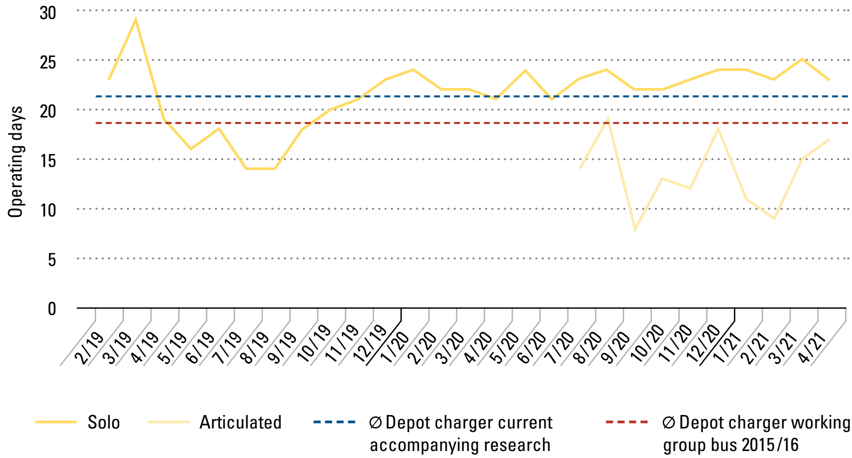


FIGURE 21 **Monthly operating days of the opportunity charging buses over the period under consideration**

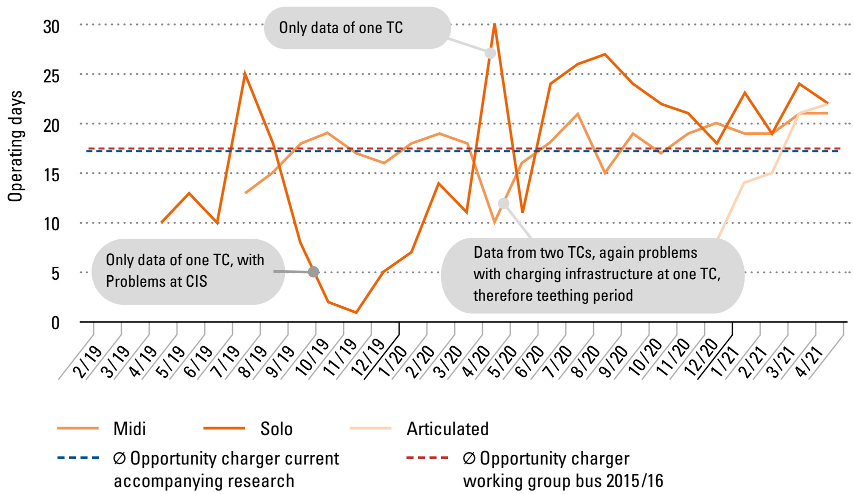
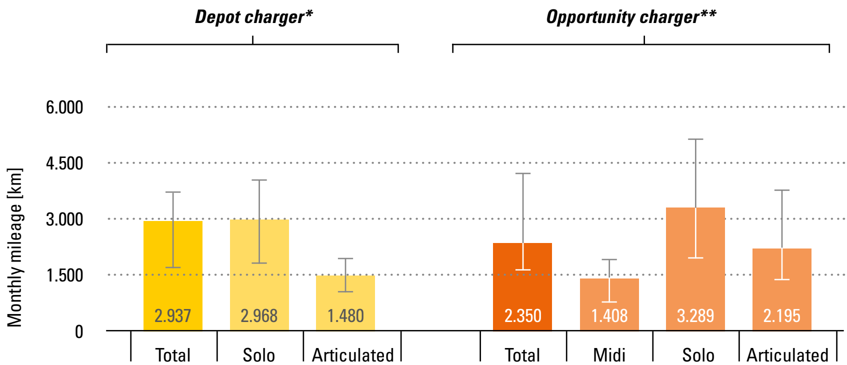


FIGURE 22 **Average monthly distance driven by battery electric buses per bus**



*** Number of depot chargers**
Solo (Ø 64 | 3 – 103 / mon. | 11 TC)
Articulated (Ø 4 | 3 – 5 / mon. | 2 TC)
*** Period of depot chargers**
Solo (2 / 19 – 4 / 21)
Articulated (7 / 20 – 4 / 21)

**** Number of opportunity chargers**
Midi (Ø 4 | 2 – 4 / mon. | 1 TC)
Solo (Ø 3 | 1 – 8 / mon. | 3 TC)
Articulated (Ø 1 | 1 / mon. | 1 TC)
**** Period of opportunity chargers**
Midi (7 / 19 – 4 / 21)
Solo (4 / 19 – 4 / 21)
Articulated (12 / 20 – 4 / 21)

The large fluctuations in operating days of the solo buses with opportunity charging can again be explained by the small numbers of vehicles. Up to April 2020, only two buses from one TC were in operation, which means that the average number of operating days can fluctuate greatly. In the middle of 2019 until the end of 2019, the TC had technical problems with the charging infrastructure, which is why the buses could only be used on a few days. In April 2020, on the other hand, the buses were operated daily without exception. From April 2020, another solo bus with opportunity charging was added, and towards the end of the year, another 6 buses were put into operation, which also stabilises the curve of the average number of operating days. Despite the difficulties mentioned above, the average number is 17 monthly operating days, which is similar to the earlier accompanying research.

Comparing the distance driven by the solo and articulated buses of the depot and opportunity charging buses shows an expected higher distance driven by the opportunity charging buses, as the opportunity charging buses do not have to go back to the depot for recharging, but can be charged directly on the route. The lower average value across all opportunity charging buses compared to the depot charging buses is due to the midi-buses, which are designed from the ground up for significantly shorter vehicle schedules than solo or articulated buses. This ultimately reduces the overall average significantly.

As can be seen in Figure 22, the average monthly distance driven for depot charging buses of 2,937 km is higher than the monthly distance driven for opportunity charging buses of 2,350 km.

This difference in distance driven can also be seen in the operating days of the depot and opportunity charging buses, as can be seen in Figure 19. The number of monthly operating days of the opportunity charging buses is about 4 – 5 days less than that of depot charging buses. Based on the two different charging concepts, the opportunity charging buses should generally achieve a higher distance driven with the same number of monthly operating days as the depot charging buses due to the charging technology. Theoretically, this means that more schedules and thus also more kilometres can be driven per day. As already mentioned, about 25% of the opportunity charging buses are midi-buses, which have a lower daily distance driven and thus a lower monthly driven distance of 1,408 km for several reasons. It can also be seen that the range between minimum and maximum distance driven by the opportunity charging buses is larger than that of the depot charging buses. This is partly due to the wider range of operational contexts for the TCs. Moreover, each TC had at least one month in which one or more buses were unable to achieve the desired distance driven.

Currently, monthly driven distances of over 5,000 km can already be achieved with the solo opportunity charged buses and up to just under 3,800 km with the articulated opportunity charged buses. The maximum monthly distance driven for solo depot charging buses is now over 4,000 km; and for articulated depot charging buses it is still quite low at just under 2,000 km. Further efforts are needed by the manufacturers to increase the reliability of the vehicles.

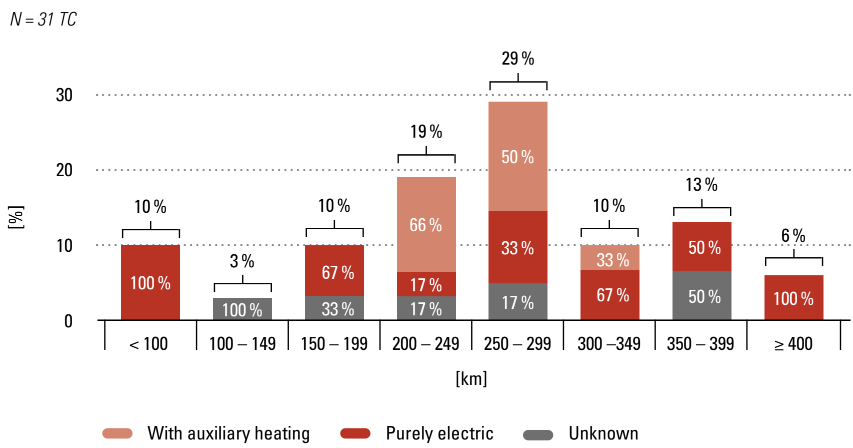
As with the daily driven distance, no comparison can be made between the depot charging buses of the previous and the current accompanying research due to the different bus sizes. Comparison of the solo and articulated buses with opportunity charging between the previous accompanying research (Ø 2,591 km) and the current accompanying research, shows an increase of 15% for the solo buses.

Comparison of daily distance driven achieved with range requirement

If we compare the daily distance driven achieved so far with the range requirements of the transport companies, it becomes clear that this is currently one of the key challenges for the use of battery electric buses. As can be seen in Figure 23, the vast majority (77%) of the 31 transport companies monitored require a daily range of at least 200 km. Most (58%) require a daily range of 200 to 350 km and around one fifth (20%) consider a daily range of more than 350 km to be necessary.

The majority of transport companies (52%) would like the battery electric buses to operate fully electrically. However, the range of more than 200 km expected by 11 transport companies in combination with a purely electric heating and air conditioning concept can only be achieved with high battery capacities. Only two transport companies that already operate electric buses have not implemented the purely electric heating and air conditioning concept demanded at the beginning.

FIGURE 23 **Range requirements – battery electric buses**[16]



16 For three transport operators, a battery electric bus only needs operating ranges of less than 100 km. This low range requirement is primarily attributable to the intended purpose, such as opportunity charging or for an inner city route as often seen in narrow historic city centres.

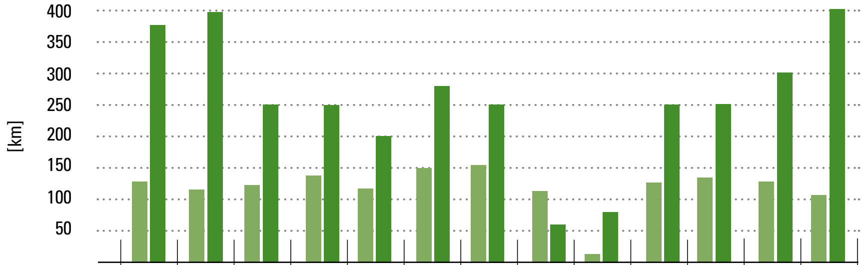
Data on the actual daily distance driven as well as the desired range and the heating concept are available from 13 transport companies with battery electric buses (see Figure 24). The comparison makes it clear that the currently achieved ranges do not yet correspond to the range requirements of the transport company. On average, the requirements are 2.4 times higher than the current average daily distance driven achieved. Therefore, the buses are charged at least once a day in the depot and used on routes that are feasible with the currently available cruising ranges. Thus, the depot charging solo buses are sometimes used on two routes per day, as can be seen from the calculated average of 1.1 charging operations per day.

TC 8 is the only TC that already exceeds the range requirement of the TC. TC 8 is also the only transport company that uses opportunity charging as a charging concept. Therefore, range is considered a less critical issue, and the TC lists the range requirement in accordance with the range specified by the manufacturer for BEV buses without recharging.

For TC 9, there is also a relatively low range requirement due to the specific application context of operations on the airport apron. The average daily distance driven achieved so far is very low here, as only very limited passenger service was required due to the outbreak of the COVID-19 epidemic. The achieved distance driven is therefore not low because of technology disruptions or failures, but can be attributed to the changed operating conditions.

Source: VAG Freiburg, 2021

FIGURE 24 **Range requirements compared to daily distance driven – battery electric buses with depot charging**

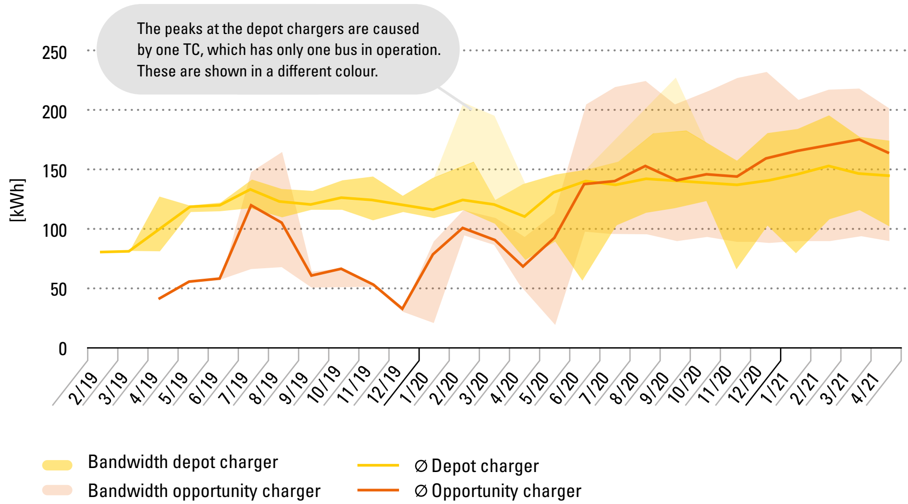


Transport company (TC)	1	2	3	4	5	6	7	8	9	10	11	12	13
Heating concept	With diesel auxiliary heating							Purely electric					
∅ Installed battery capacity	242	243	262	288	355	385	404	160	213	240	240	243	390
Desired range / Daily mileage	2,9	3,4	2,0	1,8	1,7	1,9	1,6	0,5	5,8	2,0	1,9	2,3	3,7
Desired range	375	396	250	249	200	280	250	60	80	250	250	300	400
Daily mileage	128	116	123	138	117	150	154	113	14	126	134	128	107

Desired range — Daily mileage achieved to date

Looking at the evolution of the daily distance driven over time in Figure 25, it can be seen that the average daily distance driven increases over time for both depot charging buses and opportunity charging buses. Due to the COVID-19 pandemic, there is a collapse in daily distance driven for both charging concepts in March 2020. As a result of the fluctuations at the beginning, the average daily distance driven over the entire period is higher for depot charging buses than for opportunity charging buses (see Figure 25). From July 2020, the average daily distance driven by the opportunity charging buses exceeds that of the depot charging buses and reaches a maximum of 172 km/bus. The maximum range of the opportunity charging buses has been above 200 km per bus since June 2020. In isolated cases, a higher range is also recorded for depot charging buses. With buses in cross-country use, even daily distances of over 200 km/bus in rural operation are feasible. However, only the data of one bus with low energy consumption and high travel speeds are available.

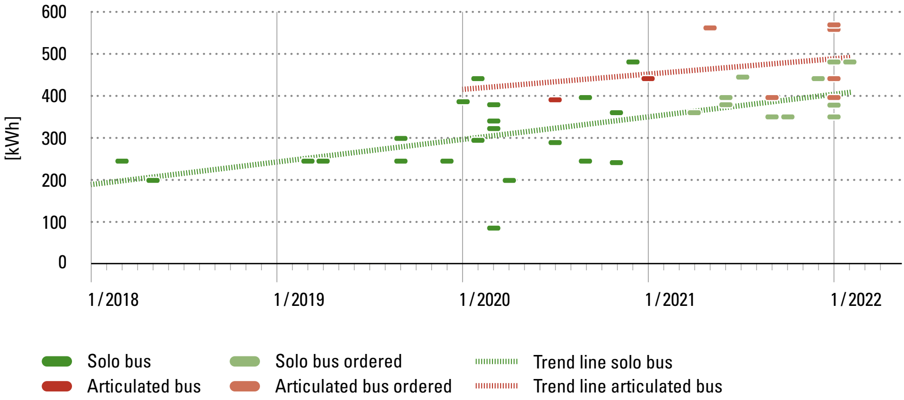
FIGURE 25 **Development over time of the daily distance driven by battery electric buses**



The two relevant factors affecting range are the energy consumption per km and the installed battery capacity. While the energy consumption is examined in detail in the following chapter 2.3, the analysis of the installed capacities of the commissioning of the funded buses shows that they are steadily increasing over time (see Figure 26). While the average installed battery capacity for the funded solo vehicles with depot charging is close to 300 kWh, Figure 26 shows that solo buses procured at the beginning of the accompanying research had installed battery capacities, which were in part well below 300 kWh. In the future, it is expected that battery capacities of significantly more than the currently procurable 400 kWh will be possible. Vehicles with approx. 550 kWh battery capacity have already been ordered for articulated vehicles. The opportunity charging buses are not considered here, since no major increase in the installed battery capacity is required due to the existence of charging points, usually at the terminal stops or turning points. Further analysis of the expected battery capacity development can also be found in chapter 4.2.

With higher battery capacities in the future, longer ranges are also possible. However, there are foreseeable technical limitations to the amount of battery capacity that can be installed, and the capacity increase cannot be unlimited for weight reasons (see chapter 4.2). Low battery capacities can also be practical depending on the application context, such as use for airport operations. The above-mentioned ranges are average values over the entire period. Buses with an earlier start of operation show a significantly lower range.

FIGURE 26 **Installed battery capacities of depot charging buses after start of operation and outlook**



Fuel cell buses

Fuel cell buses are currently being used in line operation by two transport companies. These are all solo buses. The average daily distance driven by the fuel cell buses is 137 km (see Figure 27) with a range of 90 to 204 km per day.

Current restrictions in refuelling, including a refuelling station located outside the depot, the H_2 refuelling station awaiting formal acceptance, as well as the lack of trained refuelling personnel, have negatively impacted the distance driven. At one of the TCs in particular, the decentralised location of the H_2 refuelling station means that the vehicles are only refuelled about every second day for operational reasons. This means that the buses reliably achieve more than 250 km between two refuelling stops, with the distance driven being spread out over several days. Generally, fuel cell buses can achieve ranges of more than 300 km between two refuelling stops.

As Figure 28 shows, fuel cell buses are in use for an average of just under 14 days per month. On average, the diesel reference vehicles achieve monthly operating days of between 26 and 27 days. Thus, the fuel cell buses are currently used less than the diesel reference vehicles. Apart from the limitations due to the refuelling strategy, this can also be explained by availability (see 2.2.2).

The monthly distance driven by the fuel cell buses averaged around 1,900 km (see Figure 29); which is currently still significantly lower than that of the diesel reference vehicles, whose monthly distance driven averaged around 4,000 km. Depending on the transport company, the average monthly distance driven by the fuel cell buses varies between 985 and 3,467 kilometres.

Like the daily distance driven, the monthly distance driven is also influenced by the restrictions on refuelling that are currently still in place (see Figure 29).

FIGURE 27 **Average daily distance driven by the fuel cell buses per bus***

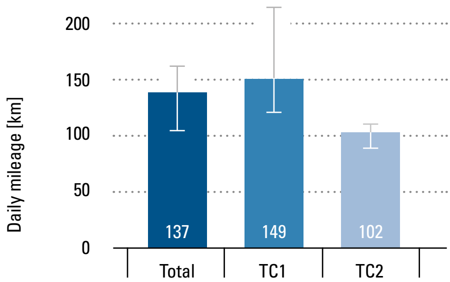
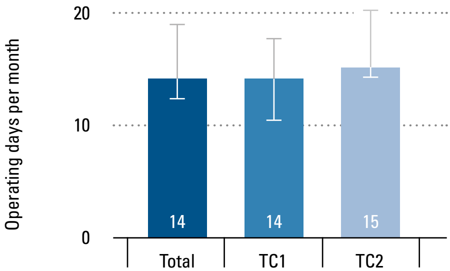
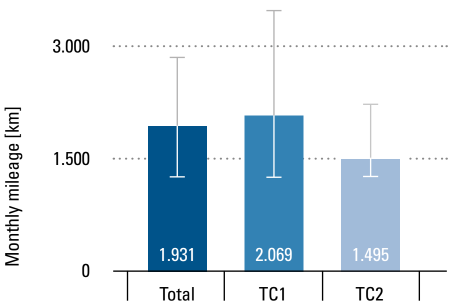


FIGURE 28 **Monthly operating days of the fuel cell buses per bus***



*** Number of fuel cell buses**
45
*** Period of fuel cell buses**
1 / 20 – 4 / 21

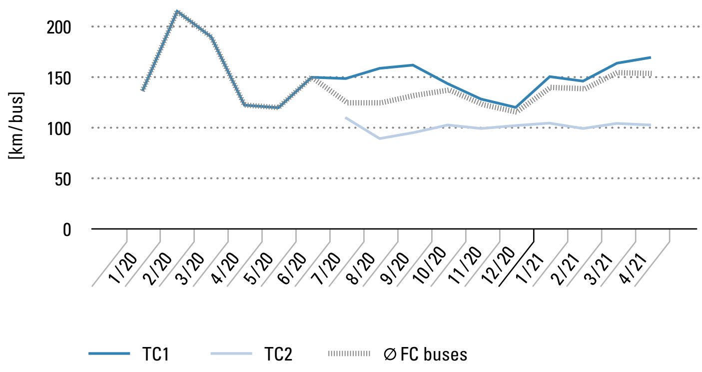
FIGURE 29 **Average monthly distance driven by the fuel cell buses per bus***



The required range from four transport companies for fuel cell buses were 250, 300, 340 and 400 km respectively. The air conditioning and heating concept is fully electric due to the drive technology, with only one feedback about the required heating concept, which demands fully electric operation.

Figure 30 shows the development of the daily distance driven which was higher in the beginning than later in the study period. This can be attributed to the COVID-19 pandemic and the increasing number of buses in the further course of the study. When more buses are integrated into regular operation, the distance driven by each bus is lower due to planning. However, it should also be noted that the restrictions due to special refuelling situations at both transport companies reduced the daily distance driven. Another factor is the availability of the buses, which is affected by long waiting times for spare parts, especially for the conventional part of the bus (see next chapter 2.2.2).

FIGURE 30 **Temporal development of daily distance driven – fuel cell buses***



*** Number of fuel cell buses**
45 (∅ 26,5 | 5 – 45 / mon.)

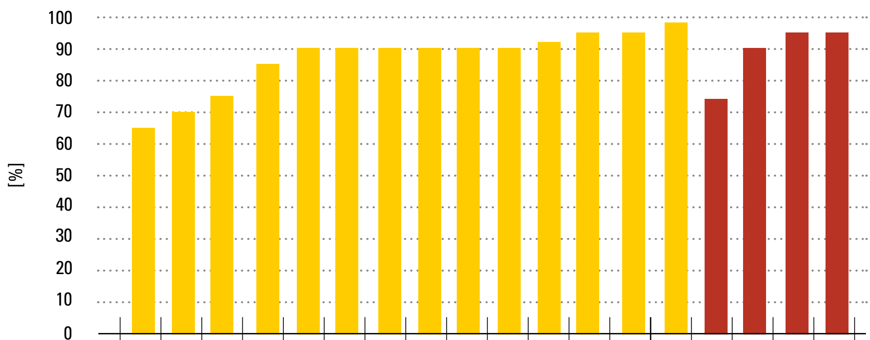
2.2.2. Availability

Battery electric buses

The highest possible availability is required for the reliable use of the battery-electric drive technology in daily line operation. Availability is a good indicator of the maturity of the drive technology.

Information on the availability of battery electric buses is available from 18 transport companies, 14 of which operate depot charging buses and 4 transport companies rely on opportunity charging. The battery electric buses they used have an average availability of approx. 87% in the period under consideration (see Figure 31). The depot charging buses have an availability of just under 87%, while the opportunity charging buses have an availability of ~ 88%. This is a significant improvement compared to the availability of 72% for depot charging buses and 76% for opportunity charging buses determined in the last status report of the WG Bus in 2016.

FIGURE 31 **Achieved availabilities of the battery electric buses**

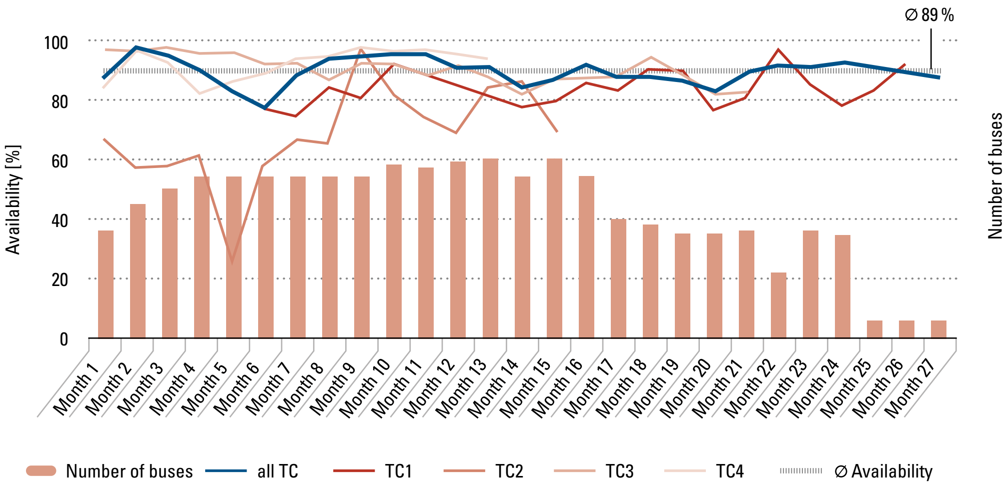


Transport company (TC)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Battery bus actual [%]	65	70	75	85	90	90	90	90	90	90	92	95	95	98	74	90	95	95

Depot charger   Opportunity charger

Detailed availability data of up to 60 buses on a daily or weekly basis is available from four transport companies. They include 58 solo and 2 articulated buses, with only 3 months of data available for the articulated buses due to their later commissioning in Q1 2021. All buses are depot charging buses. Figure 32 shows the development of the availability of these four TCs over time, as well as an averaged curve ('ARe') over all buses, in each case from the first month of operation. Depending on the date of commissioning of the buses, data for a period of 15 to 27 months are available for the individual TCs. The average availability of all buses for which detailed availability data are available is just under 90% and corresponds to the data in Figure 31. As can be seen in Figure 32, the vehicle availability of transport companies 3 and 4 is consistently higher than 80% with an average around 90%. The availability of the vehicles of transport company 1 fluctuates somewhat more and ranges from 76% to 97%, with an overall average availability of 85%. TC 4 had problems with the vehicles after commissioning, which is why availability was around 60% and even dropped below 30% in one month due to a technical defect. After about half a year, availability improved noticeably, with monthly availabilities of up to 90%; and an average vehicle availability of just under 70% with an overall positive trend.

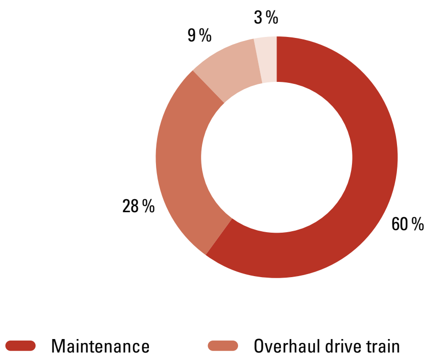
FIGURE 32 **Development of the availability of battery electric buses over time**



There is always a question of how availability is defined or measured. While TCs 2 – 4 measure availability based on a daily availability report, TC 1 determines availability via the ratio of target and actual kilometres.

Based on the data for breakdown reasons from two transport companies with up to 36 buses (see Figure 33), the main cause of breakdowns is the maintenance of non-drive-related vehicle parts of the buses (60%), followed by maintenance measures on the electric drive train (28%). Another 9% of breakdowns are due to accident repairs and 3% are due to material defects.

FIGURE 33 **Downtime reasons – battery buses***

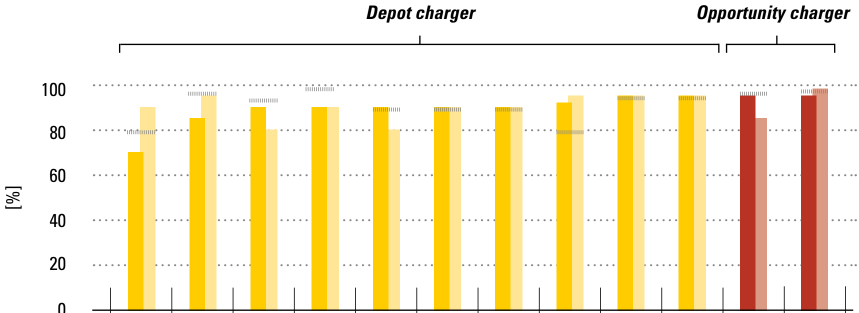


***Number of battery electric buses**
Solo (6 – 36 / mon. | 2 TC)
***Period of battery electric buses**
Solo (2 / 19 – 10 / 20)

Availability is therefore not yet at the level of established diesel drive technology which was used as the reference technology and had an availability of 93%. However, if one considers that battery electric bus technology has only been available on the market to a relevant extent for about 5 years or less, depending on the manufacturer, the average availability of close to 90% achieved so far is quite satisfactory. What is important here is the extent to which the technology meets the expectations of the individual transport companies in terms of availability. Based on the data from 12 transport companies, the availability expectation was on average 89%, with 70% of the transport companies demanding an availability of at least 90% and more than half (58%) of the transport companies expecting an availability comparable to the applied reference technology (see Figure 34). These are rather high expectations of the transport companies given a drive technology that has only been available on the market for a relatively short time. This should be considered when the expectations regarding the availability of vehicles in conjunction with the deployment strategy are formulated, especially if the drive technology is being used for the first time by a transport company.

On a positive note, the expected availability was achieved or exceeded in the vast majority of cases (75%).

FIGURE 34 **Expected and so far achieved availabilities of the battery buses with comparison to the reference technology**



Transport company (TC)	1	2	3	4	5	6	7	8	9	10	11	12
Battery bus actual [%]	70	85	90	90	90	90	90	92	95	95	95	95
Battery bus expectation [%]	90	95	80	90	60	90	90	95	95	95	85	98
Diesel reference bus [%]	80	97	94	99	90	90	90	80	95	95	97	98

Depot charger   Opportunity charger

In four transport companies, the battery electric buses had lower operational availability than required. This may be attributable to the vehicle manufacture, but may also be due to the restrictions caused by the COVID-19 pandemic as well as the associated partially reduced workshop operations in conjunction with the repeated delivery delays for spare parts. It is interesting to note that one transport company saw differences in the availability of buses per manufacturer, but also cited the Coronavirus restrictions as a reason for the lower figures. The presented availabilities were collected individually by the transport companies, and the recording processes may differ between the transport companies.

Data on vehicle availability was available for 14 other transport companies. However, they were not included in Figure 34 because either only data on actual availability (6 transport companies) or only data on expected availability (8 transport companies) was available

Availability of charging infrastructure

A reliably functioning energy supply infrastructure is essential for any type of drivetrain technology. The supply and refuelling via underground or aboveground diesel tanks with several 10,000 l of diesel fuel and stockpiling which is sufficient for often several weeks of operation, is state of the art for the established diesel drive technology. However, the situation is different for battery and fuel cell buses.

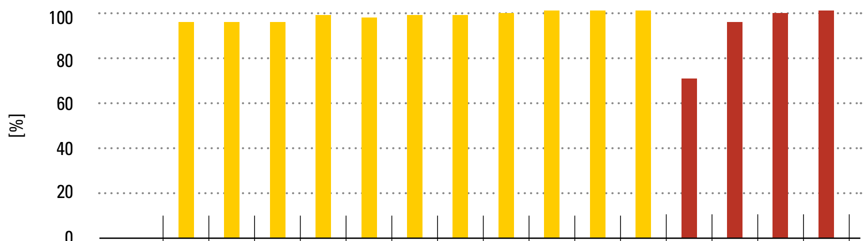
The power supply for battery electric buses in Germany can generally be said to have very good availability[17] ; Nevertheless, storms and floods, for example, can lead to prolonged local power outages. Emergency concepts must be developed for these scenarios. In addition to the issue of power supply in an emergency situation, the availability of the required charging power at the depot or its connection to the local power distribution grid plays a pivotal role in operational practice. It cannot be assumed that the required charging power will always be available at short notice. Consequently, it is necessary for the transport company to check with the distribution grid operator for each individual case as early as possible in order to clarify how much power can be provided without additional grid reinforcement measures to cope with emergencies. If grid reinforcement measures are necessary, they require a considerable lead time of at least 6 months, but often a year or more, especially if adjustments are required in the upstream grid system.

17 According to the German association of electricians (VDE), the average power interruption time per customer in Germany was 12 minutes in 2019. (https://www.vde.com/de/fnn/arbeitsgebiete/versorgungsqualitaet/versorgungszuverlaessigkeit/versorgungszuverlaessigkeit2019, last accessed on 23/07/2021)

In contrast to diesel, the storage of electrical energy for the operation of a battery electric bus fleet (e.g. via battery storage) is only possible to a very limited extent and is associated with high costs, especially for larger vehicle fleets. Another alternative is the provision of (diesel) emergency generators to provide all or at least some of the required charging power in the event of a grid failure. However, from a climate protection point of view, this alternative is an absolute emergency solution and should not be chosen or used as a standard solution.

High, ideally close to 100% availability of the charging infrastructure is essential for reliable operation of the battery electric buses. Currently, the charging infrastructure can be certified as having high availability with an average availability of 96% (see Figure 35).

FIGURE 35 **Achieved availability of the charging infrastructure**



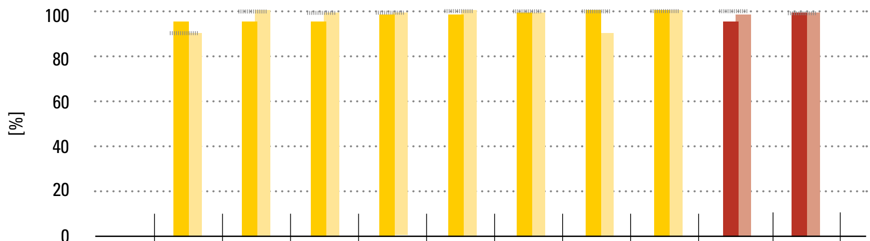
Transport company (TC)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Charging infrastructure actual [%]	95	95	95	98	97	98	98	99	100	100	100	70	95	99	100

Depot charger　Opportunity charger

The connection of the charging infrastructure to a tram substation was implemented, which resulted in a total of six to seven months of downtime. The reason for the problem, which has since been resolved, was the incompatibility of the charging stations with the input voltage fluctuations occurring in the substation. The remaining three transport companies report availability in the range of 95 to 100%, similar to the depot charging buses. In conclusion, the charging infrastructure availability of only one transport company is below 90%.With regard to the expectations of the availability of the charging infrastructure, it is mostly currently fulfilled (see Figure 36). The expected availability was 97% on average. For depot charging buses it was fulfilled with 98%. For opportunity charging buses it was below the expected value, based on the mean value of 81%, for the reasons mentioned above, although a significantly improved availability can be noted in 2021. Overall, availability is met or exceeded in 60% of the transport companies considered (see Figure 36).

For the reference infrastructure used by all transport companies, i.e. refuelling with diesel fuel, an average operational availability of 98% is reported. Hence, half of the transport companies assumed an initially lower availability of the charging infrastructure. Looking at the expectation of all operators as a whole, an availability similar to that of the reference technology is expected, which is understandable from an operational perspective. It is expected that the buses can simply leave at any time according to schedule. An energy supply infrastructure close to 100% is a basic prerequisite for this and is already largely fulfilled by the charging infrastructure under consideration.

FIGURE 36 **Expected and already achieved availabilities of the charging infrastructure with comparison to the reference technology**



Transport company (TC)	1	2	3	4	5	6	7	8	9	10
Charging infrastructure actual [%]	95	95	95	98	98	99	100	100	95	99
Charging infrastructure expectation [%]	90	100	99	98	100	99	90	100	98	99
Reference technology [%]	90	100	99	99	100	100	100	100	100	99

Depot charger   Opportunity charger

Fuel cell buses

Detailed data on availability of fuel cell buses is available from one TC for up to 35 solo buses for the period from January 2020 to April 2021, calculated based on downtimes. With an average availability of 78% it is thus currently still significantly below the operational availability of the reference diesel buses, which is specified as 90% by the transport company. The average availability between the buses in use varies between 53% and 91%. In individual months, the availability for individual vehicles reached values of up to 97%. When new buses are put into service, the availability of the entire fleet initially decreases. Downtimes of FC buses are also prolonged due to long delivery times for spare parts. According to the transport companies, however, the problems are mainly with spare parts for the conventional part of the bus.

FIGURE 37 **Average availability per bus – fuel cell buses ***

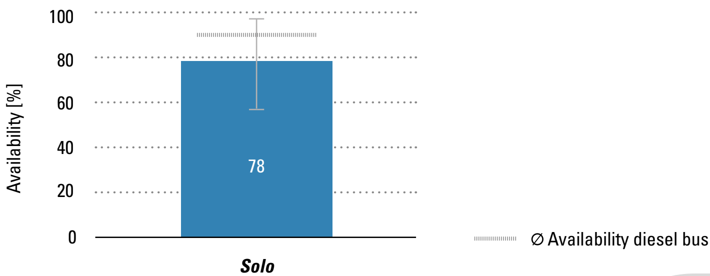
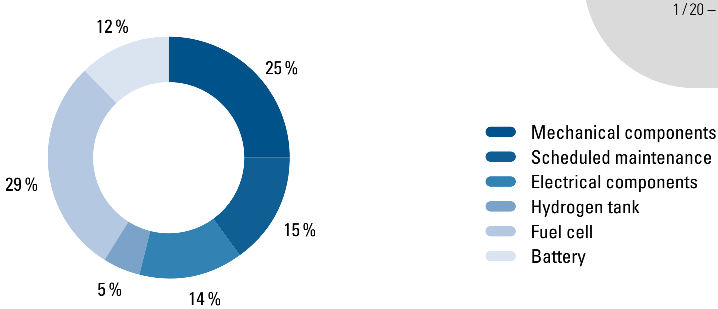


FIGURE 38 **Reasons for downtime – fuel cell buses ***



*** Number of fuel cell buses**
5 – 35 (1 TC)
Period of fuel cell buses
1 / 20 – 4 / 21

Availability of H_2 *refuelling infrastructure*

While the performance of the energy supply is essential for battery electric buses, for fuel cell buses it is a matter of guaranteeing the energy supply in terms of stocking hydrogen. Detailed analyses within the framework of the European NewBusFuel project[18] co-funded by the FCH JU, have shown that from today's perspective, stockpiling in the order of 2–3 days represents a sensible compromise between space requirements, storage costs, and security of supply. The resulting hydrogen fuel storage is therefore significantly lower in terms of quantity than is the case with the reference diesel technology.

18 See http://newbusfuel.eu/publications/

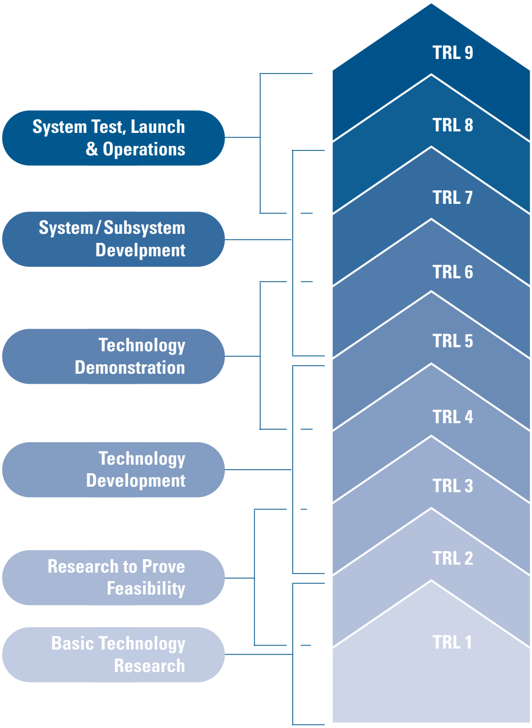
It is important to ensure reliable availability of the H_2 refuelling infrastructure through an appropriate redundancy concept for the relevant components, which are significantly more capital-intensive than diesel refuelling technology. This includes items such as the compressor, storage tank and dispenser.

Data on the operational availability from one transport company and a refuelling station are available. A redundant design of numerous components makes it possible to bridge minor faults and defects. This results in an operational availability of 93%.

2.2.3. Operational maturity / Technology readiness level

Another parameter that can be used to measure the operational maturity of the innovative drive technologies is the 'Technology Readiness Level', (TRL). Originally developed by NASA in the 1970s for space exploration technologies, the TRL measures the maturity of a technology during its research, development and deployment phases. TRLs are based on a scale of 1 to 9, with 9 representing the highest technology readiness level. At the completion of this level, a product or process is ready for series production. The assignment of technology readiness levels is a method for understanding the technical maturity of a technology during its development phase, with the goal to provide the most consistent reference point for understanding technology development.

FIGURE 39 **Definition of technology readiness levels based on NASA's TRL definition.**[19]



Important features of the individual technology levels

TLR 9 Qualified system with proof of successful deployment.
TLR 8 Qualified system with proof of functional capability in the field.
TLR 7 Prototype in use (1 – 5 years). Field test.
TLR 6 Prototype in deployment environment. Close to applicationsystem design. Test under realistic conditions.
TLR 5 Test setup in application environment. Start of integration of the system in its Test under laboratory conditions.
TLR 4 Test setup in laboratory; 'Brassboard system'. Proof of the basic system capability of the components.
TLR 3 Proof of the functional capability of a technology (5 – 13 years until market maturity) through research and development. Components are not yet integrated.
TLR 2 Description of the application of a technology. There is not yet a 'proof of concept'. It is essentially about process studies.
TLR 1 Observation and description of the Functional Principle (8 – 15 years until market maturity). Start of transfer of research into applied research and development, e.g. through principle technology studies.

19 Ornetzeder M. et al.: Monitoring of urban technologies, based on Research Centre Jülich. Reports from Energy and Environmental Research, 18/2016. Vienna, 2016

In order to assess the maturity of the technology and the expectations of the transport companies regarding the operational maturity of the e-bus technologies, the transport companies were asked before the technology was put into operation the TRL they expected at the beginning of the operation of the vehicles, and which one after one year of operation. To check the extent to which these expectations were met, a new survey was conducted in June 2021. Feedback was received from a total of 21 transport companies.

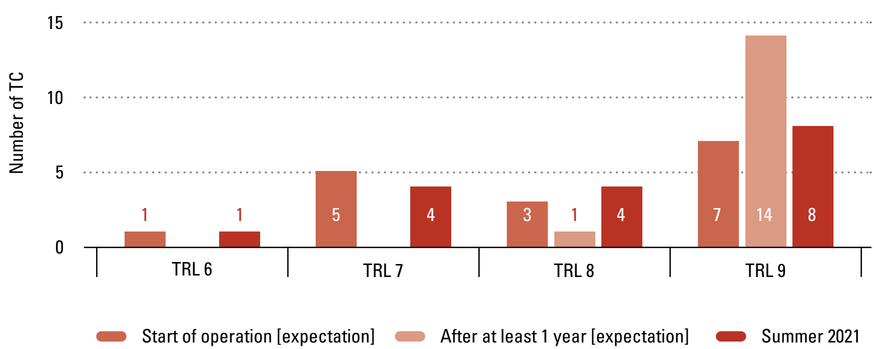
Battery electric buses

Figure 40 shows that 44% of the respondents expected to receive a fully mature series product (TRL 9) at the start of operation. Conversely, this means that more than half of the transport companies were aware that they were receiving new, not yet fully mature technology. 19% expected to receive vehicles close to series production (TRL 8), while 31% were preparing for 'mature' prototypes (TRL 7) and 6% of transport operators expected to receive prototype maturity (TRL 6).

With regard to the expected level of maturity after 1 year of operation of the battery electric buses, the vast majority of transport companies expected a significant increase in operational maturity. Thus, 93% of the responding transport companies had the expectation that the e-bus systems would be reliably usable after 1 year, corresponding to a product that is ready for series production (TRL 9).

As of summer 2021, the level of operational maturity does not yet fully meet those expectations. However, considering the short market availability of the various battery electric bus models, which is in the range of <1 to a maximum of 5 years, these expectations can be considered as quite demanding. 47% of the reporting transport companies describe the current technology readiness level as 'ready for series production' (TRL 9), while 24% describe the technology as close to readiness for series production (TRL 8) and another 24% as 'mature' prototypes (TRL 7). 6% still see significant potential for improvement with regard to operational maturity and rate it equivalent to prototype status (TRL 6).

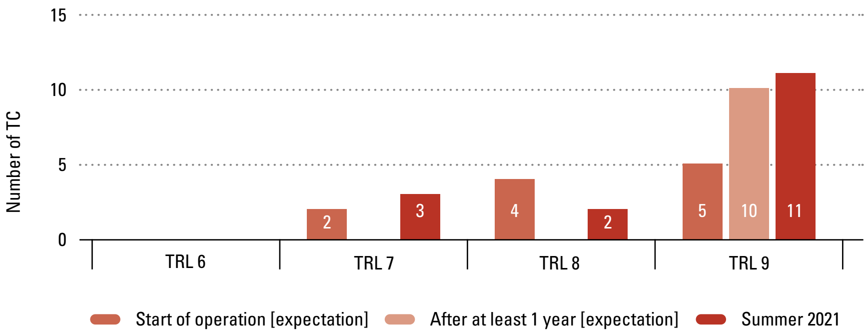
FIGURE 40 **Operational maturity at the beginning of operation and after one year of operation – battery electric buses**



Charging infrastructure

The technology readiness level of the charging infrastructure for electric buses is generally considered to be high, which is not surprising, considering that the charging infrastructure contains very few completely new components or concepts. Thus, 45% of the transport companies formulated the expectation that the charging infrastructure should be 'ready for series production' (TRL 9) from the outset, and another 36% indicated a technology readiness level close to series production (TRL 8) (see Figure 41). After one year, all responding TCs assumed that the technology was mature. Almost 70% of the transport companies also confirm that this is currently (as of June 2021) the case. 12.5% state that the charging infrastructure is almost ready for series production (TRL 8). However, 19% of the transport companies still see further potential for improvement (TRL 7). Only one transport company estimates that the TRL is currently lower than the required TRL stated at the beginning.

FIGURE 41 **Technology readiness level of the charging infrastructure**



Fuel cell buses

The transport companies with fuel cell buses expected at least a TRL 7 at the beginning of operation and a TRL 8 after one year of operation. Currently, they rate the fuel cell buses in the range of TRL 7 to 8. This means that the fuel cell buses do not yet fully meet the companies' expectations of the technology . It should be noted here that only 2 transport companies currently have fuel cell buses in operation. A somewhat lower technology readiness level can be assumed due to the currently still low market penetration. The only TC that plans to use both drive technologies classified the technology readiness level expected at the start of operation for FC buses as TRL 7 and for BEV buses as TRL 9 which gives an indication what the expectations of transport companies of the two e-bus technologies.

One TC gave the initial expected technology maturity as the same as the actual experience after more than one year of operation. The TC expected a technology maturity of TRL 8, close to series production, at the beginning, and reported the same after one year of operation.

H_2 refuelling infrastructure

In an initial survey, the transport companies also demanded at least a TRL 8 at the beginning of operation and TRL 9 after one year for the H_2 refuelling infrastructure. The refuelling stations currently achieve a TRL of 4 – 8. One transport company uses several refuelling station concepts with research status, which is why the TRL expectation here is lower: TRL 3 at the beginning (proof of functionality of the technology) and currently TRL 5 (trial set-up in a simplified operational environment) for one refuelling station and TRL 4 (trial set-up in the laboratory) for another refuelling station.

The planning period for installing the H_2 refuelling infrastructure is 24 months, which is longer than for the charging infrastructure. The construction itself can also take up to one year. When using Hydrogen an adjusted operational timeframe for the refuelling process is required. An adjusted timeframe is acceptable according to the transport companies feedback and is known from other gaseous fuels such as CNG). This can either be an extension of the refuelling window, or a more even distribution of refuelling operations throughout the day. The extension of the refuelling window results from slightly longer refuelling times of 10 – 15 minutes per bus compared to diesel buses. The extent of these adjustments will depend on the amount of H_2 to be refuelled in the case of concerted refuelling in the evening or at night by dedicated bus supply personnel. The distribution of the refuelling processes throughout the day means that the compressor can be smaller, as it does not have to be designed to cope with a high 'back-to-back' refuelling capability when there are a number of buses to be filled directly one after the other.

2.2.4. Summary of the results for practical feasibility and operational maturity

Battery electric buses

- The accompanying research has operational data for 131 battery electric buses for the period from February 2019 to April 2021. Of these, 117 are depot charging buses (112 solo buses, 5 articulated buses) and 14 are opportunity charging buses (4 midi-buses, 9 solo buses, 1 articulated bus).

- The average monthly distance driven is over 2,900 km for depot charging buses with 21 operating days/month and 2,350 km/month for opportunity charging buses with 17 operating days/month. It is important to differentiate between the various bus sizes. Despite only 16 operating days/month, the solo buses with opportunity charging achieve a distance driven of almost 3,300 km/month; the articulated buses with opportunity charging currently reach approx. 2,200 km/month; and the midi-buses reach 1,400 km/month, which is mainly attributable to their use in historic town districts at low travel speeds. The solo and articulated buses with opportunity charging thus have higher average monthly distance driven compared to their counterparts with depot charging, with currently fewer operating days/month.

- The battery electric buses in use have an average availability of approx. 87% in the period under consideration (depot charging buses 87%, opportunity charging buses 88%). This represents a significant increase compared to the last status report of the WG Bus from 2016, in which the depot charging buses had an availability of 72% and the opportunity charging buses an availability of 76%.

- The charging infrastructure has a high availability with an average of 96%. For depot charging, the availability is in the range of 95 to 100%, with an average availability of 98%. For the four transport companies with opportunity charging, it is 81%. This is primarily attributable to the low availability during the first six months of using a TC's CIS. The remaining three transport companies indicate an availability of 95–100%.

- The technology readiness level (TRL) of the buses is considered ready for series production (TRL 9) by 47% of the surveyed transport companies. 24% classify the TRL as 'close to series production' (TRL 8) and another 24% as 'mature prototypes' (TRL 7). About 6% classify the buses as 'prototype' (TRL 6) with potential for improvement.

- The charging infrastructure is classified as 'ready for series production' (TRL 9) by 68.5% of the surveyed TCs and as 'close to series production' (TRL 8) by 12.5%. The remaining 19% still see further potential for improvement and therefore classify the technology readiness level as TRL 7.

Fuel cell buses

- The current accompanying research analyses fuel cell buses, being an additional alternative e-bus drivetrain, for the first time. The fuel cell buses investigated travelled a total of 801,314 km in the period under review.
- On average, the fuel cell buses were used on 14 days/month with an average distance driven of more than 1,900 km/month, depending on the operational planning.
- The availability of the fuel cell buses is currently around 78% on average and is thus 12 percentage points below the reference diesel system. The main reasons for the downtime or failure of the fuel cell buses are the fuel cell and standard bus mechanical components.
- According to the estimates of the transport companies, the fuel cell buses had a TRL of at least 7 in the summer of 2021.
- The reported operational maturity of the hydrogen refuelling stations currently has a wider range and lies between 4–8. The TRL depends on the realised concept; in some cases, system concepts with a lower degree of maturity were deliberately implemented, with the aim of increasing the TRL through operational experience. At the same time, however, there are also refuelling stations in operation that are currently already rated with a TRL of 8 by the respective utility.
- Overall, the availability and use of the fuel cell buses still demonstrate a need for optimisation.

2.3. Energy efficiency and energy consumption

The analysis of the energy consumption of the subsidised battery and fuel cell buses is an important subject of the accompanying research. It involves an analysis of the energy consumption determined on the vehicle side and an analysis of the influence of the 'outside temperature' and 'average travel speed' parameters on energy consumption. The energy consumption of the charging infrastructure, including additional consumption for battery balancing and vehicle preconditioning, was also investigated.

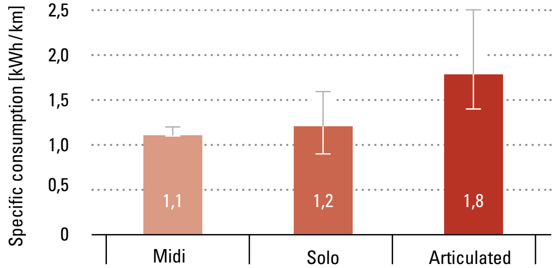
2.3.1. Vehicle energy consumption

Battery electric buses

Figure 42 presents the average energy consumption of the battery electric buses over the entire period under consideration. As can be seen, the midi-buses have an average on-board consumption of 1.1 kWh/km. All midi-buses had an all-electric heating concept. The ranges shown refer to the minimum and maximum average energy consumption of the individual reported buses. Within the course of the year, buses with a purely electric heating concept experience fluctuations in energy demand due to the outside temperature. Detailed analyses of the impact of climatic conditions can be found in the following chapter 2.3.2. Other reasons for the rather high average energy consumption of the midi-buses compared to the solo buses as a result of the low average speeds of the historic town district line served, and the maturity of the vehicles used which were developed in 2017. The technology maturity of these buses is assessed by the transport company as TRL 7 which is lower compared to the solo buses monitored in the accompanying research.

The solo buses have an average consumption of 1.2 kWh/km and the articulated buses an average of 1.8 kWh/km due to their increased weight. The ranges shown result from the different average consumption of individual buses within each vehicle size categories over the data collection period.

FIGURE 42 **Average consumption of the battery electric buses ***

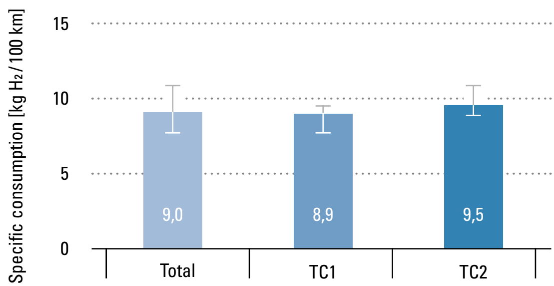


*** Number of buses**
BEV (Ø 69 | 9 – 101 / mon.)
Midi (Ø 4 | 2 – 4 / mon.)
Solo (Ø 64 | 9 – 92 / mon.)
Articulated (Ø 4 | 3 – 6 / mon.)

Fuel cell buses

The average hydrogen consumption of the fuel cell buses is 9 kg H_2/100 km (see Figure 43). The consumption values per TC (8.9 and 9.5 kg H_2/100 km) align with the diesel consumption values determined by the TCs, which are 38.5 and 43.2 l/100 km respectively.

FIGURE 43 **Average hydrogen consumption of the fuel cell buses ****



**** Number of buses**
BZ (45)
**** Period**
(1 / 20 – 4 / 21)

2.3.2. Influence of climatic conditions on energy consumption

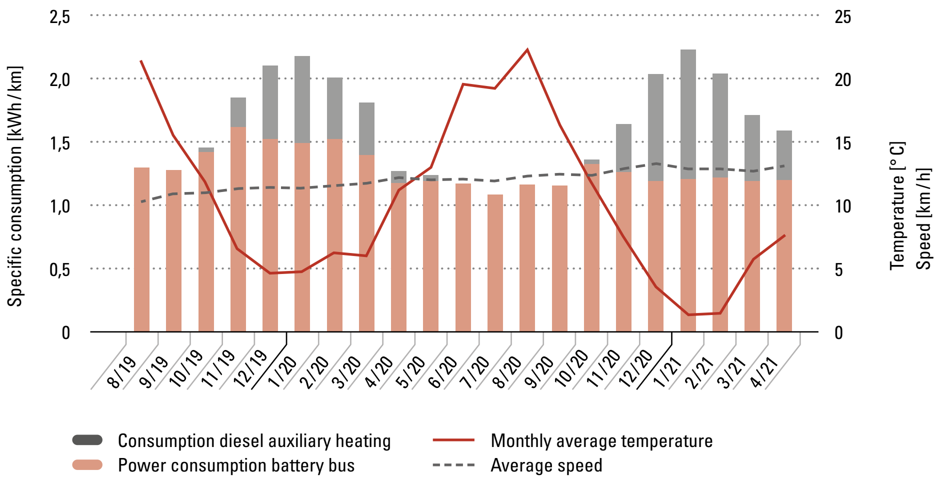
Battery electric buses

For the battery electric buses, heating the passenger compartment in the cold months of the year represents a challenge in terms of the additional energy demand. Basically, there are two options. Either the heating energy required to heat the driver's workplace and the passenger compartment is provided purely electrically (e.g. via a heat pump in combination with an electric resistance heater), or via a burner-based auxiliary heater (e.g. using [bio-]diesel or [bio-]ethanol). The burner-based auxiliary heating is combined with an electrically operated heat pump in about 40% of the buses. The purely electric heating offers the advantage that the bus has completely emission-free operation locally, whereas an e-bus equipped with burner-based auxiliary heating has climate and pollutant emissions (CO_2 of fossil or biogenic origin depending on the energy source used), nitrogen oxide (NOx), particulates, etc. when the bus is in heating mode. At the same time, this means that the range of the purely electrically heated e-bus is significantly reduced on cold days, while the bus equipped with auxiliary heating does not experience any reduction in range or, in the case of combined use with a heat pump, only a slight reduction.

Fuel-powered auxiliary heating

As an example, Figure 44 shows the energy consumption of the 12 m battery electric buses of a transport company divided into electrical energy demand and the energy demand of the auxiliary heating in the form of diesel fuel. In addition to the auxiliary heating, half of the monitored buses are equipped with a heat pump which, depending on the manufacturer, heats the passenger compartment when the outside temperature reaches down to 5 °C to 8 °C. The other half is equipped with an electric resistance heater in addition to the diesel auxiliary heater.

FIGURE 44 **Battery electric buses with diesel auxiliary heating – energy consumption for traction drive and heating**



*** Number of buses**
BEV (15–30 | 1 TC)

While the average outside temperature dropped below 5 °C in the winter of 2019/20, the specific electrical energy demand for operating the bus (approx. 1.5 kWh/km) and the diesel consumption (approx. 0.7 kWh with a conversion of 10 kWh per litre of diesel) for heating increased. A similar situation emerged in the winter of 2020/21, in which the average outside temperature was 1 °C at times. This lead to a diesel consumption of up to 1 kWh/km, which is in line with the lower outside temperatures observed in comparison to the previous year. One explanation for the approx. 0.2 to 0.3 kWh/km lower electric energy consumption of the buses in the winter 2020/21 with its lower outside temperatures compared to winter 2019/20 can be found in the slightly higher average speed of the buses. On average, the required energy consumption of the diesel auxiliary heating was just under 20% of the total energy consumption over the entire period under consideration. This represents a noticeable reduction compared to the 37% share of heating energy that was determined for another transport company in the previous accompanying research from 2013 to 2016. The value from the previous accompanying research was for vehicles where the entire heating power was provided by the diesel auxiliary heating and was thus correspondingly higher. Progress in terms of energy management, especially for the heating and air conditioning of the electric buses, is therefore discernible. The use of energy-efficient heat pumps, for example, could make a significant contribution here. On an annual average, the energy demand of the monitored battery electric buses with auxiliary heating is 1.3 kWh/km electrical energy and 0.34 kWh or 0.04 l diesel/km[20].

20 3.5 l Diesel/100 km

A detailed analysis of the consumption for the three articulated buses with auxiliary heating cannot yet be completed, as the buses only went into operation in December 2020 and January 2021, and two of the three buses broke down for a month shortly after they were commissioned. Nevertheless, the few months showed that, as with the solo buses, only a small amount of additional electrical energy is consumed for drive technologies in winter.

Purely electric heating

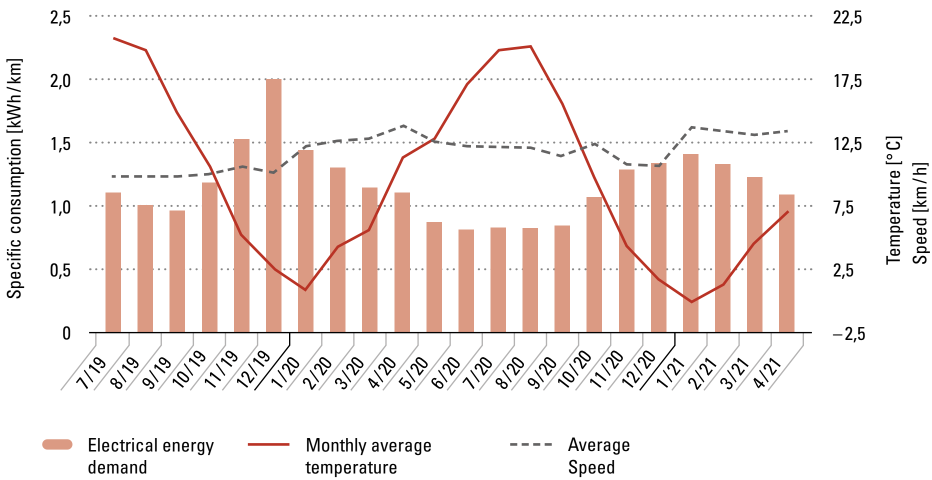
Figure 45 and Figure 46 illustrate the influence of temperature on energy demand, especially for battery electric buses with purely electric heating. At low temperatures and the resulting heating demand, the energy demand increases up to approx. 66% compared to the annual average, depending on the size of the bus (consumption of midi-buses in December 2019 excluded).

As can be clearly observed for the midi-buses (see Figure 45), the energy consumption increases significantly more in the cold season than for the previously monitored buses with additional heating. The increased average speed from just under 10 km/h in July 2019 to up to 13.6 km/h in January 2021 can explain the somewhat reduced energy consumption in the winter of 2020/21, despite similar temperatures as the

Source: Stadtverkehr Lübeck 2021

previous winter. According to the transport company, the sometimes very high energy consumption in the winter of 2019/20 is attributable to initial technical problems with the heating of the buses. This is also reflected in the information on the TRL of the buses (TRL 7). The average energy demand throughout the year is 1.1 kWh/km.

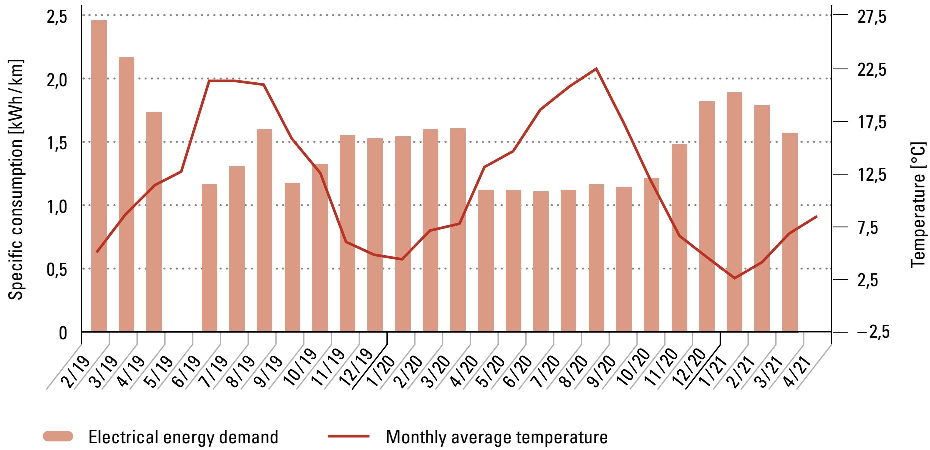
FIGURE 45 **Energy consumption of the midi-battery electric buses with purely electric heating** *



*** Number of buses**
BEV (4 | 1 TC)

The energy consumption of the purely electrically heated solo buses is based on data from one transport company with up to 6 buses in use. Due to an operational changeover, no operational data is available for May 2019. Nevertheless, the buses of this TC were in operation the longest and most regularly, which makes it most suitable for this evaluation. As with the previously monitored midi-buses, there is a marked increase in energy consumption on cold days – in this case, from 20% to 66% – compared to the annual average of 1.5 kWh/km. An analysis with regard to the average speed of the buses is not possible due to a lack of data.

FIGURE 46 **Energy demand of the solo battery electric buses with purely electric heating ***



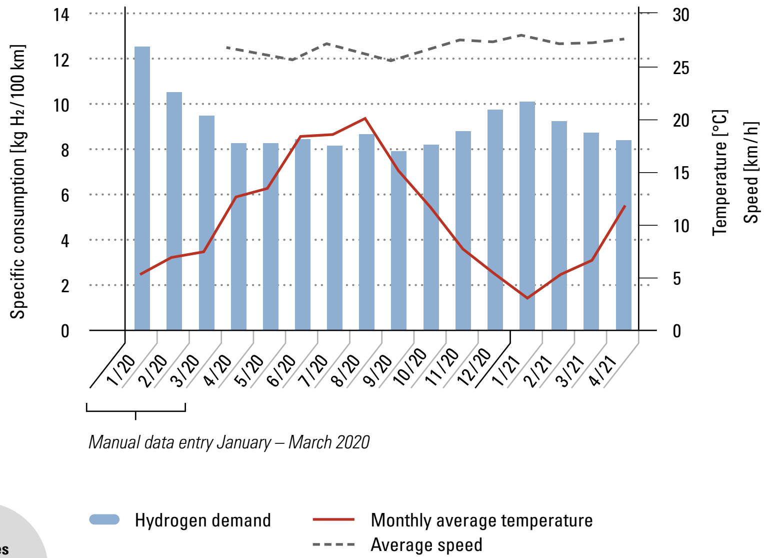
*** Number of buses**
Solo (3 – 6 | 1 TC)

Due to the currently still very limited data situation (data from 1 – 3 buses at 2 TCs over 3 and 5 months) and partly missing information for the articulated battery electric buses (energy demand in each case without heating energy demand), it is still impossible to carry out a meaningful analysis for this vehicle class.

Fuel cell buses

Figure 47 shows the average consumption of the fuel cell buses over time together with the average daily temperatures and the average speed. The consumption of the fuel cell buses is highest at the beginning of the data collection period. This may be attributable to colder temperatures during this time and the learning curve for the driving personnel during the introduction of the buses into regular operation, but also to the type of data collection at the beginning of operation. In the first three months, data from operational planning and refuelling station data were combined. After that, data from data loggers installed on the bus side were available, which are considered to provide more accurate data. The data shows that the energy consumption of FC buses also increases when temperatures drop.

FIGURE 47 **Development of H_2 consumption of fuel cell buses over time***



*** Number of buses**
45 BZ (Ø 26 |
5 – 45 / mon.)

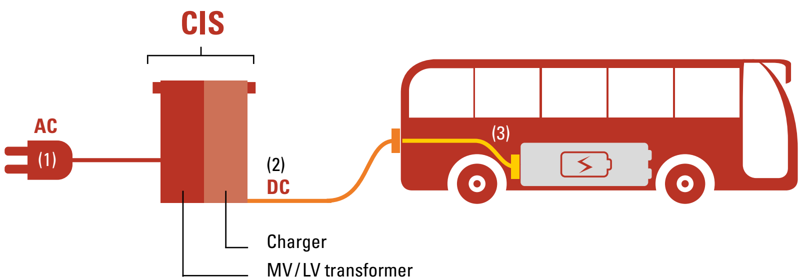
2.3.3. Energy consumption of charging infrastructure

All the results shown above refer exclusively to the energy consumption on the vehicle side. From an economic point of view, the energy costs to be paid to the power provider are more relevant for transport companies. They are measured on the infrastructure side at the electrical junction box, which means that they include losses of the charging infrastructure and additional energy consumption. Among other things, the additional energy consumption is attributable to battery balancing and vehicle preconditioning, essentially from preheating the vehicle and partly also the HV battery in the colder season.

The CIS-side energy consumption of depot charging buses is therefore discussed in more detail below. First, the charging process with all losses is explained using a simple charging scheme. Next, the individual losses are discussed in more detail. The data for this analysis comes from 3 different manufacturers of chargers in combination with 2 different vehicle OEMs.

Figure 48 shows a charging diagram with the three most important measuring points. This is used to describe the charging process with the resulting charging losses and energy consumption. First, the charging infrastructure is connected to the electricity grid, (1). Usually, the connection must be made to the medium-voltage grid due to the power requirement. Since direct current (DC) (2) is needed to charge a battery electric bus, the alternating current (AC) coming from the grid connection must be converted to the required voltage level (low voltage) and into direct current. This is done via transformers and rectifiers that are part of the charging infrastructure and are installed in the chargers. Losses occur during this conversion process. After conversion into direct current, the current is transferred to the bus or its HV battery (3). In this process, storage losses occur during the charging of the HV battery. There are also line losses, especially if there are large distances between the transformers and the charging devices.

FIGURE 48 **Charging diagram of battery electric bus**



In addition to these losses, additional consumption occurs in connection with battery charging due to battery balancing. In order to conserve the battery, the cell blocks in the battery are balanced to create a uniform state of charge. This process, called ‘balancing’, has an additional energy requirement.

The preconditioning of the bus, which is particularly important in the winter months, represents further additional consumption. To provide additional comfort for the driver and passengers, the vehicle is preheated before the start of operation. Not preconditioning the vehicles would further decrease the range, especially with the purely electrically heated battery electric buses. Preconditioning, which is supplied via the charging infrastructure, ensures that a vehicle can start operation preheated and with a fully charged HV battery.

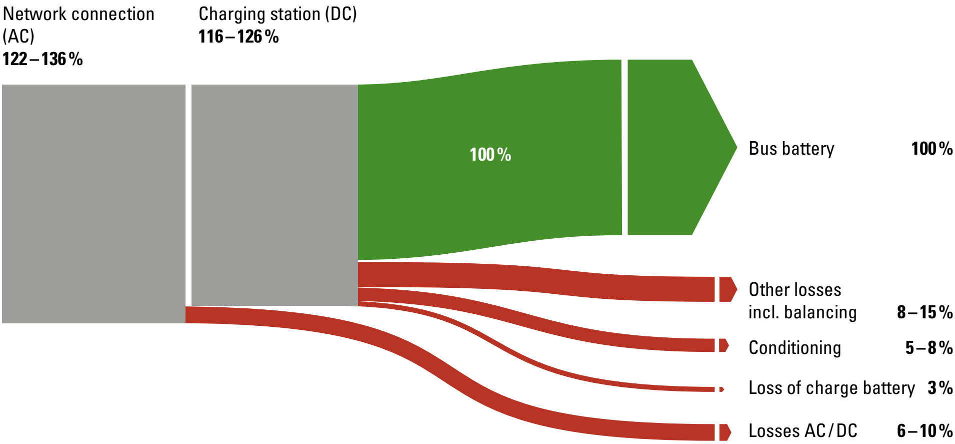
Figure 49 illustrates how the different losses and additional consumption are distributed. The energy stored in the HV battery (point 3 in Figure 48) is chosen as the reference point (= 100%). The losses during AC/DC conversion are between approx. 6% and 10%, depending on the charging station manufacturer. The evaluation of these conversion losses is based on data from two different manufacturers. For the charging points of the third manufacturer, no separately measured AC meter readings were available from the transport company.

The charging loss caused by feeding into the HV battery is not measured separately and was calculated based on the available data at approx. 3%.

The calculated additional energy requirement for preconditioning is in the range of 5–8% and is also dependent on the respective outside temperature and the specification of the vehicle’s interior temperature to be achieved. Since the amount of energy required for preconditioning is provided from the grid via the charging infrastructure, it does not need to be taken from the battery, which avoids any reduction in the range.

This results in an additional energy requirement for the charging infrastructure and vehicle charging, which includes the energy requirement for the balancing described above to charge the HV battery evenly. A more precise breakdown of this additional demand of approx. 8% to 15% additional consumption was not possible based on the available data. The different additional consumptions can be attributed to the different charging station manufacturers as well as to the different OEMs.

FIGURE 49 **Sankey diagram of charging losses and additional consumption of battery electric buses**



Taking a closer look at the vehicles shows that there are ranges between the vehicle types: While one bus OEM shows an increased charging energy demand in the range of ±1% at the charging systems of two different CIS manufacturers, the data for the second OEM in combination with three different CIS manufacturers shows significantly larger fluctuation ranges of ±8% points, and an overall higher energy demand. This illustrates that there is still potential for optimisation in the area of charging control in the interaction between the charging infrastructure and the vehicle.

In summary the overall energy demand of the system is 25 – 40% higher than that measured on the vehicle side. This increase is particularly relevant for energy costs for the transport company.

Fuel cell buses

- Currently, the average consumption of solo fuel cell buses is around 9 kg H_2/100 km.
- Hydrogen consumption increases with low outside temperatures and, according to the available data, is in the range of about 1 kg H_2/100 km above the annual average consumption at average daily temperatures of just above 0 °C.

2.3.4. Summary of the results for energy efficiency and energy consumption

Battery electric buses

- The average energy consumption is 1.1 kWh/km for midi-buses, 1.2 kWh/km for solo buses and 1.6 kWh/km for articulated buses.

- The outside temperature and the bus heating concept implemented play a crucial role with regard to the energy demand. A distinction is made between purely electric heating concepts and concepts using burner-based auxiliary heating. Buses with a purely electric heating concept do not produce any emissions locally, but the electrical energy demand increases by 20% to 66% on cold days compared to the annual average energy consumption, depending on the outside temperature and bus size. For buses with auxiliary heating, this additional energy required for heating is obtained via the respective fuel.

- The charging infrastructure plays a crucial role for the transport companies, not only in terms of energy, but also in terms of costs due to the charging losses and additional consumption. Depending on the charging station manufacturer, losses of between 6 and 10% are incurred during conversion of the alternating current (AC) from the electrical junction box into direct current (DC). Another 3% charging loss occurs directly at the HV battery during storage. Depending on the combination of bus and charging station manufacturer, additional consumption is also incurred for vehicle preconditioning and battery balancing, among other things. Preconditioning (i.e. preheating the vehicle and, in the colder months of the year, also the battery) results in additional consumption of 5–8% depending on the outside temperature. Among other things, the additional energy requirement of 8–15% during charging results from battery balancing, which serves to ensure a uniform state of charge of the individual cells or cell blocks and thus contributes to extending the service life of the HV battery. Adding up all losses and additional consumption results in an additional energy demand of 22–36%, based on the amount of energy stored in the vehicle or in the HV battery.

2.4. Environmental impact

This section was published in slightly modified form in the official local public transport publication 'Der Nahverkehr 7/8 2021'.

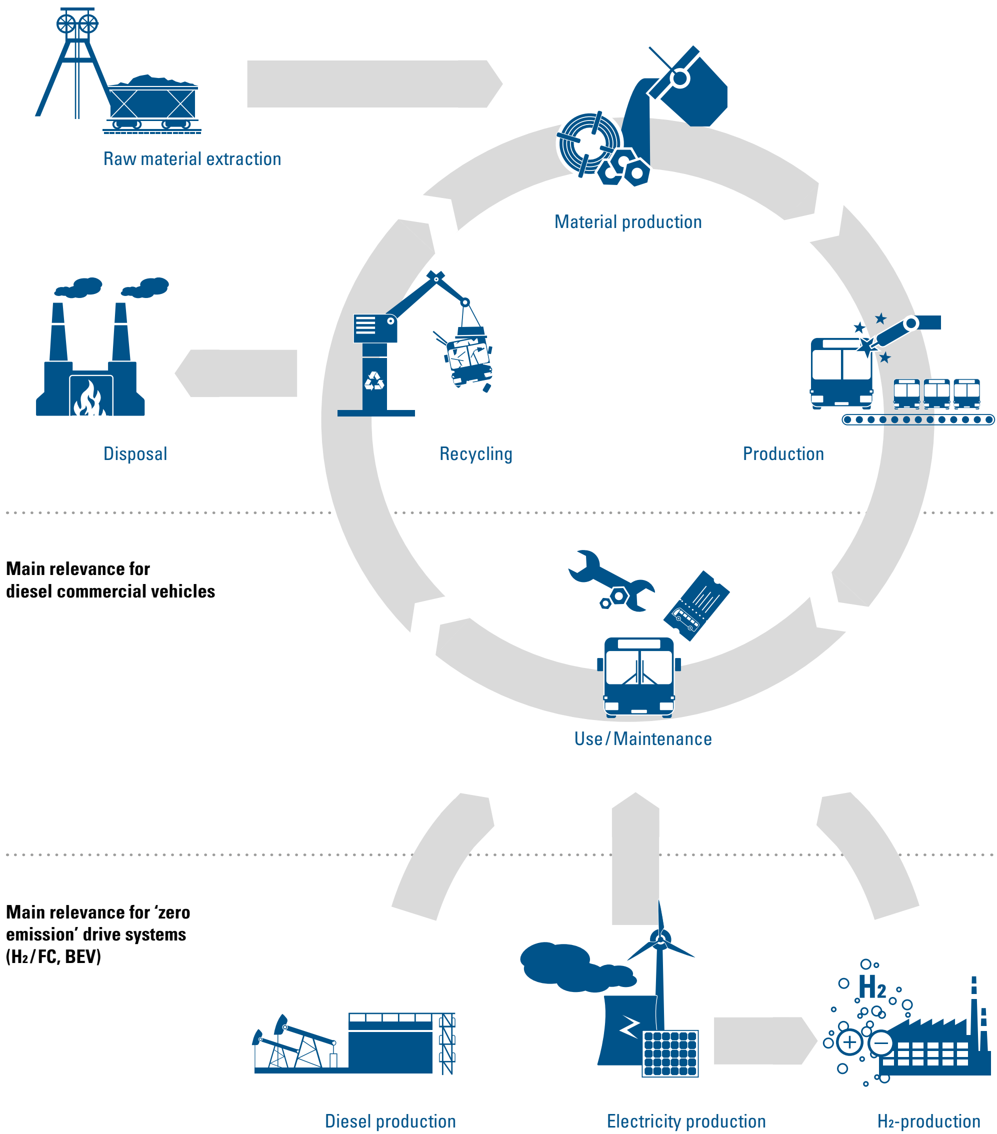
A methodology based on the life cycle assessment according to EN ISO standard 14040/44 [21] was used for the ecological assessment of battery and FC buses. The life cycle assessment considers the entire life cycle of a product or service. The required extraction of raw materials, the manufacturing of semi-finished products, the production and use phase of the buses as well as the disposal are considered (see Figure 50).

For the life cycle assessment, the resource consumption and emissions along the life cycle of the individual buses are recorded, added up and expressed in the impact assessment as environmental indicators (e.g. climate change or greenhouse gases). The objective of the assessment is to show ecological differences over the life cycle that result from the use of the zero-emission drive systems for the buses compared to conventional diesel buses. Diesel buses produce emissions that are harmful to the climate and to health, resulting from the combustion of the diesel. However, in the case of the locally emission-free e-drives, environmental impacts are shifted to the provision of the energy source (electricity or hydrogen).

21 Environmental management – Life cycle assessment – Principles and framework; German and English version EN ISO 14040:2006 edition 2009-11 & Environmental management – Life cycle assessment – Requirements and guidance; German version EN ISO 14044:2006 + A1:2018

Source: Südwestdeutsche Landesverkehrs-AG, 2021

FIGURE 50 **Overview of the life cycle of a city bus**



2.4.1. Scope of the study

Table 3 summarises the scope of the assessment.

TABLE 3 **Scope of the environmental impact analysis**

Topic	Determination
Product	12 m and 18 m city buses for public transport with different drive concepts and fully electric heating concept. Configurations are based on current products from European manufacturers. See Table 4 for the bus specifications considered.
Functional unit	12 m or 18 m city bus, 12-year service life, annual mileage 60,000 km. Due to the currently lower ranges of battery buses (see assumed battery capacity, Table 4) as well as operational aspects (e.g., in the case of the opportunity charger, overlapping turns are sometimes required to extend the charging time in the case of short schedule-related turning times), an additional requirement for buses of 35 % for depot chargers and 10 % for opportunity chargers is taken into account in order to realise the daily rotations compared to diesel or fuel cell buses. This value depends on the context of use and is derived from various studies carried out by the authors. on the full conversion of existing fleets or existing schedules. In the case of a partial conversion of the fleet or an adjustment of the rotation schedule, this value will probably be lower, as the shorter rotations can initially be served with the battery buses and the additional vehicle requirements arise for the longer and more energy-intensive rotations. Furthermore, the selected heating concept plays an important role due to the range issue in winter. For the analysis the relevance of this parameter to the environmental impacts, it is examined again in more detail as one of several parameters in the sensitivity analysis (see chapter 2.4.2).
System boundaries	The ecological assessment refers to the vehicle and covers the entire life cycle including bus production, use, maintenance and disposal. Repair and general expenses for workshop/depot or operation control as well as production & maintenance of the charging infrastructure for the battery buses are not considered.[22] For electric power and hydrogen production (including transportation and refuelling/charging), infrastructure (plants, pipelines, trailers, etc.) is included. The only exception is the natural gas steam reforming plant. 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 life cycle assessments in the automotive industry.
Temporal / geographical / technical reference	LCA datasets used from GaBi database system for energy and material provision refer to 2017, electricity and H_2 provision datasets refer to 2020. Current bus configurations from European manufacturers were used. Place of operation is Germany, therefore all energy references are also based on data from Germany. The bus consumption data used are matched with measurement data from the operational data collection of the bus monitoring research for the period Jan 2019 – Jan 2021. The consumption and emission data for the 12 m and 18 m diesel bus were taken from the Emission Factors manual. The e-buses are heated or air-conditioned purely electrically in the sense of completely emission free operation. Of buses considered in the accompanying research, 36% of the battery buses are heated purely electrically).
Environmental categories	Climate change (according to Environmental Footprint 3.0[23] expressed in CO_2-equivalents. Nitrogen oxide emissions are considered as a proxy indicator for the impact on air quality in urban areas.
Life Cycle Assessment Database	Life cycle inventory data (emissions and resource removals) for the provision of materials and energy were taken from the current database of the life cycle assessment software GaBi 10.[24]

One configuration as a depot charging bus and one as an opportunity charging bus were considered for 12 m buses and 18 m buses battery electric buses. FC buses included one configuration as a pure FC bus with a small HV battery as a buffer and one as an FC range extender (FC REX). Midi buses are not examined in detail due to their significantly fewer numbers in the monitored fleet (2%, see Figure 3), as well as in Germany's public transport bus fleets (11% share ≤ 12 t gross vehicle weight in the bus fleet[25]). However, the results obtained, especially the relative changes between the drive technologies investigated, are generally applicable to midi-buses. The specifications of the selected drive concepts presented in Table 4 are mainly based on current product catalogues of European manufacturers and suppliers, as well as assumptions of the authors. The unladen weights were calculated based on information provided by individual manufacturers as well as based on weights of specific components (lithium-ion battery, fuel cell, hydrogen pressure accumulator, etc.) for the respective BEV/FC/FC REX configurations. While these specifications are intended to describe a vehicle configuration that is as representative as possible, data for individual models will naturally deviate from this. For all monitored lithium-ion batteries analysed [NMC (cathode: lithium nickel manganese cobalt oxide) or LTO (anode: lithium titanate oxide)], a service life of six years and thus replacement during the life cycle of the bus was assumed. For the fuel cell, a replacement of the stack after six years was also specified. These assumptions regarding component service life are deliberately rather conservative.

Source: Regionalverkehr Köln GmbH, 2021

TABLE 4 **Bus specifications for ecological assessment**

	Length	Charging infrastructure	Empty weight [t]	Battery			Fuel cell		H_2 tank	Number of drive axles (with 2 wheel-mounted e-motors à 125 kW max.)
				Type	Capacity [kWh]	Replacement	Power [kW]	Replacement	[kg] / Number of bottles	
Battery	12 m	Depot charger	14,2	NMC	396	once				1
	12 m	Opportunity charger	12,7	LTO	110	once				1
	18 m	Depot charger	20,4	NMC	495	once				2
	18 m	Opportunity charger	18,7	LTO	150	once				2
FC	12 m		12,7	LTO	36	once	70	once	38 / 5	1
	18 m		18,9	LTO	54	once	100	once	46 / 6	2
FC REX	12 m	Depot charger	13,8	NMC	252	once	45	once	19 / 4	1
	18 m	Depot charger	19,8	NMC	300	once	60	once	28 / 6	2
Diesel Euro VI	12 m		11,1							
	18 m		16,1							

The consumption values for all buses and the combustion emissions of the diesel buses are documented in Table 5. According to DIN EN 16258, a diesel admixture of 5.8 vol.% biofuels results in an emission factor of 2.52 kg CO_2-eq/l diesel compared to 2.67 kg CO_2/l for pure fossil diesel. The electric energy consumption for the battery electric buses and the FC REX is specified on the vehicle side. The consumption of the electric buses includes the consumption of the electrically operated heating and air conditioning in terms of an average annual consumption, averaged over all seasons. To estimate the effective electricity consumption, an efficiency of approx. 88% is assumed for the charging infrastructure (connection of medium voltage, conversion of alternating current to direct current, charging and discharging of the battery). It is assumed that there is an additional electrical energy demand of approx. 10% for battery balancing and vehicle preconditioning. The specific electrical energy requirement of 160 kWh/100km for the 12 m opportunity charging bus thus results in an effective (and payable) energy requirement of 201 kWh/100km on the grid connection side, and 251 kWh/100km for the 18 m opportunity charging bus.

TABLE 5 **Consumption and emission values of the buses (SORT 2, medium topography)**

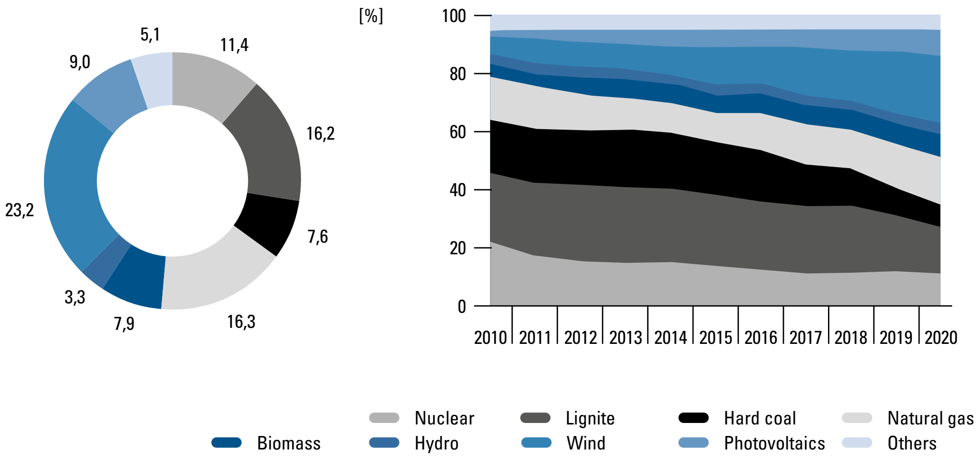
		Diesel		Battery				FC		FC REX	
				Depot charger		Opportunity charger					
		12 m	18 m	12 m	18 m	12 m	18 m	12 m	18 m	12 m	18 m
Energy demand [26]	**Diesel [l/100 km]**	43,7	57,2								
	Hydrogen [kg/100 km]							8,5	11,3	5,7	8
	Electricity [kWh/100 km] (onboard)			160	200	150	190			47	62
	Electricity [kWh/100 km] (mains side)			201	251	189	239			59	78
Emissions during operation	**NO_x [g/km]**	0,874	0,734	Locally emission-free operation							
	$PM_{2.5}$ [g/km]	0,0068	0,0077								
	CO_2 [g/km]	1.100	1.440								

Energy supply

26 Based on the Handbook of Emission Factors for Road Transport. (HBEFA) 4.1. SORT 2 cycle (ø 19 km/h), average topography for Germany

Figure 51 shows the German electricity mix by energy source for 2020 as well as the predicted development between 2010 and 2020. There is a steady increase in the share of renewable energies in the electricity mix, which is mainly characterised by growing electricity generation from wind power and photovoltaics. The shares of electricity from biomass and hydropower are largely stagnant due to the current policy framework conditions or because the expansion capacities are largely exhausted. A renewable electricity mix from wind power and photovoltaics with the current ratios (2020: 72% wind/28% PV) is defined as the baseline scenario for the direct use of electricity in battery electric buses, as well as for hydrogen production via electrolysis. As part of the sensitivity analyses conducted in section 2.4.2 additional hydrogen supply routes are analysed such as the use of the current German electricity mix or hydrogen production via steam reforming of natural gas.

FIGURE 51 **Electricity mix in Germany 2020 & 2010 – 2020**[27]

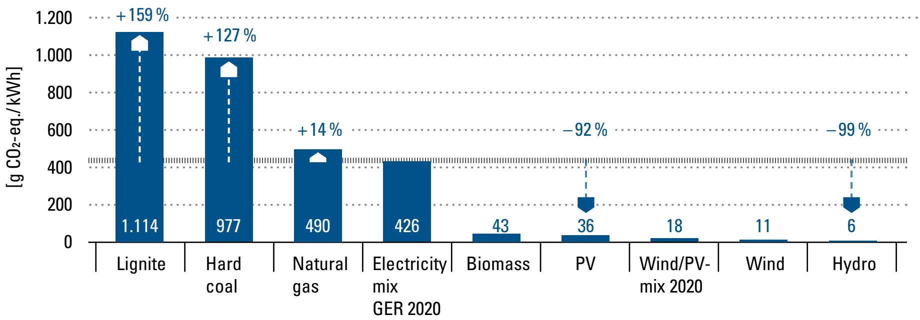


27 Working Group on Energy Balances: Electricity generation by energy source 1990–2020 (as of February 2021, preliminary data for 2020), https://www.ag-energiebilanzen.de/, last accessed on 08/06/2021

Figure 52 and Figure 53 illustrate that the energy carriers used to produce electrical energy and hydrogen have a decisive influence on the greenhouse gas emissions (GHG) of the energy supply. The GHG emissions displayed for electricity and hydrogen production include the supply of energy sources, conversion and, to a large extent, the infrastructure. Assumptions for the supply of the individual energy sources (electricity, hydrogen and diesel) are discussed below.

Figure 52 provides an overview of the greenhouse gas intensity of electricity generation from various fossil and renewable energy sources. The reference case is the German electricity mix 2020 with 426 g CO_2-eq/kWh. It accounts for the impacts from upstream energy source provision as well as the impacts from power generation plants and grid losses. Electricity generation from renewable resources in Germany leads to GHG reduction of at least 90% compared to the German electricity mix.

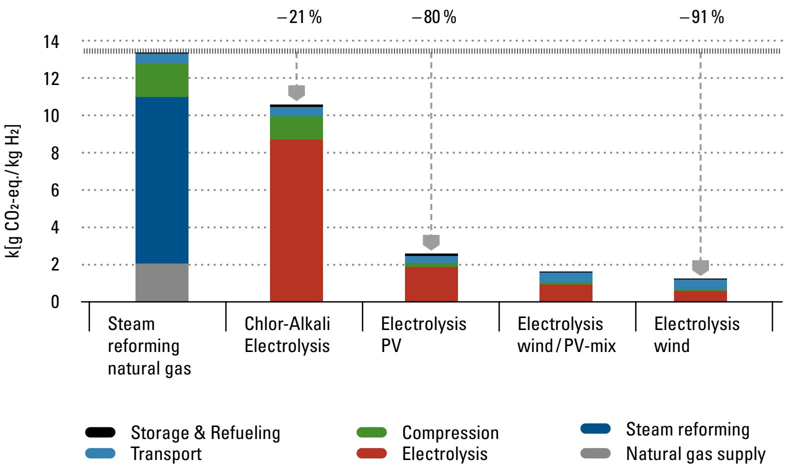
FIGURE 52 **Greenhouse gas intensities of electricity supply in Germany**



In addition to the actual production, the greenhouse gas emissions for specific hydrogen pathways presented in Figure include transport of 50 km using a 200 bar transport trailer, the compression and storage at the refuelling station as well as the refuelling itself. Steam reforming includes the greenhouse gas emissions from the reforming of natural gas to hydrogen as well as the carbon dioxide resulting from the provision of the required heat and steam. The greenhouse gases resulting from the provision of natural gas for steam reforming are displayed separately.

FIGURE 53 **Greenhouse gas intensities of hydrogen production in Germany[28]**

28 Working Group on Energy Balances: Electricity generation by energy source 1990–2020 (as of February 2021, preliminary data for 2020), https://www.ag-energiebilanzen.de/, retrieved on 08/06 at 5.10 p.m.



For the production of hydrogen as a by-product, the more conservative case from an ecological point of view was depicted using the current German electricity. Applying the CertifHy certification system[29], an allocation was conducted to align it with the market value, which means that the environmental impacts are distributed among the three products chlorine, caustic soda and hydrogen based on their market value. For steam reforming and chlor-alkali electrolysis, the current electricity mix was used for compression and fuelling. For electrolysis, the same electricity supply was assumed for compression and refuelling as for electrolysis. For example, using wind power for compression and refuelling for steam reforming or chlor-alkali electrolysis could reduce emissions by approx. 1.4 kg CO_2-eq/kg H_2.

29 CertifHy is a certification system for proof of origin and GHG intensity of hydrogen, developed on behalf of the Clean Hydrogen Partnership under the coordination of Hinicio, see www.certifhy.eu.

For the conventional diesel buses, diesel with a current admixture of 5.8 vol.% biofuels was considered for the assessment. The greenhouse gas emissions associated with the provision of diesel in Germany are 473 g CO_2-eq/l diesel.

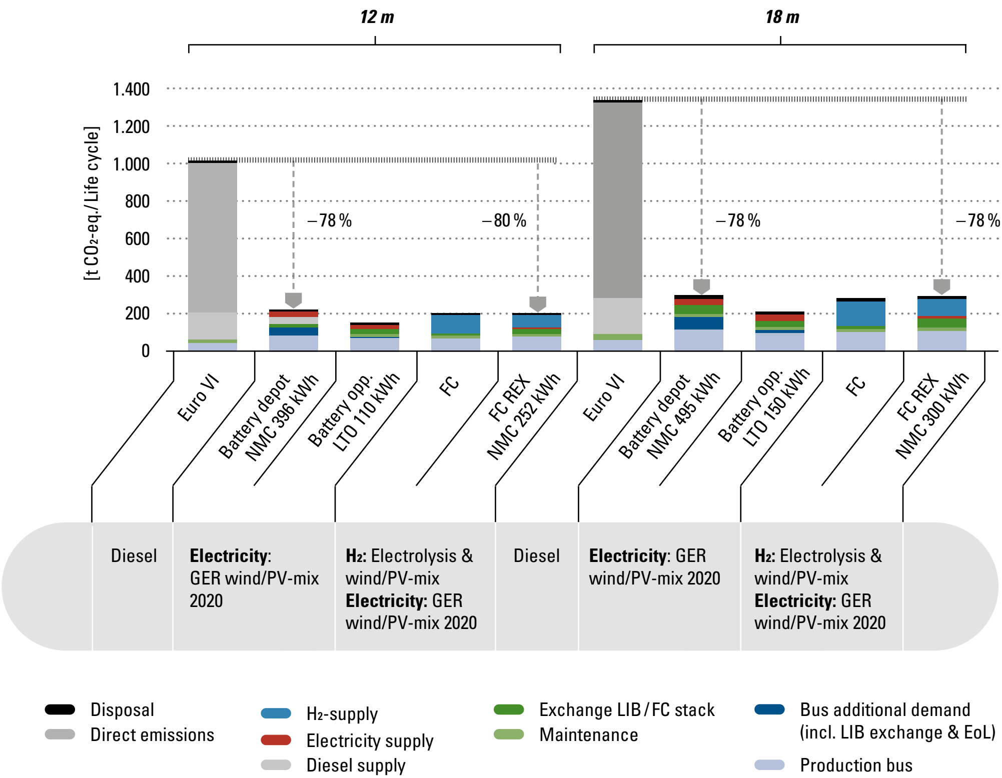
2.4.2. Results

Greenhouse gases

Figure 54 shows the results using the baseline scenario. The impact of the various energy source supply paths is presented in the sensitivity analysis in the following section.

The results of the greenhouse gas emissions (GHG) in carbon dioxide equivalents (CO_2-eq) show significantly higher values for the production of the buses with innovative drives. For the manufacturing of a 12 m diesel bus 46 t CO_2-eq (18 m: 66 t CO_2-eq) were determined, while the monitored battery and FC buses cause between 70 and 86 t CO_2-eq (18 m: 98-118 t CO_2-eq). There are also additional impacts from the replacement of the lithium-ion battery (LIB) or the fuel cell stack, which is assumed to occur every 6 years which is once in each life cycle. The manufacturing of the LIB contributes additional emissions depending on its capacity (38 t CO_2-eq for 396 kWh NMC/ 24 t CO_2-eq for 110 kWh LTO). There is also currently an additional impact for battery electric buses due to the lower range causing a demand for additional buses to maintain the daily schedules compared to the diesel or FC buses. This is assumed to be 35% for depot charging buses and 10% for opportunity charging buses. The greenhouse gas emissions resulting from this additional demand in Figure 54 include replacement of the LIBs and the expenses for disposal.

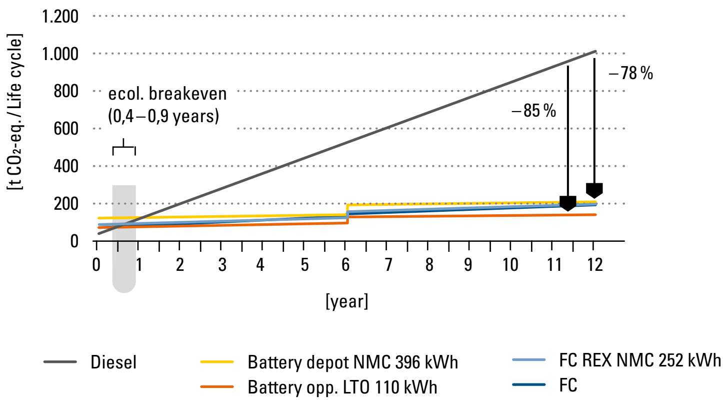
FIGURE 54 **Greenhouse gas emissions life cycle 12 m & 18 m buses**



For the FC buses, in addition to the LIBs the main contributors to the GHG emissions of production are the hydrogen pressure tanks with high carbon fibre content (approx. 13 t CO_2-eq for a 38 kg tank) and the fuel cell (3.4 t CO_2-eq for 70 kW). A platinum loading of 0.7 g/kW was assumed for the fuel cell. At the same time, the ecological life cycle assessment shows that the higher greenhouse gas emissions from the production of the e-buses are significantly offset when renewable electricity from wind and photovoltaics is used directly in the battery electric bus/FC REX or for the electrolysis of water to hydrogen with subsequent use in the FC bus compared to the diesel buses. The battery electric bus (12 m) with a large NMC battery and depot charging can reduce 78% of the greenhouse gas emissions over the life cycle compared to diesel, while the opportunity charging bus reduces 85% in the use phase due to the smaller battery and its lower energy consumption because of the lower vehicle weight. For the hydrogen buses (FC and FC REX 12 m), the higher conversion losses for electrolysis and fuel cell compared to the battery electric buses are offset due to the unneeded additional vehicle demand, resulting in an 80% reduction compared to the diesel bus. The reductions for the 18 m BEV and FC buses compared to the 18 m diesel buses are roughly the same. In terms of kilometres travelled, a 12 m diesel bus results in 1,412 g CO_2-eq/km; for depot charging buses and the FC bus the GHG emissions are 311 and 285 g CO_2-eq/km respectively when using electricity from the current wind/PV mix in the German electricity mix.

Figure 55 illustrates the environmental payback period or the break-even point or distance driven at which the higher GHG emissions for the production of the buses (12 m) with emission-free drive concept are offset. As in Figure 54, an additional bus capacity requirement of 10% was considered for the opportunity charging bus and 35% for the depot charging bus. Using the wind/PV mix for direct use or for electrolysis, the higher expenses for BEV and FC buses are already offset after 0.4 – 0.9 years or approx. 25,000 – 55,000 km of driving. From this point on, there is a 'net' greenhouse gas reduction of 78 – 85% or approx. 800 – 850 t CO_2-eq over the entire life cycle.

FIGURE 55 **Greenhouse gas emissions break-even point – life cycle of 12 m buses**



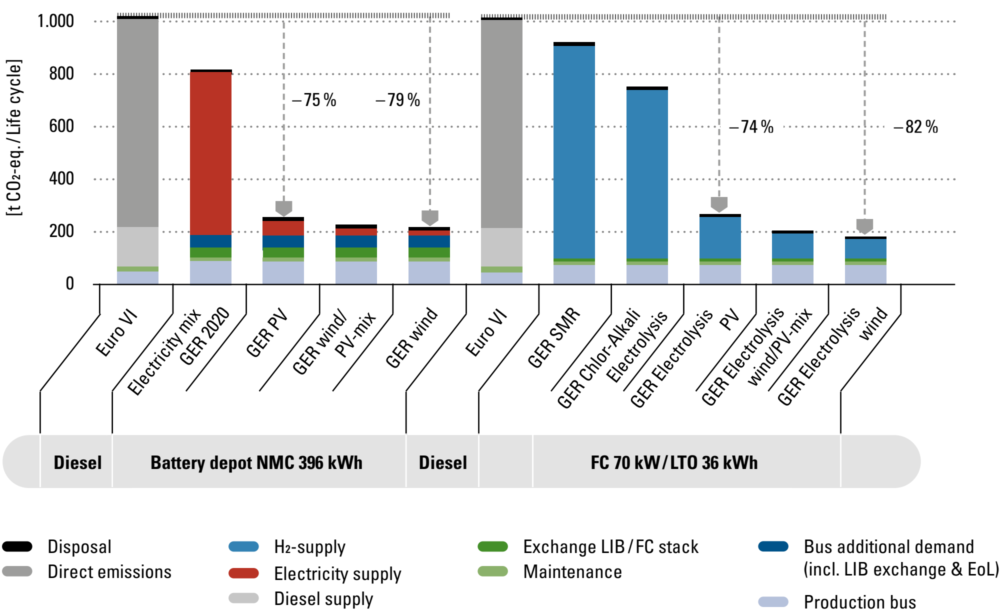
Sensitivity analysis

Figure 56 below shows the effect of the electricity supply for the utilisation phase using the example of the depot charging bus (12 m bus, 396 kWh NMC battery). For the battery electric bus, the use of the 2020 electricity mix already leads to a greenhouse gas reduction of ~20% (break-even point after approx. 2.6 years, at 60,000 km annual distance driven). With PV electricity, 75% of the greenhouse gases can be reduced compared to the diesel bus, and 79% with pure wind electricity. Similarly, Figure 56 in the diagram on the right shows the effect of the hydrogen supply path on the life cycle of the FC bus (12 m bus, 36 kWh LTO). For the FC bus, a supply of hydrogen through natural gas reforming (SMR) would lead to approx. 9% lower greenhouse gases compared to the operation of a diesel bus. Using hydrogen from chlor-alkali electrolysis powered by electricity from the German grid, applying the (preliminary) allocation approach according to CertifHy for the distribution of greenhouse gases among the three co-products results in a reduction of 26% compared to diesel buses. Hydrogen supply through electrolysis with an efficiency of 65% (based on calorific value) results in a reduction of 74% for PV electricity and 82% for wind electricity compared to diesel. The use of the electricity mix for the production of hydrogen currently leads to significantly higher greenhouse gas emissions than with the diesel bus due to the conversion losses (not shown in the diagram). Only at a greenhouse gas intensity of approx. 260 g CO_2-eq/kWh (approx. 40% GHG reduction compared to the current German electricity mix) would the use of hydrogen from electrolysis with average grid electricity produce the same greenhouse gases as the use of diesel.

For the GHG emissions of the battery electric bus (depot charging bus) shown in Figure 56, using the 2020 German electricity mix, a simplified assumption is made that the 2020 electricity mix is used for the entire 12-year lifetime (2020 – 2031).

Derived from Germany's reduction targets, which are formulated in the Climate Protection Plan 2050 and Climate Protection Programme 2030, various institutions have developed possible scenarios for the development of electricity production up to 2050 under the premise that the reduction targets can be met.

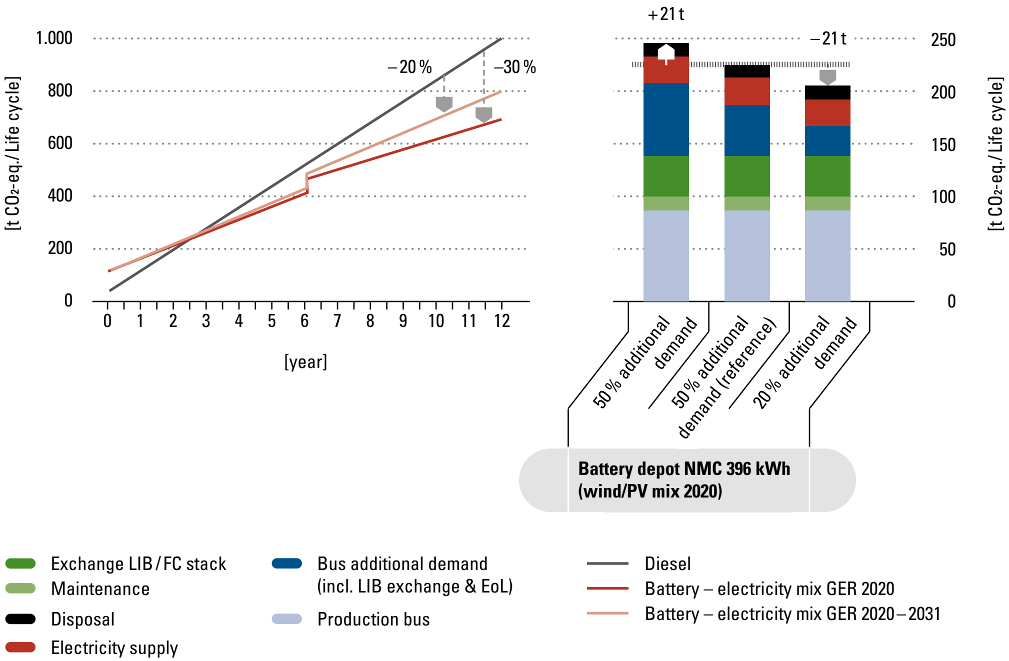
FIGURE 56 **Effect of electricity & hydrogen supply on GHG emissions over the entire life cycle of 12 m buses**



The diagram on the left in Figure 57 represents the additional reduction potential if the development of electricity generation is considered in the period from 2020–2031 according to calculations by the grid operators[30] in Germany. If the emissions of the 12 m depot charging battery electric bus are reduced by approx. 20% GHG compared to diesel based on the assumption that the 2020 electricity mix is applicable for the entire lifetime, that figure would rise to a 30% reduction if a potential development of the electricity mix, derived from the reduction targets of the German government, is assumed. This result must be understood as a projection, but it shows the potential that can result from the future development of the energy mix for electricity generation during the bus's use phase.

30 50 Hertz, Amprion, TenneT TSO, TransnetBW: Grid Development Plan for Electricity 2035, Version 2021 First Draft of the Transmission System Operators, 2021, NEP_2035_V2021_1_Entwurf_Teil1.pdf (netzentwicklungsplan.de), 14 June at 4.30 p.m.

FIGURE 57 **Effect of development of the electricity mix and additional demand for depot charging 12 m buses on GHG emissions**

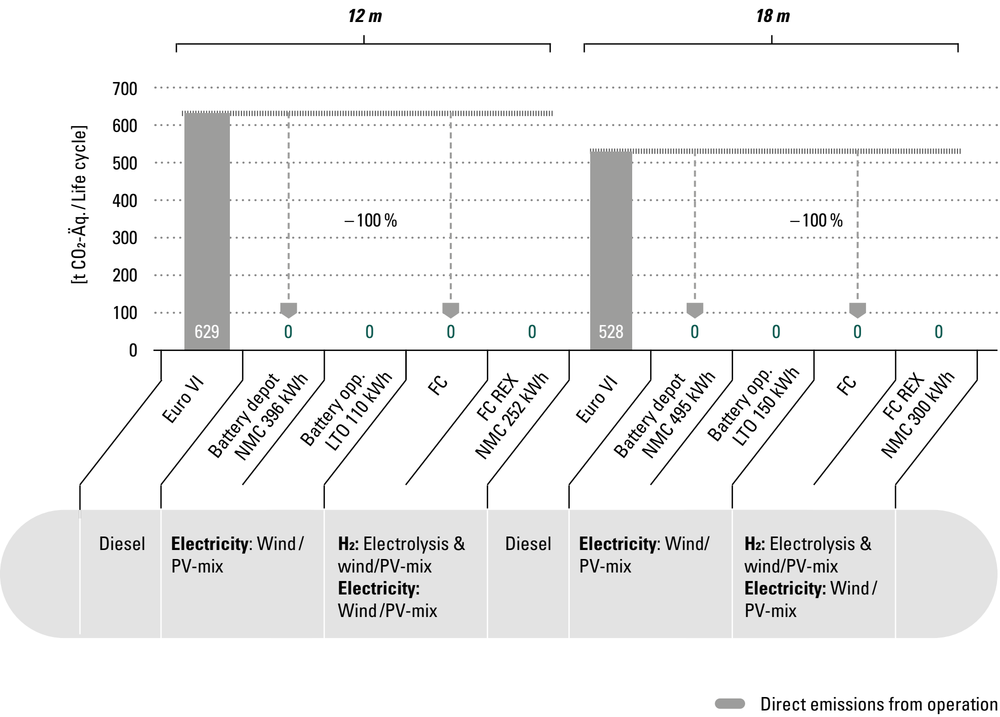


The right-hand diagram in Figure 57 shows the effect of the assumed additional demand for battery electric buses for the depot charging bus, which results from the shorter range. As a reference case, an additional demand of 35% was assumed for the depot charging bus. A reduction or increase of 15 percentage points each leads to approx. 21 tonnes higher or lower greenhouse gas emissions over the life cycle. For a depot charging bus that is operated with an electricity mix from wind/PV, this results in approx. 9% higher or lower greenhouse gas emissions. A reduction in the additional demand is the more relevant case to consider. Depending on the operational context and the selected heating concept, the additional demand for vehicles can be further reduced by adjusting the vehicle scheduling.

Nitrogen oxides

Using nitrogen oxide emissions as an example of harmful emissions from motorised traffic, local effects are the most relevant to be considered. This means that, in contrast to CO_2 and other greenhouse gases, which have a global impact, the location of the emission is relevant for the environmental impact.

FIGURE 58 **NO_X emissions from bus operation of 12 m & 18 m buses**

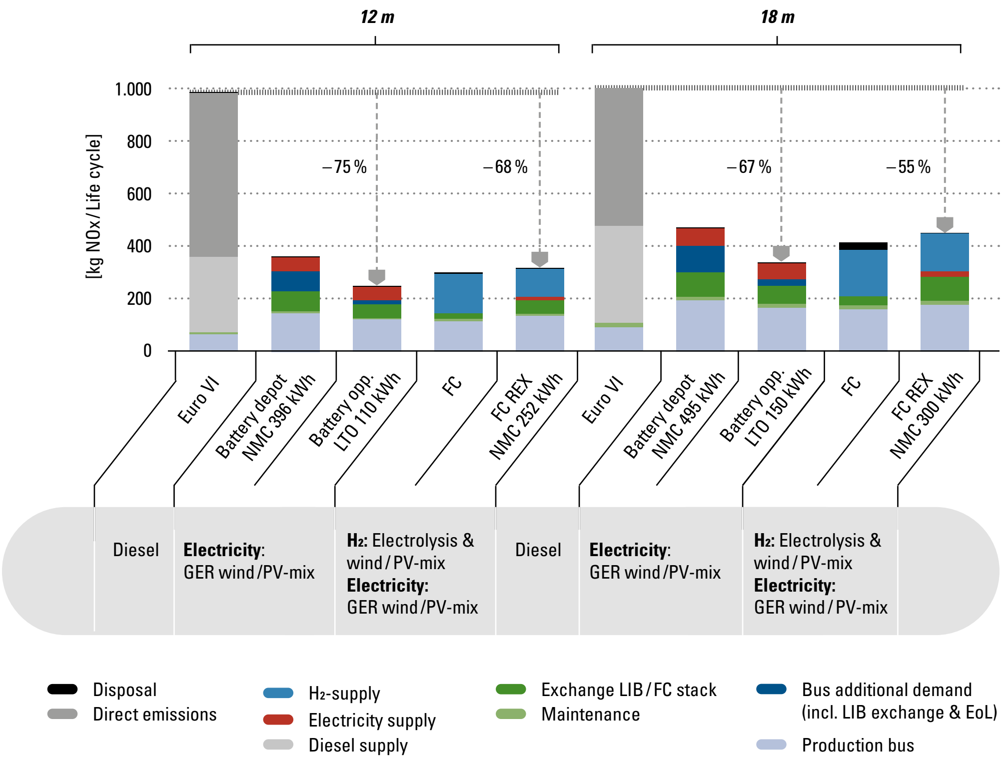


Accordingly, for the diesel bus as a representative of the internal combustion engine operated buses, the NOx emissions of the use phase (i.e., its operation) are of particular relevance, as they are usually emitted in urban areas with a high population density and close to where people are in the road space. Conversely, NOx emissions from raw material extraction, material production (bus manufacturing as well as infrastructure for electricity generation such as wind turbines and photovoltaic modules) or the combustion of coal and gas in power plants are usually released outside of cities, i.e., in areas with significantly lower population density and via chimneys in higher air layers. The e-buses therefore have advantages in daily scheduled operation in cities and municipalities (i.e., settlement areas with high population densities), due to the locally emission-free e-drive. Direct exhaust emissions of NOx, as well as fine dust, carbon monoxide, etc. are completely avoided.

While 100% reduction in NOx emissions is achieved during operation along a bus route, the NOx emissions occurring over the life cycle are shown in Figure 59. As was the case with greenhouse gases, the production of battery electric and FC buses (111 – 143 kg NOx for 12 m) leads to significantly higher emissions of NOx compared to the manufacturing of diesel buses (63 kg NOx for 12 m). Moreover, the additional bus capacity required for the battery electric buses results in 50 kg NOx for the depot charging bus and 12 kg NOx for the opportunity charging bus (each for the 12 m bus).

In total, the battery electric buses have reduced nitrogen oxide emissions over the entire life cycle compared to diesel by approx. 50 – 75% (depot or opportunity charging bus). For FC buses the reduction is approx. 55 – 70%. It should also be noted that nitrogen oxide emissions from operation are lower for the 18 m diesel bus than for the 12 m diesel bus (see Table 5), which is why the relative reduction for the 18 m e-buses compared to the 18 m diesel bus is lower than in the case of the 12 m buses.

FIGURE 59 **NO_X emissions life cycle 12 m & 18 m buses**



If a renewable electricity mix from wind and PV is used, the additional emissions from the production of the battery electric buses are offset after approx. 1.0–2.4 years of use due to avoidance of the combustion emissions of the diesel bus as well as the emissions during diesel provision.

If the German electricity mix is used to provide electricity for battery electric buses, there is a slight reduction of 3%. If the hydrogen used in FC buses is obtained from steam reforming of natural gas, the reduction over the lifetime of the bus is 35% compared to diesel buses. If the German electricity mix is used for the electrolytic production of hydrogen, higher NOx emissions result. This confirms once again that the basic prerequisite for the desired ecological improvements using e-buses is the use of renewable energy sources.

2.4.3. Summary of the results on ecology

Conclusion

- By using wind and PV electricity, the higher GHG and NOx emissions in the manufacturing of the e-buses can be in most cases offset within the first year of operation.
- For GHG emissions, a reduction of 75–85% is possible over the entire life cycle; for NOx emissions it is 50–75%.
- For battery electric buses, the use of the current electricity mix or, for FC buses, the use of hydrogen from the steam reforming of natural gas already leads to GHG reductions compared to diesel; at the same time, combustion emissions along the bus routes are completely eliminated in urban areas.
- While the use of hydrogen as a by-product of chlor-alkali electrolysis in fuel cell buses operated with current German grid electricity leads to an approx. 26% reduction in GHG emissions compared to the operation of conventional diesel buses, the use of hydrogen produced via electrolysis of water using German grid electricity would lead to significantly higher GHG emissions compared to diesel buses due to the conversion losses
- Increasing shares of renewable energies (in Germany and internationally probably mainly wind and PV) in the electricity mix not only reduce the specific emissions per kWh of electricity, but also the emissions from the manufacturing of the vehicles or, for example, the photovoltaic modules. Furthermore, the emissions from battery production can also continue to drop through further development of the technologies (increase in energy density, substitution of critical metals, etc.).

2.5. Economic viability

The (additional) costs associated with the drive technologies under consideration and their future development are an essential factor for the successful market ramp-up of these technologies.

To assess the economic viability, the investment and operating costs of the entire bus system must be determined as completely as possible to calculate the total cost of ownership (TCO). The TCO include the costs of the vehicle, energy supply infrastructure in the depot and/or on public roads, training costs, the necessary adaptations in the depot and the operating costs. At the present time, this can realistically only be approximated, as the basic knowledge and experience is still being developed due to the novelty of the technologies. This is precisely where funded projects, including the accompanying research on buses, make a valuable contribution.

The total cost of ownership for the drive technologies under consideration is determined based on an application scenario, in each case in comparison to the reference technology (diesel buses, Euro VI standard).

The application scenario defined included:

- Fleet size and composition
- Assumptions on operational parameters (e.g. consumption, distance driven),
- Technical specifications of the vehicles and the energy supply infrastructure (energy storage size, heating concept, lifetime of critical components such as HV battery and fuel cell, charging capacity, etc.).

A significant component in the operating costs are the energy costs and the levies included currently or prospectively, such as the EEG levy, grid fees for electricity and hydrogen, or the CO_2 pricing for diesel, see chapter 2.5.2.

The results of the economic evaluation can be found in chapter 2.5.3. The calculation of the costs per drive technology depends on a number of parameters and assumptions. They can vary from transport company to transport company due to their specific boundary conditions, e.g., energy consumption of the vehicles due to the nature of the network served (average travel speed, topography, distances between stops, passenger volume) or possibly necessary additional vehicle requirements due to the vehicle schedules to be served. Regarding various input variables of the cost calculation, assumptions still must 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 total cost analysis carried out as part of the accompanying research is less concerned with determining the specific absolute costs of operating the individual technologies (expressed in €/km) or comparing them with each other. Instead, the analysis focuses on determining the main parameters influencing the costs and the effect on the total costs caused by a change in the respective parameter. This analysis was carried out in the form of a sensitivity analysis for various parameters identified as relevant, the results of which are summarised in 2.5.3.

2.5.1. Reference scenarios

The assumed fleet size comprises 50 vehicles. Based on the current fleet composition in the city bus sector according to VDV, the proportion of 12 m and 18 m buses was designed as shown in the following table.

TABLE 6 **Composition of the assumed sample fleet**

Vessel size	Share	Quantity
12 m standard buses	53 %	27
18 m articulated buses	47 %	23
Total fleet	100 %	50

The following drive technologies were monitored:

- Diesel bus (reference technology)
- Batteriebus
  - Depot charging bus
  - Opportunity charging bus
- Fuel cell bus
  - FC REX bus (FC as range extender)
  - FC bus (FC as main energy source)

The associated supply infrastructures for electrically powered buses considered are shown in the table 7.

The technical specifications of the vehicles and supply infrastructures for each technology path are shown in Table 8. Inductive charging systems for battery electric buses or overhead line infrastructures for hybrid buses were not examined in detail. This is due to their absence in the bus fleet monitored in the accompanying research or due to their market share, which is still considered to be small in the short to medium term. Should these technologies become more relevant in the future, a more detailed investigation would be appropriate in the context of future accompanying research activities.

TABLE 8 **Vehicle design**

Vehicle category	**Vehicle concept**	**Vehicle size**	**Energy storage (HV battery)**		
			Battery type	*Energy content*	*Battery exchange*
		[m]	*[Text]*	*[kWh]*	*[Quantity]*
Diesel bus		12	–	–	–
		18	–	–	–
Battery bus	*Depot charger*	12	NMC	396	1x
		18	NMC	495	1x
	Opportunity charger	12	LTO	110	1x
		18	LTO	150	1x
FC REX bus	*Delivery + CIS*	12	NMC	252	1x
		18	NMC	300	1x
	On-site production + CIS	12	NMC	525	1x
		18	NMC	300	1x
FC bus	*Delivery*	12	LTO	36	1x
		18	LTO	36	1x
	On-site production	12	LTO	36	1x
		18	LTO	36	1x

TABLE 7 **Considered energy supply infrastructure**

Supply infrastructure	related drive technology	
Charging infrastructure		
Automated contact systems (e. g. pantographs)	**Battery bus**	
	Depot charger	Opportunity charger
Plug-in system	**Battery bus**	
	Depot charger	Opportunity charger
	Fuel cell bus	
	FC REX bus	
Hydrogen supply		
Delivery/on-site production	**Fuel cell bus**	
	FC REX bus	FC bus

Fuel cell		Hydrogen storage		Consumption *		
Power	*Exchange*	*Type IV Bottles*	*Hydrogen tank*	*Diesel*	*Electricity*	*Hydrogen*
[kW]	*[Quantity]*	*[Quantity]*	*[kg]*	*[l/100km]*	*[kWh/km]*	*[kg/100 km]*
–	–	–	–	43,7	–	–
–	–	–	–	57,2	–	–
1x	–	–	–	–	1,60	–
1x	–	–	–	–	2,00	–
1x	–	–	–	–	1,50	–
1x	–	–	–	–	1,90	–
45	1x	4	18,8	–	0,47	5,7
60	1x	6	28,2	–	0,62	8
45	1x	4	18,8	–	0,47	5,7
60	1x	6	28,2	–	0,62	8
70	1x	5	38	–	–	8,5
100	1x	6	45	–	–	11,3
70	1x	5	38	–	–	8,5
100	1x	6	45	–	–	11,3

*Assumption: SORT 2 (19 km/h), Average topography HBEFA

TABLE 9 **Configuration of supply infrastructures**

Vehicle category	Vehicle concept	Charging infrastructure depot					
		Number of transformers	*Power class transformers*	*Required connected load*	*Number of charging points*	*Type of charging point*	*Charging power per charging point*
		[Piece]	*[kVA]*	*[kVA]*	*[Piece]*	*[Text]*	*[kW]*
Battery bus	Depot charger	2	1.600	2.100	50	CCS	75
	Opportunity charger	2	630	800	50	Panto-graph	35
FC REX bus	Delivery + CIS	2	800	1.100	50	CCS	40
	On-site production + CIS	2	800	1.100	50	CCS	40
FC bus	Delivery	–	–	–	–	–	–
	On-site production	–	–	–	–	–	–

2.5.2. Energy sources

The energy costs, together with the costs for driving personnel, maintenance and repair costs for the vehicles, are the input variables for the operating costs.

In addition to the actual generation costs, the statutory levies have a decisive impact on the costs for electricity and hydrogen. The costs for electricity, hydrogen, and diesel as well as their composition are presented below.

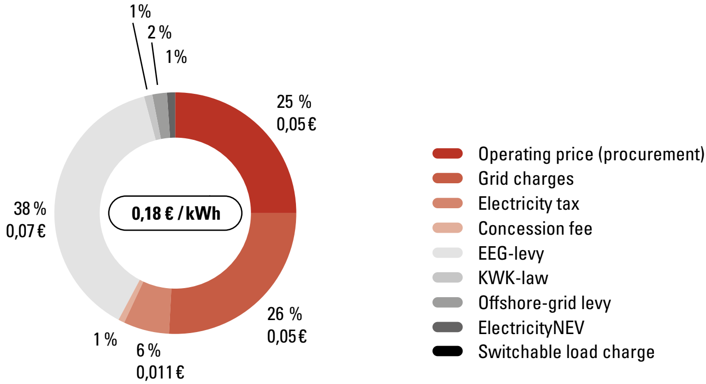
	Charging infrastructure				**Electrolysis**				**Hydrogen filling station**		**Delivery H_2**
	Number of transformers	*Power transformers*	*Number of charging points*	*Charging power per charging point*	*Power consumption of the electrolyser*	*Mains connection*	*Number of compressors*	*Capacity pressure accumulator*	*Number of modules*	*Number of taps*	*Number of trailer docks*
	[Piece]	*[kVA]*	*[Piece]*	*[kW]*	*[kW]*	*[kW]*	*[Piece]*	*[kg]*	*[Piece]*	*[Piece]*	*[Piece]*
	–	–	–	–	–	–	–	–	–	–	–
	8	630	8	300	–	–	–	–	–	–	–
	–	–	–	–	–	–	–	–	3	3	4
	–	–	–	–	3.000	3.600	2	1.250	3	3	–
	–	–	–	–	–	–	–	–	3	3	4
	–	–	–	–	4.000	4.800	2	1.820	3	3	–

Electricity

The actual electricity procurement costs, which include electricity generation incl. CO_2 costs, distribution costs and margin, account for only a quarter of the electricity price for the reference year 2020. For the following profitability analysis (see 2.5.3), electricity procurement costs of 18 ct/kWh were determined for battery electric buses. This value also matches the information provided by the transport companies on their electricity procurement costs. On average, they were 19 ct/kWh with a range of 11 – 30 ct/kWh. The additional costs for the purchase of green electricity, e.g., via a bilateral power purchase agreement (PPA), can be assumed to be negligible. As an example, the value of 0.15 ct/kWh published by the EID[31] for certificates of origin when concluding 5-year supply contracts for electricity from renewable energies (on- or offshore wind or PV plants) can be mentioned here. 76% of the TCs are already supplied with green electricity or plan to use green electricity for the operation of the e-buses.

31 Energy Information Service, EID: PPA monitor, under www.eid-aktuell.de. Last accessed in July 2021.

FIGURE 60 **Cost components for electricity** (reference year 2020)



Reduction in EEG levy from 2021

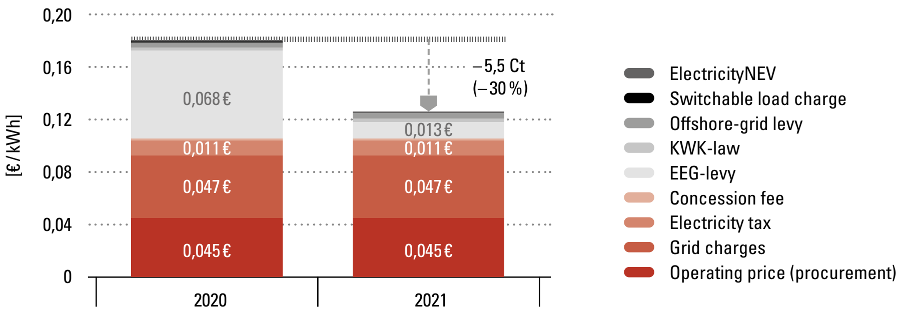
While in 2020 the reduction of the electricity tax for operation of e-buses from 2.05 to 1.142 ct/kWh was the only tax reduction, the adoption of the Renewable Energy Sources Act 2021 established a reduction of the EEG levy by 80% in accordance with § 65a. The reduction must be requested from the Federal Office of Economics and Export Control (BAFA) for the following year[32]. The prerequisite for this is that a minimum annual consumption of 100 MWh is incurred purely for driving operations. This is already exceeded, for example, by the use of two 12 m buses with an average annual consumption of 1.2 kWh/km (without electric heating) and less than 50,000 km annual distance driven per bus. Figure 61 illustrates the effects of the reduction of the EEG levy from 2021, which corresponds to a reduction of the levy by 5.5 ct/kWh of electricity. With an examplary average energy consumption of 1.2 kWh/km for a 12 m bus, and an assumed annual distance driven of 60,000 km, this reduction corresponds to an operating cost reduction of approx. €4,000 per bus and year.[33]

The cost components for the energy procurement price and grid fees were assumed to be constant in Figure 61 for the purpose of direct comparability between 2021 and 2020. The other levies correspond to the status in 2021, whereby the changes in the other levies only have a minimal effect on the result. For electricity procurement costs and grid fees, however, an increase in the order of 1 – 2 Ct/kWh in total can be observed in the course of 2021 (as of summer 2021) .

32 Application for EEG reduction for electrically powered buses under https://www.bafa.de/DE/Energie/Besondere_Ausgleichsregelung/Antragsverfahren/antragsverfahren_node.html, last accessed on 30/07/2021.

33 BDEW electricity price analysis 2021 | BDEW, last accessed on 30/7/2021.

FIGURE 61 **Reduction of the EEG levy to 20% according to EEG 2021 § 65 (annual consumption >100 MWh, reference year for energy price and grid fees: 2020)**



Grid fees

One factor that influences electricity costs is the hours of use of the grid connection capacity registered with the grid operator and the resulting grid fees. The so-called annual hours of use are calculated using the ratio of the amount of electricity consumed annually to the connected load. As can be seen from Table 10, for an annual utilisation period of more than 2,500 hours, a higher demand charge is incurred, which is levied on an annual basis per kW of registered connected load, while the energy charge, which is payable per kWh of electricity consumed, is lower. If the annual hours of use are less than 2,500 h, a higher connected load is used in relation to the amount of consumed electricity. This results in lower demand charge, but noticeably higher energy prices. As a result, an annual utilisation period of < 2,500 h usually leads to higher grid fees, which, when apportioned to the kWh of consumed electricity, are in the order of approx. 1 ct/kWh. The use of a charging management system, which ensures that the charging power remains constant and thus avoids peak loads during recharging of battery electric buses leads to a reduction in energy costs. This so-called 'peak shaving' can be achieved, for example, by reducing the charging power per bus with a corresponding extension of the charging time or by staggering the charging of the buses during the night. The grid fees shown in Figure 60 and Figure 61 correspond to an annual usage period of > 2,500 hours.

TABLE 10 **Average grid fees in 20 German cities in 2020**

Reference year 2020	Metering point operation	Power price		Working price	
		< 2500 h	> 2500 h	< 2500 h	> 2500 h
	[EUR/a]	[EUR/kW*a]	[EUR/kW*a]	< 2500 h	[ct/kWh]
Mean value from Germ. 20 cities	626,66	13,06	92,61	4,06	0,88

Grid connection costs and duration

Another cost block that arises in the course of setting up the charging infrastructure required for battery electric buses is the establishment of the grid connection. As part of the planning for the introduction of e-buses, it is generally important to contact the power grid operator as early as possible to clarify the current power supply situation of the depot. It is even more important to find out about the possibilities of extending the grid connection to the charging capacity that is likely to be required. For this, the grid operator needs an initial assessment of the desired connection capacity. Generally, the grid operator must carry out a case-by-case assessment, as the grid situation regarding available capacities within a city or municipality can vary from one street to the next. Depending on the result of the grid check, the grid operator can use it as a basis for an initial estimate of the costs and the time required to establish the grid connection with the required capacity.

The time required (see also chapter 2.1.2) depends on the grid situation, the grid upgrading measures that may be necessary, possibly also in upstream, higher voltage levels, and the planning capacities of the grid operator. It is necessary to find out how many grid connections the grid operator currently needs to build in the supply area. A grid connection can be established within a few months in the best-case scenario, but in less favourable cases the establishment duration can also be 1 – 2 years. In general, the grid operator is obligated to establish the grid connection, apart from exceptional cases where it must be justified by the grid operator.

From a technical point of view, it must be considered that the maximum power that can usually be drawn from the existing low-voltage grid is 250 kW. If more power is required, a separate transformer station to be erected by the transport company is necessary for the supply, which must be connected to the medium-voltage grid by the grid operator.

For the construction of a transformer station with an illustrative output power of 500 kW, purchase costs of approximately €40,000 should be expected. Moreover, the connection to the 10/20 kV medium-voltage grid costs several thousand euros. Especially the costs for the connection to the distribution transformer station are strongly dependent on the local boundary conditions. Influencing factors include the distance and the proportion of sealed areas that need to be restored if cables must be laid, etc. Ultimately, a building cost subsidy must be paid to the grid operator, which is calculated per kW of requested connected load. In accordance with the specifications of the Federal Grid Agency, this building cost subsidy can correspond to a maximum of the capacity price for an annual utilisation period of > 2,500 h in the respective voltage level of the responsible grid operator. For the illustrative evaluation of over 20 German cities shown in Table 10, this value is rounded to 93 €/kW. The grid operator can grant discounts for the determination of the building cost subsidy.

Hydrogen *(H_2)*

The basic prerequisite for smooth operation with H_2-powered buses is the availability of the hydrogen refuelling station and the reliable supply of hydrogen. The costs for the refuelling station to supply the sample fleet of 50 FC buses amount to about €1.8 million. These costs refer purely to the H_2 refuelling station, and do not account for any equipment for H_2 production, e.g., electrolysers. Generally, the following options exist for supplying the hydrogen refuelling station with hydrogen:

- Delivery of hydrogen
- On-site production, usually through electrolysis of water.

Delivery of hydrogen

Hydrogen is usually delivered by lorry trailer in gaseous form, compressed to 200 – 300 bar. As a rule, the trailer supply is alternated (see chapter 1.3). This means the refuelling station has 2 trailer parking spaces, one of which is occupied by an H_2 trailer during normal operation, which supplies the refuelling station with hydrogen.

FIGURE 62 **Example of a hydrogen refuelling station with H_2 delivery via trailer [34]**

34 Stuttgart Tram, 2020

If larger quantities of hydrogen are required, trailer delivery with liquid hydrogen is an option. While up to 1 t of H_2 is delivered per trailer in gaseous form, the supply of liquid hydrogen enables approx. 3.5 to 4 times the amount of hydrogen to be delivered by lorry. H_2 delivery via pipeline is also possible. However, for economic reasons this usually only makes sense if the H_2 pipeline can be connected to an existing H_2 pipeline system with the required H_2 purity or if the hydrogen production (for example chemical industry or electrolyser) is located in the immediate vicinity of the depot or H_2 refuelling station.

The delivery costs for hydrogen are generally dependent on a number of factors. These include the origin of the hydrogen (from renewable/non-renewable resources), the purchase quantity, the transport distance, agreements on delivery reliability, etc. Accordingly, there is a relatively wide range for the costs of delivery hydrogen, which is currently estimated in the range of 4.50 – 9 euros net per kg of hydrogen.

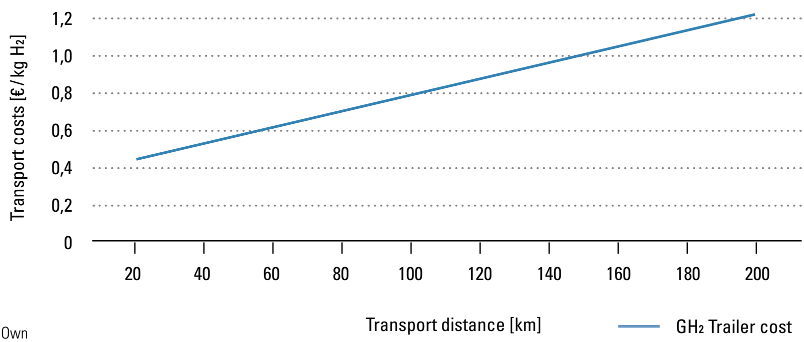
The main cost factor for H_2 delivery is the logistics element, particularly the transport distance to the H_2 refuelling station. Due to the higher purity requirements for fuel cell buses, transport distances of 200 km and more are currently still common for hydrogen, depending on the location of the trailer refuelling station where the required H_2 purity can be provided (see Figure 63).

FIGURE 63 **Hydrogen supply options in Germany**[35]

35 VDV – Verband deutscher Verkehrsunternehmen e.V.: Emission-free energy and drive concepts for city buses to implement the European Clean Vehicles Directive, 2020

Figure 64 illustrates the effect of transport distance on H_2 logistics costs. Currently, extensive efforts are underway in Germany (e.g., within the framework of the German Hydrogen Strategy) as well as in Europe more broadly to significantly expand the production capacities for hydrogen from electrolysis plants. Among other things, several large-scale plants with 100 MW electrolysis capacity and greater (> 40 t H_2/d) are proposed to be built in Germany in the coming years. To make the desired contribution to climate and environmental protection renewable electricity supply needs to be used for these H_2 production plants (see also chapter 2.4).

FIGURE 64 **Effect of transport distance on H_2 transport costs using the example of a 300 bar trailer with ~ 1,000 kg H_2 capacity**[36]



36 Sphera: Own calculations on H_2 transport costs, 2020

Fuel cell electric buses require high levels of H_2 purity. This reduces the number of possible sources, as the necessary facilities for purification to the required H_2 quality are currently not available at all H_2 production sites. This represents a fundamental advantage of the hydrogen-powered internal combustion engine, which do not have such high demands for H_2 purity[37] . However, if both H_2 ICE and fuel cell-powered vehicles are intended to be supplied at the same H_2 refuelling station, hydrogen of two different purities must be kept available, including separate storage, compression, and delivery points. The associated investment costs are offset by the cost advantages for the reduced cost of hydrogen for the ICE engines.

37 Put simply, an H_2 combustion engine requires an H_2 purity > 99.9% H_2, while a fuel cell has a purity requirement in the range > 99.999% H_2.

On-site generation of hydrogen

One advantage of proximity of the refueller to the production site is the elimination of H_2 logistics and associated costs. At the same time on-site production has the disadvantage of the additional space required for the electrolysis plant with upstream and downstream processes for water treatment and product gas purification (usually drying and oxygen separation).

Whether on-site generation is economically competitive depends on the plant and operating costs for the electrolyser, as well as on the H_2 delivery costs according to the specific boundary conditions of the respective transport company.

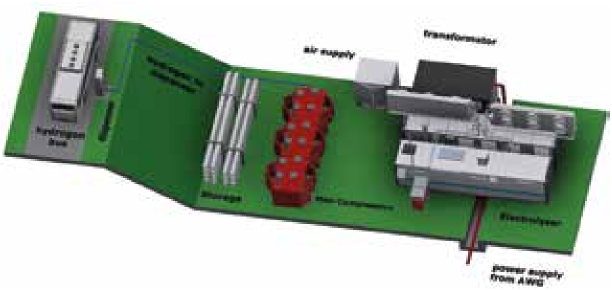
With regard to the operating costs, the electrical energy costs represent the main influencing variable. Figure 65 illustrates the relevance of the electrical energy costs. The Capex describes the investments and the Opex the operating expenses. In general, there are various tax exemption or tax reduction options for the operation of an electrolysis plant. For example, with the adoption of the EEG 2021, companies that belong to the 'production of industrial gases' [38] sector and for which the electrochemical production of hydrogen makes the largest contribution to the company's total value creation can claim an 85% reduction in the EEG levy. If only electrical energy from renewable sources according to the EEG ('green electricity') is used for H_2 production, the EEG levy does not apply at all [39].

An electrolysis plant is exempt from grid fees[40] for 20 years and there are also possibilities to reduce the other levies (see detailed report on energy source costs in the 'Electromobility starter kit'). In summary, it can be assumed that electricity purchase prices of less than 7 ct/kWh are possible for hydrogen electrolysis. In general, the exemption from levies, like the profitability analysis of on-site hydrogen production, requires a case-by-case assessment (see chapter 2.5.3 below).

38 according to sequential number 78 under Annex 4 EEG

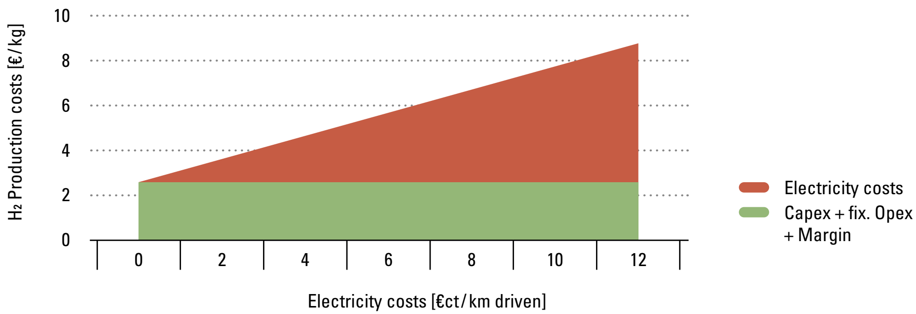
39 Green hydrogen as defined in the statutory exemption from payment of the EEG surcharge under § 69b of the Renewable Energy Sources Act is hydrogen that has been produced electrochemically through exclusive consumption of electricity from renewable energy systems. Furthermore, only hydrogen produced within the first 5,000 full-load hours of the plant within the calendar year is considered green. See VCDBi Ordinance on the Implementation of the EEG 2021, May 2021

40 § 118 (6) sentence 7 EnWG



Hydrogen production and filling station in Wuppertal
Source: Abfallwirtschaftsgesellschaft mbH Wuppertal

FIGURE 65 **Dependence of H_2 generation costs on electricity costs**
(simplified representation for 4 MW electrolyser @ 4,000 full load hours)[41]



41 Sphera: Own calculations on transport costs, 2020

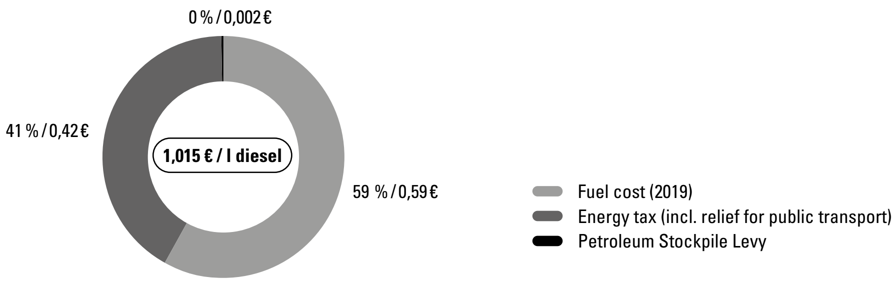
Diesel

As of today, diesel is the predominant energy source in bus-based local public transport and therefore serves as a reference for the following economic viability analysis in chapter 2.5.3. For the diesel costs, the average wholesale price[42] for the reference year 2019 is used as a base value for the calculations. It is 1.015 €/l diesel. The year 2020 was deliberately not chosen because a significant drop in the price of diesel was observed due to the COVID-19 pandemic and this special effect was considered by the project consortium to be a non-representative one-time effect.

42 Petroleum Industry Association: https://www.mwv.de/statistiken/verbraucherpreise/, last accessed in March 2021.

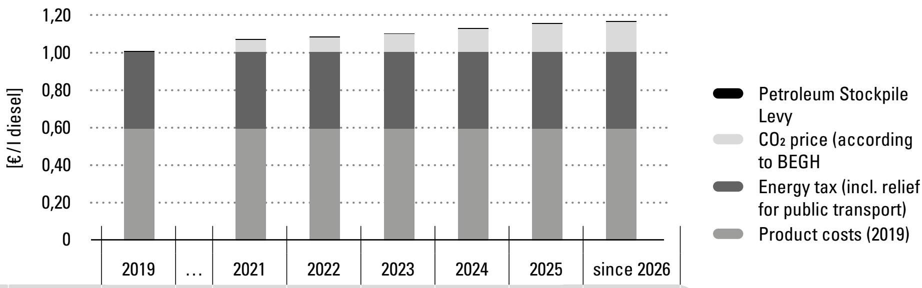
The main cost components for the reference year 2019 are the actual product costs, i.e., oil extraction, processing, delivery and margin with 59%, and the energy tax with 41% (see Figure 66).

FIGURE 66 **Cost components for diesel** (reference year 2019)



From 2021, a government levy will also be imposed on diesel in the form of a CO_2 certificate price in accordance with the Fuel Emissions Trading Act (BEHG). The amount is set until 2025 and is levied on all fossil fuels used in transport and heat generation. Figure 67 shows the current CO_2 prices at set in the BEHG and their effect on diesel costs. The other cost components were kept constant according to the reference year 2019.

FIGURE 67 **Development of diesel costs depending on the statutory (BEGH) CO_2 price** (based on 2019)



	2019	…	2021	2022	2023	2024	2025	since 2026
CO_2 price [€/t CO_2]			25	30	35	45	55	60 (var. 55–65)

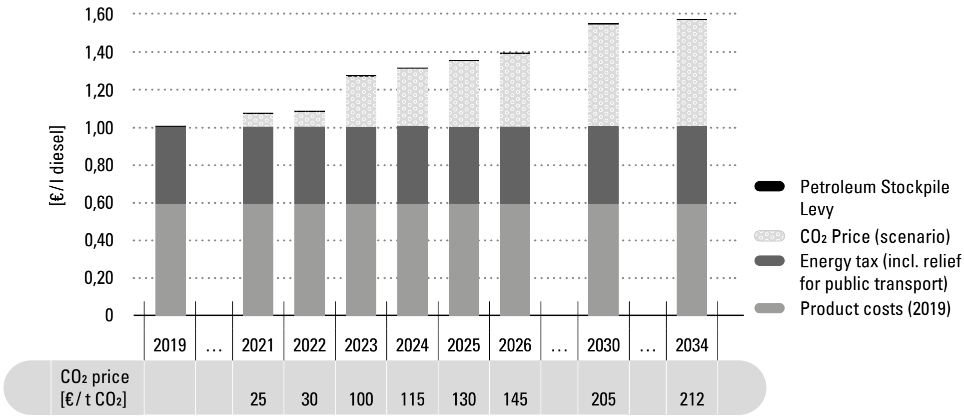
Another increase in the CO_2 price is currently being discussed in the context of the debate on further tightening of the climate targets at EU level[43], but also to promote alternative drive systems[44]. Based on the costs for consequential climate damage as determined by the Federal Environment Agency for 2030[45] (205 €/t CO_2), a CO_2 price scenario was established, and this is used in the following chapter for a sensitivity analysis. The objective of this sensitivity analysis is to determine the economic impact such a CO_2 price increase has on the additional/reduced costs of the innovative drives compared to diesel. Figure 68 illustrates the effect of this assumed CO_2 price increase on the development of diesel costs under the assumption that the other cost components remain unchanged compared to the base year 2019.

43 European Green Deal: https://ec.europa.eu/commission/presscorner/detail/de/IP_21_3541 July 2021

44 Federal Environment Agency on climate protection: 'The CO_2 price will have to go up' | tagesschau.de, 12 June 2021

45 Federal Environment Agency, Methodological Convention 3.0 for the Determination of Environmental Costs – Cost Rates, 2019

FIGURE 68 **Scenario for the development of diesel costs as a function of rising CO_2 prices** (based on 2019)



2.5.3. Economic viability analysis

An economic feasibility analysis was carried out for four different e-bus drive technologies. They are battery electric depot charging bus (BEV DC), battery electric opportunity charging bus (BEV OC), fuel cell range extender (FC REX) and fuel cell bus (FC bus). The hydrogen required for the two fuel cell (FC) based drive concepts is either supplied or produced on site (through electrolysis). Both supply options are analysed.

In terms of an overall cost analysis, the economic viability analysis is carried out as a total cost of ownership (TCO) analysis over the life cycle. This means that it includes the investment costs as well as the operating costs for an observation period of 12 years.

The cost analysis is carried out for each e-bus drive technology in comparison to a sample fleet consisting of 50 diesel buses as reference technology. The diesel reference fleet determines the distance travelled in that period which then enables the determination of the number of the different alternatively powered buses needed to achieve the same distance driven.

The complete report on the profitability analysis can be found in the 'Electromobility starter kit'. It presents the resulting investment costs with and without subsidies according to the defined input data, including information on the subsidy rate used as a basis for the individual cost items for the different drive technology being analysed. The investment costs are shown as total costs and per vehicle, divided into the cost categories 'vehicle costs', 'infrastructure costs' and 'other costs' for workshop equipment, training and other costs. The sub-category 'other costs' includes project costs, material costs, planning costs and construction cost subsidies for the grid connection.

The results are summarised in a cost increase/decrease analysis compared to the diesel bus. The results are given as the absolute differential costs in euros over 12 years and the TCO costs in € per km, in each case with and without consideration of a 3% return on capital on the additional acquisition costs as well as with and without assumed subsidies. The results presented in this section all include the 3% return on capital. The results without the return on capital can be found in the detailed report on the profitability analysis mentioned above.[46]

46 See https://www.durchstarterset-elektromobilität.de/OPNV/

47 As of July 2021, the 80% reduction in the EEG levy for electrically powered buses adopted with the EEG 2021 was still subject to review by the EU Commission under government assistance scrutiny.

The basis of the economic viability analysis is the determination of the total operating costs in €/km based on the used input data. However, the economic viability analysis does not focus specifically on the absolute €/km values for the investigated technologies. The main objective of the analysis is to provide stakeholders with specific information on the influence of different input parameters on the total costs per technology. This is intended to make it easier for the stakeholders (transport companies and public transport authorities) to estimate which costs can be expected for the different drive technologies under their own specific boundary conditions.

To make this possible, sensitivities were calculated for each drive technology to identify the parameters with the greatest impact on economic viability. Each factor was examined separately while all other factors were held constant (ceteris paribus). The parameters examined include:

- the additional vehicle demand assumed for the depot charging bus (BEV DC),
- the development of the CO_2 price for diesel,
- expected lower costs for the innovative drives due to further technical developments and economies of scale through higher unit numbers,
- the reduction of the EEG apportionment by 80% for electrically powered buses introduced as part of the EEG 2021[47] , as well as
- changes in electricity and hydrogen procurement costs.

Key input variables and calculated total cost of ownership

The main input variables (see Table 11) and the resulting total cost of ownership (TCO) per km (see Table 12) are presented below in order to establish a reference base for the sensitivity analyses.

The reference fleet[48] comprises 50 diesel buses (Euro VI), of which 27 are standard buses and 23 are articulated buses. An annual distance driven of 60,000 km was assumed, which is provided on 300 operating days per year in medium urban traffic (SORT 2[49]), corresponding to an average daily distance driven of 200 km per bus. The reference period selected had a fictitious transport company starting planning and preparing the operation of the fleet in 2020/21, so that it can go into operation in 2023, including procurement and installation of the energy supply infrastructure.

48 Fleet composition of solo/articulated buses according to VDV (53% 12 m and 47% 18 m buses)

49 SORT (Standardised On-road Test cycle) 2: medium-heavy urban traffic with an average cruising speed of 18 km/h

The values shown in Table 11 were used for the vehicle procurement costs. For the 12 m vehicles, 240,000 € were used for the diesel bus, and for the electrically powered ones, a range from 468,000 € for the opportunity charging bus (BEV OC with 110 kWh battery capacity) to 625,000 € for the FC REX and FC bus. The procurement costs for the electrically powered 12 m buses are more than twice as high as for the diesel bus. The situation is similar for the articulated buses.

The additional vehicle demand for depot charging buses was assumed to be 35% due to the assumption of all-electric heating to ensure all-electric operation. For the opportunity charging buses, an additional vehicle demand of 10% was assumed. This assumption on the additional vehicle demand has a significant effect on the total costs, especially for the depot charging buses (see sensitivity analysis below) and can vary greatly from one transport company to another depending on the vehicle scheduling. The authors are aware of several specific examples of lower as well as higher additional vehicle requirements.

TABLE 11 **Key input data for the profitability analysis**[50]

Solo buses (12 m)	**diesel**	**BEV DC** (12 |18 m: 396 kWh/ 495 kWh)	**BEV OC** (12 |18 m: 110 kWh | 150 kWh)	**FC REX**		**FC**	
				H_2-Delivery (T)	*H_2-On-site production (OS)*	*H_2-Delivery (T)*	*H_2-On-site production (OS)*
Vehicle procurement costs	12 | 18 m: 240.000 € | 350.000 €	12 | 18 m: 613.200 € | 842.000 €	12 | 18 m: 468.000 € | 675.500 €	12 | 18 m: 625.000 € | 825.000 €		12 | 18 m: 625.000 € | 825.000 €	
Additional vehicle demand	–	35 %	10 %	–		–	
Energy consumption (annual average)	12 | 18 m: 43,7 | 57,2 l / 100 km	12 | 18 m: 1,6 | 2,0 kWh / km[49] (vehicle side)	12 | 18 m: 1,5 / 1,9 kWh/ km[47] (vehicle side)	12 m: 5,7 kg H_2 / 100 km 0,5 kWh / km 18 m: 8,0 kg H_2 / 100 km 0,6 kWh / km		12 | 18 m: 8,5 | 11,3 kg H_2 / 100 km	
Energy costs	1,02 € / l diesel	0,18 € / kWh	0,19 € / kWh	5,7 € / kg H_2	6,4 € / kg H_2	5,5 € / kg H_2	5,7 € / kg H_2
CO_2 price (€/t CO_2)	2023: 35 € From 2026: 60 €	–	–	–	–	–	–
Increase of energy costs p. a.	2 %	2 %	2 %	2 %		2 %	
Maintenance costs	0,52 € / km	0,39 € / km	0,49 € / km	0,49 € / km		0,49 € / km	
Maintenance costs p. a.	1 %	1 %	1 %	1 %		1 %	
Lifetime HV battery / fuel cell	–	HV battery: 6 years	HV battery: 6 years	HV batteryy: 6 years FC: 10 years		HV battery: 6 years FC: 8 years	
Cost HV battery / fuel cell	–	700 € / kWh NMC	1.200 € / kWh LTO	1.000 € / kW FC 700 € / kWh NMC		1.000 € / kW FC 1.200 € / kWh NMC	
Cost degression p. a.	–	9 %	9 %	9 %		9 %	
Costs driving personnel	25 € / h	25 € / h	25 € / h	25 € / h		25 € / h	
Increase driving personnel costs p. a.	1,5 %	1,5 %	1,5 %	1,5 %		1,5 %	

50 Further information on assumptions and sources for the cost calculation can be found in the detailed report on the economic viability analysis in the 'Electromobility starter kit'

51 Purely electric heating

The energy costs of energy consumption, which was determined for an operational context with hilly topography and an average speed of 19 km/h (SORT 2), and the specific energy source costs also make a significant contribution to the TCO costs. For diesel fuel, 1.015 €/l [52] diesel was used (see also chapter 2.5.2). The CO_2 certificate costs accruing from 2021 onwards were considered in accordance with the legal requirements of the BEHG. For electricity and hydrogen, procurement costs of 0.18 and 0.19 €/kWh and 5.48 – 6.36 €/kg/H_2 were assumed. The costs for the energy supply infrastructure, including its operation and maintenance, are not included. They were considered separately[53]. The range for hydrogen procurement costs results from the consideration of two supply options (delivery over 100 km and on-site generation) as well as from the different hydrogen demand for FC REX and FC buses. The latter have a higher hydrogen demand since hydrogen is the sole energy carrier used, so that a lower H_2 purchase total cost was used due to the larger purchase quantity for these vehicles.

52 Current net purchase price (2019) from the company (reimbursement tax 4 Ct/l already taken into account as well as 1 Ct for purchase of larger quantities); (price for 2019 due to coronavirus crisis)

53 Operating and maintenance costs for the charging infrastructure and H_2 refuelling station were reflected at 2% and 4% of the investment costs per year respectively.

The km-based maintenance costs were estimated to be 25% lower for the battery electric buses compared to the diesel bus (0.39 €/km instead of 0.52 €/km) due to the lower complexity of the electric drivetrain and reduced maintenance efforts, e.g. no oil changes for engine and transmission and fewer mechanical components. For the FC-based vehicle concepts, similar maintenance costs (0.49 €/km) to the diesel bus are estimated due to the additional gas-carrying components (fuel cell, H_2 storage). For the cost-intensive drive components HV battery and fuel cell, lifetimes of 6 and 8 – 10 years respectively were assumed, as well as an annual cost reduction of 9%, which primarily results from technical developments and increasing numbers of units.

For energy, maintenance and driver costs, an annual price increase in the range of 1 – 2% was assumed.

Based on the input variables described above, the total operating costs shown in the following table were determined for each drive technology for the examined fleet of 12 and 18 m buses. While the depot charging buses (BEV DC) display the highest additional costs compared to diesel buses due to the high vehicle acquisition costs and the assumed additional vehicle demand, the opportunity charging buses (BEV OC) exhibit the lowest additional costs. The fuel cell buses (FC bus) have lower additional costs compared to the FC REX buses, whereby the difference in TCO costs between these two drive technologies is in the order of 5% and can therefore be considered as comparable given the various assumptions made. Overall, the fuel cell-based drives rank between the two battery electric bus variants in terms of additional costs.

TABLE 12 **Overview of total cost of ownership (TCO) per drive technology**

Sample fleet (incl. 3 % interest on capital)	**Diesel**	**BEV DC**	**BEV OC**	**FC REX**		**FC**	
				H_2-Delivery (T)	*H_2-On-site production (OS)*	*H_2-Delivery (T)*	*H_2-On-site production (OS)*
Without funding							
Total cost of ownership [€/km]	3,39	4,68	3,94	4,46	4,49	4,25	4,26
Additional / reduced costs		1,29	0,55	1,07	1,10	0,86	0,87
With funding							
Total cost of ownership	3,39	3,83	3,41	3,75	3,74	3,57	3,52
Additional / reduced costs		0,44	0,02	0,36	0,35	0,18	0,13

If the existing subsidies of 80% for the eligible additional vehicle costs and 40% for the infrastructure and other costs are also considered, the additional TCO costs are significantly reduced by at least 66%. For the opportunity charging bus, there is almost cost parity with the reference system based on the assumed subsidy, while the subsidised depot charging bus has additional costs of 0.44 €/km and thus still has additional costs of 13% compared to the diesel drive. The additional TCO costs for the FC-based bus fleets amount to 0.13 to 0.36 €/km and are thus 4 – 11% higher than the diesel TCO costs. The two analysed hydrogen supply options are largely comparable from an economic point of view under the assumptions made. The location of hydrogen production and the transport distance plays a significant role in the transport costs, especially for delivered hydrogen. Even greater transport distances can be required than assumed in this analysis, particularly when hydrogen is purchased from renewable resources (i.e., green hydrogen).

Generally, subsidies should be seen as support for the market ramp-up until a self-sustaining market has developed. The funding agencies therefore require the providers of vehicles and associated infrastructure to significantly reduce costs in the future (e.g., through economies of scale and further improvement and optimisation of the utilised components or the technology as a whole) so that the currently high funding intensity can be reduced in the future. The financial effects of a reduction in investment costs will be examined in more detail in the following sensitivity analysis.

However, before individual technologies are favoured solely based on the profitability analysis, it should be pointed out once again that it is necessary to examine the operational and structural feasibility of the different energy supply infrastructure for the local emission-free drive concepts under consideration. Especially for the opportunity charging bus, the operational feasibility must be specifically examined in each individual case. It must be determined if the vehicle scheduling with the planned turnaround times allow reliable recharging of the buses on the route and if it is possible to implement one or possibly several charging points for regular recharging of the opportunity charging buses at these points in the route network in terms of space, construction, and power supply. The additional costs of the individual drive technologies depend on a range of factors, such as operational (e.g., additional vehicle demand), regulatory (e.g., reduction of the EEG levy) and economic (e.g., vehicle price, energy procurement costs), as the following sensitivity analysis illustrates.

Sensitivity analysis

As already mentioned, the main objective of the profitability analysis is not to determine specific €/km values for the examined technologies, but to give stakeholders specific indications of the influence of different input parameters on the total costs per drive technology.

Therefore, using the ceteris paribus assumption, the various input parameters are analysed separately below to quantify their impact on the total costs. The detailed parameters are:

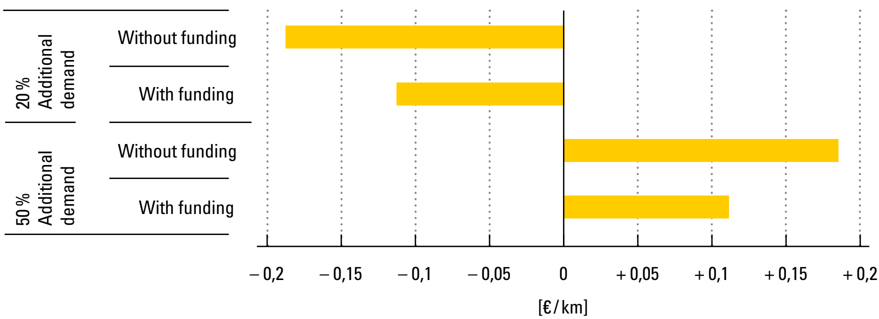
- Additional vehicle demand
- CO_2 price
- Vehicle or vehicle component costs
- EEG levy
- Supply price of hydrogen and efficiency of electrolysis
- Electricity procurement costs (electricity price)

The results are presented considering a 3% return on capital.

Additional vehicle demand

In order to meet the distance driven requirement of 3 million kilometres per year, an additional vehicle demand of around 35% is assumed for a depot charging bus fleet in the economic viability analysis, taking into account the currently available battery capacities. This corresponds to 18 additional buses, consisting of 10 solo and 8 articulated buses, compared to the reference fleet. Variation of the additional vehicle requirement has the greatest effect of all the examined parameters on the total operating costs for the depot charging bus (BEV DC) and thus the additional/reduced costs per kilometre. Reducing the number of additional vehicles required by 15% points to 20% of the fleet total would reduce the average additional costs by 0.19 €/km to 1.10 €/km. An increase by 15% points to a total additional vehicle demand of 50% leads to additional costs of 0.19 €/km (see Figure 69). The results are presented in relation to the additional costs determined in the initial calculation (see Table 12), i.e. 0 €/km corresponds to additional costs of 1.29 €/km in the case shown in Figure 69 without subsidy or additional costs of 0.44 €/km with subsidy.

FIGURE 69 **Sensitivity of additional vehicle demand for depot charging buses**



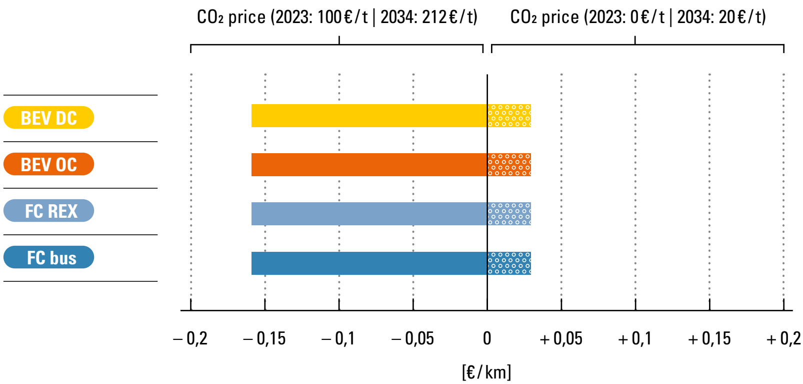
CO_2 price for diesel

An increase in the CO_2 price has also a significant impact on the additional costs of all bus systems, as it affects the total operating costs of the diesel fleet as a benchmark. With an increased CO_2 price of 100 €/t CO_2 in 2023 and an increase to 212 €/t CO_2 by 2034 based on the damage costs for CO_2 determined by the Federal Environment Agency[54], instead of the 35 €/t CO_2 in 2023 and 60 €/t CO_2 from 2026[55] used as a basis in the base scenario, the average additional costs of all e-buses decrease by 0.16 €/km. If, on the other hand, no CO_2 price is applied for diesel, the additional costs increase consistently by 0.03 €/km (see Figure 70).

54 UBA Methodological Convention 3.0 for the Determination of Environmental Costs. Cost rates. February 2019.

55 Corresponding to the Fuel Emissions Trading Act (BEHG), 2020. Last accessed: 06/08/2021.

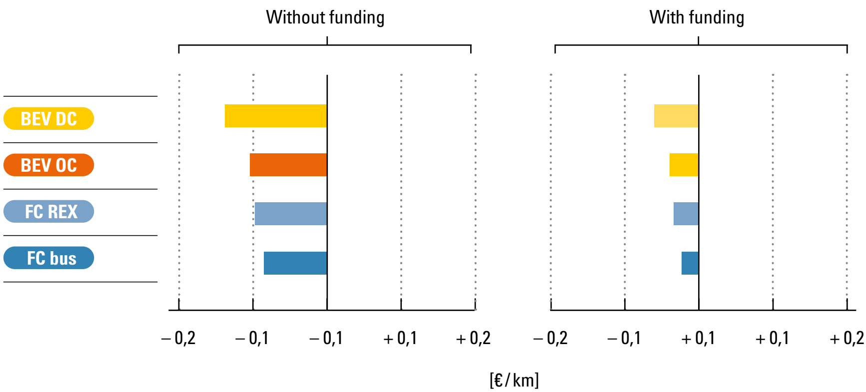
FIGURE 70 **Sensitivity of CO_2 price**



Cost reduction of bus costs

A reduction in procurement costs is expected for e-buses due to increasing numbers of units being purchased as well as further technological development, especially for the main drive components such as HV battery, fuel cell, H_2 storage tanks, e-motor, etc. Assuming that the acquisition costs of the respective vehicle are reduced by €50,000, this results in the decrease in additional costs per drive technology shown in Figure 71.

FIGURE 71 **Sensitivity – €50,000 reduction in vehicle acquisition costs**



The cost reduction was distributed linearly among the various drive components. The assumed cost reduction for the drive components HV battery and fuel cell was also considered proportionally for the replacement components (HV battery and fuel cell). In other words, if the specific costs of the HV battery were reduced by 10%, they were also reduced by 10% for the replacement battery required after 6 years. The costs of the basic vehicle were kept constant for each drive technology. Due to the assumed additional vehicle demand for depot charging buses, this bus system shows the greatest reduction in additional costs of 0.14 €/km without subsidy and 0.06 €/km with subsidy.

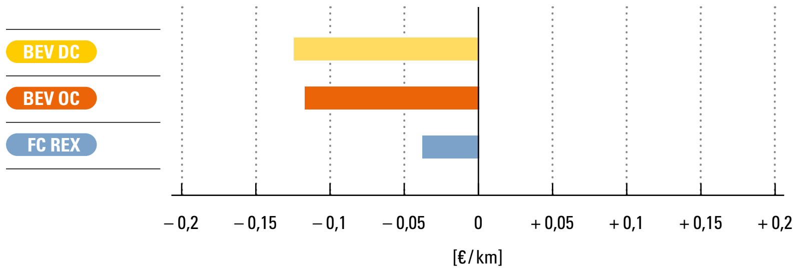
Reduction of EEG levy

With the EEG 2021, a reduction of the EEG levy by 80% can be requested by the transport company at BAFA with a minimum annual traction current requirement of 100 MWh in accordance with § 65a[56] .This reduction consequently affects battery electric buses and FC REX buses.

56 Renewable Energy Sources Act 2021, § 65a. Last accessed: 30/7/2021. Still under EU government subsidy scrutiny.

Figure 72 shows that the additional costs for depot charging buses are reduced the most, specifically by 0.12 €/km, due to the highest energy consumption. For opportunity charging buses there is a reduction of 0.10 €/km and for the fuel cell buses with range extender 0.04 €/km with the relatively low electricity consumption being reflected. An EEG levy exemption was assumed for the required hydrogen, so the EEG reduction has no impact on the additional costs of FC buses.

FIGURE 72 **ensitivity – 80% EEG reduction**

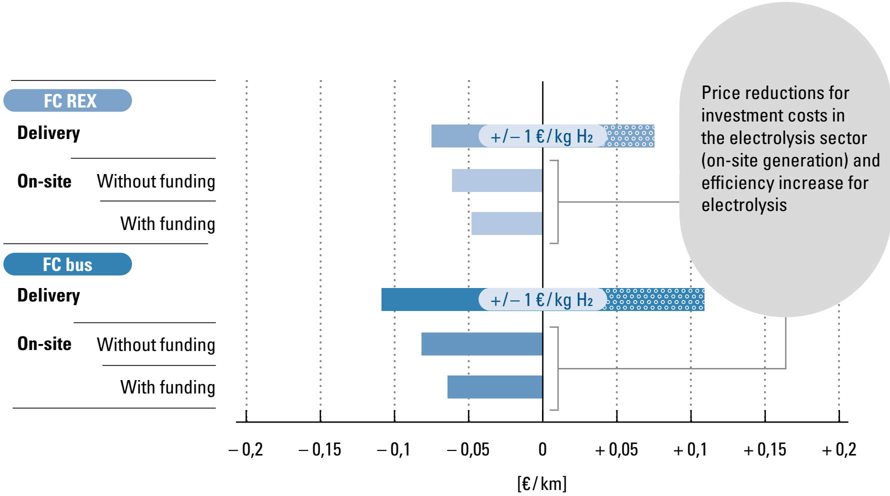


H_2 supply costs and optimisation of electrolyser

Changes in the costs of hydrogen supply have a greater impact on FC-only buses than on FC REX buses due to the higher hydrogen consumption (see Figure 73). A reduction in the purchase costs of delivered hydrogen by 1 €/kg (from 5.48 €/kg to 4.48 €/kg) reduces the additional costs for delivery concepts by 11 cents to 0.75 €/km for the FC-only buses and by 8 cents to 0.99 €/km for the FC REX buses. An increase in the price of hydrogen leads to additional costs of 0.11 and 0.08 €/km.

A reduction in the investment costs for electrolysers during the targeted market ramp-up period is expected for the water electrolysis technology used in on-site generation. An increase in energy efficiency is also forecast due to technological advances. A reduction in the acquisition costs for electrolysis to 400 €/kW and a relative efficiency increase of 10% were accordingly assumed for the sensitivity analysis. This leads to a reduction of the additional costs for on-site generation by 6 cents to 1.04 €/km for the FC REX buses and by 0.08 €/km to 0.78 €/km for the FC buses.

FIGURE 73 **Sensitivity of H_2 price and electrolysis efficiency**

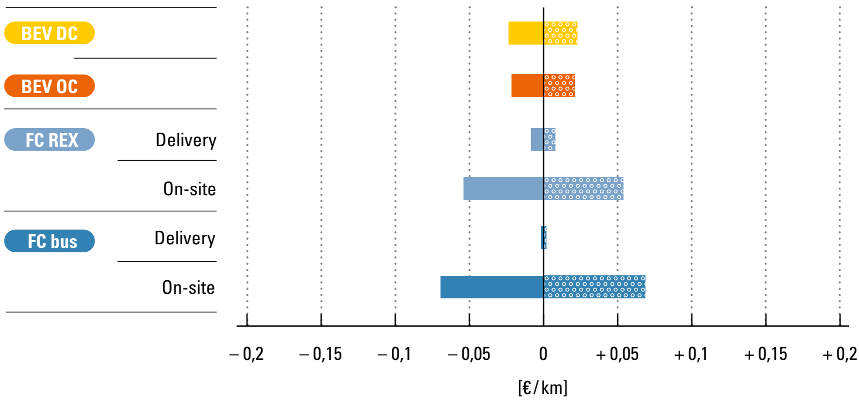


Electricity price

A variation of the electricity purchase costs by ±1ct/kWh affects the additional costs of depot charging and opportunity charging systems depending on the energy consumption of the battery electric buses by ± 0.02 €/km each (see Figure 74).

For the FC REX buses, the variation of the electricity price by ± 1 ct/kWh has a manageable effect of ±1 ct/km on the additional costs due to the relatively low demand for electrical energy and the assumed constant H_2 delivery costs. If, on the other hand, on-site generation is considered, the variation in electricity procurement costs has a much more noticeable impact. In this case, the additional costs for the FC REX buses change by ± 0.05 €/km, and by ± 0.07 €/km for the FC buses which have a higher hydrogen consumption. If the FC buses are supplied with delivered H_2, the variation of the electricity costs leads to a minimal change in the additional costs of ± 0.001 €/km, as this only affects the amount of electricity required for the compression of the hydrogen.

FIGURE 74 **Sensitivity of electricity price**



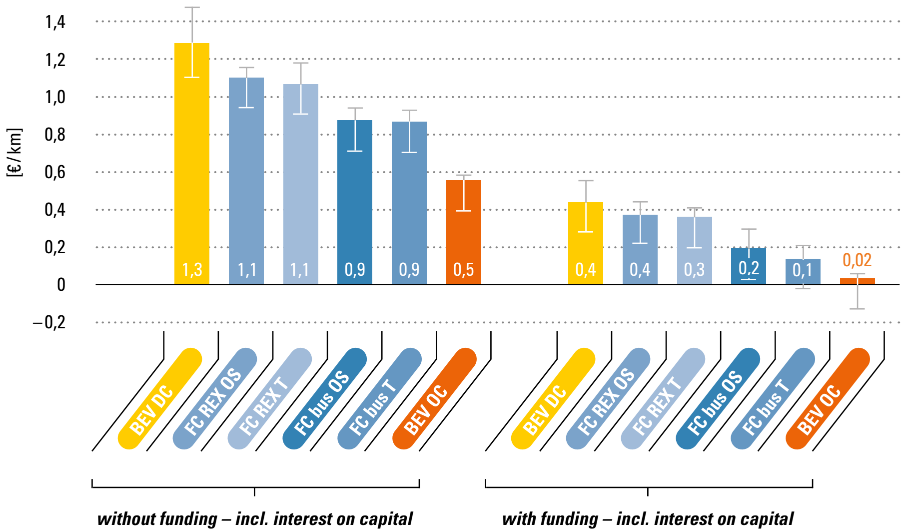
Overall consideration

Figure 75 shows the additional costs of the analysed e-bus systems, including the ranges, which resulted from the variation of the individually examined parameters in the context of the sensitivity analysis.

The range bars shown in Figure 75 represent the increase or decrease in the additional costs for the parameter that had the greatest impact on the additional costs of each technology, as determined in the initial TCO calculation (see Table 12). The remaining gap to TCO parity with the diesel reference fleet can therefore be partially closed with the assumed subsidy through the occurrence of this parameter change or the partial application of multiple parameter changes as examined in the sensitivity analysis.

In addition to the comments made in the context of Table 12 about selecting an individual drive technology, it should be noted that the additional costs of the individual technologies depend to a large extent on the specific on-site deployment and operating conditions, the further market development of vehicles and energy supply infrastructure, as well as the regulatory parameters such as CO_2 prices on diesel or levy exemptions for electricity and hydrogen.

FIGURE 75 **Overview of additional/reduced costs per e-bus drive system compared to a diesel bus fleet**



2.5.4. Summary of the results on economic viability

Conclusion

- The energy source costs, together with the driving personnel, maintenance and repair costs for the vehicles, represent the key input variables for the operating costs.
- The actual electricity procurement costs, which include electricity generation incl. CO_2 costs, distribution costs and margin, only account for a quarter of the electricity price for the reference year 2020.
- Electricity procurement costs of 18 ct/kWh were determined and used as a basis for the calculations.

- With the passing of the Renewable Energy Sources Act 2021, a reduction of the EEG for electrically powered buses by 80% for companies with a minimum consumption of 100 MWh/a was made possible in accordance with § 65a.

- Grid fees are levied depending on the hours of use of the grid connection capacity registered with the grid operator. The use of a charging management system, which ensures that the charging power remains constant over time and thus avoids peak loads during recharging of battery electric and FC REX buses, accordingly contributes to a reduction in energy costs.

- The costs for delivered hydrogen currently range from 4.50 – 9 euros net per kg of hydrogen.

- Taking into account a return on capital of 3%, this results in additional costs of €1.29/km for depot charging buses and €0.55/km for opportunity charging buses. By using the currently available subsidies, these costs decrease to 0.44 €/km for depot charging buses and to 0.02 €/km for opportunity charging buses.

- In addition to supporting the climate protection objective, the currently available funding is intended to support the market ramp-up for ZEV (zero-emission) buses. From a funding agency's point of view, subsidies need to be reduced as soon as a self-sustaining market has established. This will require considerable efforts on the part of the bus and infrastructure manufacturers to realise the necessary cost reductions.

- For delivered hydrogen, the additional costs compared to a diesel bus fleet are 1.07 €/km for FC REX buses and 0.86 €/km for FC buses. The additional costs for on-site H_2 generation are 1.10 €/km for FC REX buses and 0.87 €/km for FC buses. If subsidies are used, the costs for delivered hydrogen are reduced to 0.36 €/km for FC REX buses and 0.18 €/km for FC buses. If the hydrogen is produced on site, the additional costs drop to 0.35 €/km for FC REX buses and to 0.13 €/km for FC buses with the help of subsidies.

- It should be noted that the calculated additional costs depend on the operational context, the market development of the vehicles and the regulatory parameters.

- The sensitivity analysis shows that the remaining gap to TCO parity with a diesel reference fleet can already be partially closed with the assumed subsidy changing one or more parameters, such as CO_2 price and investment costs.

2.6. Guidance and decision tool

Under the motto 'Knowledge is the best foundation for sound decisions', a guide was developed to provide initial information to transport companies, politicians, as well as the general public. It contains high level information about zero-emission bus drives, their necessary infrastructure and the costs associated with procurement and operation.

The guide, which is available as a brochure[57] and on the website[58], describes the

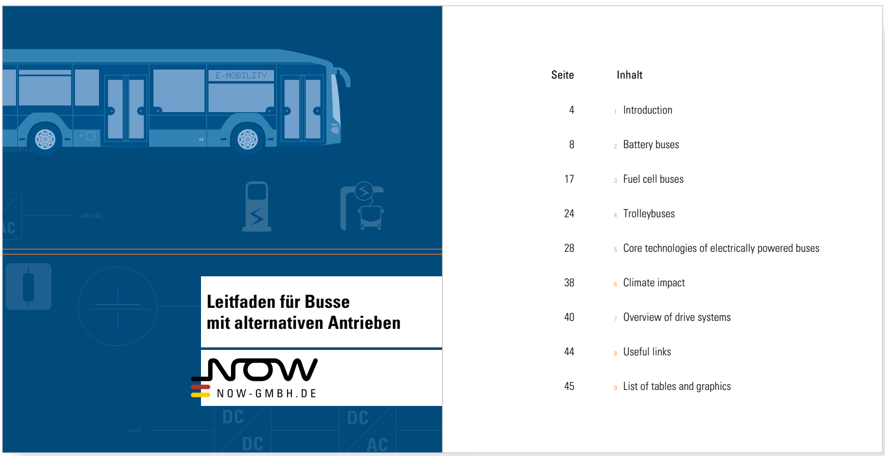
- battery electric buses (full chargers, opportunity charging buses),
- fuel cell buses (with and without range extender function) as well as
- (hybrid) trolley buses

in more detail.

57 The brochure is available in the Electromobility starter kit.

58 The interactive online version of the guide is available at www.ebustool.de.

FIGURE 76 **Cover page and table of contents of the printed version of the guide**



The online version of the guide (see www.ebustool.de) provides various entry points for finding out about the different drive variants. The guide describes the significance of the application areas (city vs. regional transport), as well as providing direct access to all essential information and data on the individual drive technologies.

FIGURE 77 **Home page of the online version of the guide**

Users can get a better fact-based overview of the drive technologies in order to avoid preconceived notions based on a lack of knowledge.

However, the introduction of buses with alternative drives is a very complex planning and decision-making process, which is largely shaped by the specific parameters in each transport company. Neither the guide nor the online decision-making tool based on it therefore claim to provide a definite decision for the transport company which must factor in its own unique operating context.

59 The online decision-making tool is also available at www.ebustool.de.

The online decision tool [59] is only intended to provide information to support decision-making. However, it gives transport companies the opportunity to generate information on

- additional requirements in terms of vehicles, driving staff hours as well as non-operational kilometres and
- the associated additional costs in the context of the total costs

based on their individual operating procedures and boundary conditions.

The optimised vehicle schedule for diesel buses is used as the basis for comparison with

- battery electric buses as full or opportunity charging buses as well as
- fuel cell buses.

The algorithms applied are essentially based on the Fraunhofer in-house tool IVInet, which developed over a decade. IVI*net* is based on energy balancing and facilitates the evaluation of entire grids based on vehicle schedules. The algorithms take into account:

- the scheduled operating procedures in the form of vehicle scheduling
- delays that vary over the course of a day
- Travel speeds
- Passenger load
- Height profiles
- Depot regime, i.e., the availability of so-called short-route vehicles for replacement schedules to ensure optimised charging options throughout the day.

While access to the website is open, the decision-making tool is primarily aimed at transport companies that have the necessary detailed information, e.g., regarding operational procedures.

Users can create their own user account, add and define application cases and upload the corresponding data. While a transport company does not have to register under its own name, access to the uploaded data is only possible for the transport company that registered and the administrator of the tool.

For each type of drive, the programme provides the user with recommendations on ranges, battery sizes and specific energy consumption, which can be modified within predefined limits. The user can also choose the form of heating and air conditioning.

Recommendations are also made regarding the cost rates to be applied, which in turn can be changed within predefined limits.

Source: SWM/MVG, 2021

3 Summary

With around 10 billion passengers transported annually in Germany, local public transport is already an indispensable component for ensuring the individual mobility of the population, both in conurbations and in rural areas. From a climate protection point of view, it is important to switch from diesel buses to emission-free, efficient and quiet buses with alternative drives in order to make bus-based public transport more climate and environmentally friendly and thus more sustainable. Based on the testing of hybrid buses, the full electrification of the drivetrain is currently the most intensively pursued technological approach for emission-free drive systems of local public transport buses. As part of the recently revised climate protection programme, the German Government is pursuing the specific goal of converting half of all city buses to electric drives by 2030. For example, emissions from local public transport are planned to be cut in half by 2045 compared to 2019 levels.

This objective is supported by a number of legal instruments including the Clean Vehicles Directive (CVD) of the EU. With the recently enforced CVD and the Clean Vehicles Procurement Act (SaubFahrzeugBeschG), which brings the implementation of the European Clean Vehicles Directive into German national law, there is now a clear legal requirement for the procurement and operation of 'emission-free' buses. The category of Class I city buses is the first vehicle category for which such a binding procurement target for zero-emission drives has been introduced. Further tightening of the share of zero-emission buses within the framework of the European Green Deal does not seem out of the question. Based on the current targets of the CVD, the market potential for buses with alternative drives in Germany alone is already in the order of 2,000 vehicles per year for ‘clean’ buses and 1,000 vehicles per year for ‘zero-emission’ buses by the end of 2025. By 2030, this potential increases further to 3,000 clean or 1,500 zero-emission buses due to the 2nd stage of the CVD Directive.

Transport companies are facing technical and operational challenges as well as economic ones: the introduction and subsequent (partial) conversion to zero-emission buses with comparatively new drive components such as high-voltage batteries or fuel cells including hydrogen pressure tanks, as well as the corresponding construction of the required energy supply infrastructure for electricity and/or hydrogen. In order to support transport companies in overcoming these challenges, the Federal Government, as well as the Federal States and the European Union, have launched various funding programmes for market initiation and market ramp-up. The BMDV provides investment support for the purchase of alternatively powered buses and the associated charging and refuelling infrastructure. The BMUV also promotes the purchase of battery electric buses and the necessary charging infrastructure in local public transport. The BMDV funds research and development projects (R&D) via the two programmes mentioned above as well as the Federal Government’s Mobility and Fuel Strategy (MKS) to further support market preparation and the market ramp-up for electromobility applications.

The BMDV initiated a programmatic accompanying research project with the goal to compile the individual results of the projects co-financed under the various funding programmes for the introduction of zero-emission local transport buses. It compiles and evaluates the findings and experiences of the individual projects from the three funding areas of vehicle procurement, electromobility concepts as well as R&D projects, to establish a general overview.

The focus of this technology analysis and evaluation of the zero-emission drive systems, which is carried out within the scope of the accompanying research on buses, is on the following evaluation categories

- Practical feasibility and operational maturity,
- Energy efficiency,
- Environmental impact
- Economic viability.

The main results are presented at the end of this section.

The evaluation took into account the individual conditions of use and the requirements formulated by the transport companies for the technology, e.g., with regard to range, availability or minimum additional costs.

The accompanying research on buses pursues the ultimate goal of creating a better understanding of the technical and operational suitability of the individual zero-emission drive technologies., This is especially important for transport companies and municipal authorities as key players in the planning and implementation of the most attractive public transport services possible within their own specific operating conditions. It also aims to shed light on the associated economic consequences.

Based on the results and findings of the technology assessment performed, fact-based information and assistance is provided and made available to support transport companies and public transport authorities in their decision-making process to select the best suited emission free drive train system or mix of drivetrains. This information is provided in different forms and formats to ensure effective, target group-oriented accessibility of the information and results.

The Working Group 'Innovative drivetrains for buses' (WG Bus), initiated by the BMDV and BMUV in 2012, serves as a platform for direct exchange of information and experience between the various stakeholders, which includes transport companies, industry (bus and component manufacturers), research institutions, funding bodies (Federal Ministries and some State Ministries) and the accompanying research team. Within the framework of the regularly held meetings, the results of the accompanying research were directly communicated and made available to the participating stakeholders, in line with the objectives of the WG Bus:

- To compile results from the individual funding projects that are open to all technologies,
- to network participating companies and organisations, to promote productive communication among them, to intensify knowledge
- to enable new stakeholders to enter the field of electromobility.
- to identify further fields of action and, if necessary, R&D requirements.

The steadily increasing number of participants in the WG Bus meetings demonstrates the interest of the various stakeholders in the results.

In addition to direct communication within the WG Bus, the manifold results of the accompanying research on buses were made available to a broader public via presentations at specialist events (e.g. BMDV specialist conference 'Elektromobilität vor-Ort', VDV E-Bus Conference, Electric Vehicle Symposium), publications in specialist literature (e.g. 'Der Nahverkehr') and via the 'Electromobility starter kit'.

A guide for buses with alternative drives was developed to provide initial information on zero-emission buses and the associated infrastructure. This is available as a print publication and in interactive form at http://www.ebustool.de. It was used as a basis to develop an online decision-making tool that provides transport companies with indicative information based on the input data they provide on their own specific on-site operational processes (e.g., vehicle scheduling and optional cost data). The provided indications relate to possible expected additional demand regarding extra vehicles, driving staff hours and non-operational kilometres as well as the resulting additional costs from these additional demands.

In light of the complexity of the necessary planning and decision-making processes for the introduction of buses with alternative drives, which are significantly shaped by the respective parameters in each transport company, it is important to note that neither the guide nor the online decision-making tool can make the decision for a transport company. It is important to have an open-minded approach to technology in order to identify the most suitable drive system for one's own operation and to avoid any preconceived notions based on a lack of or selective knowledge.

A number of publications on various topics were produced in addition to this final report. These include a funding project overview, an analysis of the e-mobility concepts with public transport relevance that were created with BMDV funding, and a chart of legislation impacting on electromobility in public transport. Together with the detailed reports on individual evaluation criteria referenced in the various chapters of this report, these documents can be found in the 'Electromobility starter kit'[60] under the Local Public Transport (LPT) module. They provide a comprehensive range of information for transport companies and municipal authorities.

60 See https://www.durchstarterset-elektromobilität.de/OPNV/

The main results of the accompanying research on buses are presented below, separated into four evaluation categories: practical feasibility, energy efficiency, ecology and economic viability. The transport companies participating in the accompanying research made this evaluation possible in the first place by providing operational data and their practical experience.

Practical feasibility and energy efficiency

Battery electric buses

The operational data of more than 130 buses from 8 different manufacturers are available for battery electric buses, in some cases over a period of more than two years. Of these, 117 are depot charging buses (112 solo buses, 5 articulated buses) and 14 are opportunity charging buses (4 midi-buses, 9 solo buses, 1 articulated bus). This much more extensive database compared to the last status report of the WG Bus from 2016 (factor 8 more vehicles and factor 27 higher distance driven) enables a robust evaluation, especially of the 12 m battery electric buses.

The battery electric buses in use have an overall availability of approx. 87% (depot charging buses 87%, opportunity charging buses 88%) in the period under review. This represents a significant increase compared to the last status report of the WG Bus (from 2016), in which the depot charging buses had an availability of 72% and the opportunity charging buses an availability of 76%. Most of the downtime or failures (60%) are attributable to general maintenance and repair measures on the conventional part of the vehicle and only 28% due repair measures on the e-drive train. To ensure smooth operations, a charging infrastructure with ideally 100% availability is needed. Currently, the charging infrastructure can be considered to already have a high availability with an average of 96%.

The average daily distance driven by the solo buses was 133 km for the depot charging buses and 179 km for the opportunity charging buses. The higher distance driven for the opportunity charging buses corresponds to the expectations of the opportunity charging concept, as there is no range limitation due to the regular recharging on the line throughout the day, at least in theory. The average daily distance driven by the diesel buses of 220 km can be used as a reference point.

If we compare the daily distance driven achieved so far with the range requirements of the transport companies, it becomes clear that this is currently one of the key challenges for the use of battery electric buses. The vast majority, almost 80%, of the 30+ participating transport companies require a daily range of at least 200 km, while the remaining 20% consider a daily range of more than 350 km absolutely necessary.

The two relevant factors affecting range are the specific energy consumption per km and the installed battery capacity. The average installed battery storage capacity is just under 300 kWh for the solo vehicles with depot charging and 230 kWh for the opportunity charging buses. The selected heating concept plays a crucial role in energy demand,. If heating is purely electric to provide completely locally emission-free operation, the currently achievable ranges are reduced by up to 50%, especially in the winter months, and are thus far below the required ranges. For articulated buses, these effects are intensified. While the average installed battery capacity of 410 kWh for the depot charging buses is larger, the increased vehicle size results in a corresponding increase of the energy demand for the traction drive as well as for the passenger compartment heating and air conditioning.

The vast majority (almost 90%) of the funded transport companies opted for the depot charging concept. The primary reason for this is that depot charging is easier to implement from a planning perspective in a first step towards the introduction of technology. This can be explained by the fact that the required charging infrastructure is set up at the company's own depot. Therefore, there is no need for a charging infrastructure in the public space, e.g., at terminal stops. This facilitates the focus on gathering experience with regard to operational planning and implementation and the battery electric buses can initially be used on the existing shorter routes without the need for additional vehicles. This means that the reduced range is acceptable with an initially small and still manageable share of battery electric buses in the vehicle fleet. However, with an increasing share of the fleet, concepts are required that guarantee the reliable supply of the route network or at least parts of it with the lowest possible additional vehicle demand. This additional demand poses challenges, not only from an economic point of view due to the additional costs incurred (e.g., in procurement), but also from an operational point of view, e.g., due to the greater space required for vehicle parking and the increased number of empty kilometres due to the additional entry and exit routes. There are various options to address this range gap:

- Increasing the energy storage capacity. Announcements on this have been made by the manufacturers or have already been introduced. However the battery capacity increase is limited by the energy density and physical properties (see also chapter 4.2).
- Examine to what extent opportunity charging is possible throughout the day on at least on some lines.
- Reduce energy consumption through lightweight construction and by improving energy management, especially with regard to vehicle heating and air conditioning

- Ecological optimisation of the use of fuel-based auxiliary heating, e.g. through the use of fuels from renewable energies such as biodiesel or bioethanol, to avoid greenhouse gas emissions and minimise the resulting pollutant emissions
- Examine the use of fuel cell buses, which have a longer range
- Adjustment of the bus scheduling so that the lower vehicle ranges are compatible with the operation of the route network. The required additional vehicle demand depends on the situation on site and can be further reduced by modifying the vehicle scheduling (see Table 3). A reduction of the additional demand has corresponding positive effects on the environmental impacts and the costs (see results of the sensitivity analysis of the additional demand on ecology (2.4.2) and economic viability (2.5.3).

Other additional energy demands that are caused by the vehicle and the charging infrastructure must be considered besides the energy demand determined directly by the vehicle itself. These energy demands result from regularly required battery balancing (to adjust the charge level of the individual battery cells and the charge losses of the battery) and from the preconditioning of the vehicle, as well as the conversion losses that occur during the conversion of the alternating current from medium to low voltage and during the conversion to direct current. This can be expected to lead to a total additional energy demand in the order of 25–30%, above the energy demand on the vehicle side. This not only affects TCO costs but also needs to be provided via the charging infrastructure and the upstream grid connection.

The transport companies' assessment of the current technology readiness level of battery electric buses is predominantly positive. Based on initial operational experience, just under half of the transport companies consider the buses to be ready for series production (TRL 9) and another quarter consider them to be close to series production (TRL 8). The expectations of more than 90% of the transport companies formulated at the beginning of the operation that the battery electric buses should be ready for series production after one year are therefore not yet fully met. With regard to the charging infrastructure, two-thirds of the transport companies consider the technology to be ready for series production and almost 15% to be close to series production, meaning that almost 80% of the transport companies consider the battery electric bus system to be ready for series production or close to series production. The perception is similar when it comes to availability. The expectations formulated by the transport companies at the beginning of the use of the new drive technologies with regard to availability were met in the vast majority of cases (75%). In operation, the battery electric buses achieve almost 90% availability. This value is only slightly below the availability of diesel buses (93% on average) as a reference technology. In general, the transport companies have high expectations of battery electric bus technology, which has only been widely introduced to the market for less than 10 years. The technology can already largely fulfil expectation with regard to availability and operational maturity.

Fuel cell buses

Fuel cell buses were included in the evaluation activities of the accompanying research for the first time. Data from 45 fuel cell buses are available that are used by two transport companies and cover a period of up to 16 months. They are exclusively solo buses from one manufacturer. This means that assessments of the fuel cell bus system can be made. However, considering the relatively small database of 800,000 kilometres driven compared to 5.6 million km for battery electric buses, the data are not yet fully reliable.

The availability of the fuel cell buses is currently around 78% on average and therefore needs to be increased further. The main causes of downtime/failure are the fuel cell system (29%) and the conventional, non-drive-related mechanical components (25%). The availability of spare parts is the main reason for the extended downtimes. With regard to refuelling station availability, initial data is currently available for one of the four refuelling stations used over a period of 15 months. The others are still in trial operation or have not yet been handed over to the transport companies. For this refuelling station, the availability is currently at 93% for the considered reporting period and for the last 6 months reached availability values above 97%.

The average consumption is about 9 kg H_2/100 km. As is the case for the battery electric buses, the energy consumption of the FC buses also increases at low temperatures, but to a lesser extent. Thus, the consumption in the winter months increased by about 1 kg H_2/100 km compared to the annual average consumption. In fact, the buses reach ranges of at least 300 km, even in the winter months, and thus fulfil expectations of the transport companies.

The currently still relatively low average daily distance driven clearly highlights the importance of efficient operational integration of vehicle refuelling into the daily vehicle supply processes. A decentralised location of the hydrogen refuelling station can lead to considerable additional personnel expenses. One possible solution would be to restructure the operational processes. For example, refuelling by driving personnel could be integrated into the vehicle's entry or exit route instead of being carried out by workshop personnel. The average refuelling time is 10–12 minutes and thus meets the operator's expectations.

Overall, the technology readiness level of the buses is currently rated by the transport companies in the range from ‘prototype in field test’ (TRL 7) to ‘close to series production’ (TRL 8), which largely corresponds to the expectations formulated at the beginning of the deployment. It is evident that the fuel cell buses have not yet reached the level of battery electric buses in terms of market maturity. However, considering the development status and the market ramp-up that is still to come, it meets the expectations of the current technology. The expectations for the operational maturity of the hydrogen refuelling stations show a wider range. In one project, for example, several refuelling station concepts were deliberately set up that were still in the research phase. Expectations ranged from proof of functionality (TRL 3) to readiness for series production (TRL 9). These expectations are fulfilled for the ‘research refuelling stations’ and are currently being evaluated in trial operation in a simplified operational environment (TRL 5). At another refuelling station, the expectation of readiness for series production (TRL 9) is almost fulfilled with the assessment of a technology readiness level close to series production (TRL 8).

In conclusion, it can be said that the practical feasibility and operational maturity of electric buses (Battery electric and FC buses) has improved further, but that there is still room for improvement. While the range of the battery electric bus is a key issue for further optimisation, the availability of the vehicles and of the hydrogen refuelling stations must be increased for the FC bus system. Generally, a number of technical and operational aspects must be considered when converting drive technology from conventional combustion engines to electric drives. Their relevance can be further reduced in part with additional technical developments. However, they cannot be completely offset on a purely technical level, but must be additionally addressed through adjustments in operational planning, e.g., with regard to the cruising range.

Ecology

Due to the shift of environmental impacts from the actual bus operation to the provision of energy sources and to vehicle production, it is necessary to consider the entire life cycle of electrically powered bus systems. This is the only possible way to assess the ecological impact of the use of local transport buses, especially for electrically powered bus systems. A consideration of the entire life cycle shows that the use of renewable energy sources is an essential prerequisite for realising relevant emission reduction potentials. For example, by using electricity from renewable sources such as wind and PV, a reduction of 75 – 85% in greenhouse gases (GHG) and 50 – 75% in nitrogen oxide emissions (NOx) can be achieved. This applies to both the direct operation of the battery electric buses and the hydrogen generation to operate the FC buses compared to the diesel bus with Euro VI standard over the entire life cycle.

Compared to diesel buses with the selected vehicle configurations, the environmental impacts of production (GHG and NOx) are about twice as high for battery electric buses and about 1.5 times as high for FC buses. From an ecological point of view, the high-voltage battery is the most relevant component. The desired increase in capacity to increase the range generally leads to higher environmental burdens in bus production. However, it can be assumed that this will be counteracted by the forecast increase in the share of renewable energies in the electricity and energy mix in Germany and internationally. This means that not only the specific emissions per kWh of electrical energy and thus the emissions from the use phase will decrease, but also the emissions from the production of the components and thus the vehicles or, for example, the photovoltaic modules. It is also foreseeable that the emissions associated with battery production or with other relevant drive components such as H_2 storage or fuel cells will continue to decrease in the future. This results from the continuous development of the technologies (changed cell chemistry [e.g., solid-state battery], increase in energy density, substitution of critical metals, extension of service life through higher number of cycles, etc.) as well as the increasing industrialisation of component production and the associated efficiency gains in terms of resources and energy requirements. Using wind and PV electricity can mostly offset the higher GHG and NOx emissions in the manufacturing of the e-buses within the first year of operation.

Importantly, after their first life cycle in the battery electric bus, high-voltage batteries offer after-use options. For example, they can be used as stationary energy storage or for recycling, both of which would have a positive effect on the overall environmental balance

The reduced noise emissions during operation are a benefit in addition to the locally emission-free operation of the e-buses. The results of the noise emission measurements carried out by the Institute of Automotive Engineering (ika) of RWTH Aachen Technical University presented in the last status report of the Working Group Bus[61] already showed a reduction potential of the linear scaled loudness of the buses with electric drive train by approx. 2/3 in all operating modes (arrival/departure, accelerated passing).

61 See WG Bus: Status report 2015/16 Hybrid and electric bus projects in Germany. (Link)

Economic viability

As part of the economic feasibility analysis, the e-bus systems battery electric bus with depot charging and with opportunity charging as well as FC bus and FC REX were examined. The profitability analysis carried out to determine the total operating costs of the different e-bus systems in the interest of a total cost of ownership (TCO) calculation makes it clear that the use of e-buses is associated with additional costs in the short to medium term. Without subsidies, these costs are 0.5 – 1.3 €/km or 16 – 38%. A number of parameters have a relevant impact on the additional costs. For the battery electric bus with depot charging, for example, the additional vehicle demand resulting from the vehicle scheduling is a key factor for the additional costs. If it is possible to adjust the vehicle scheduling taking into account the technical and operational performance (i.e. the range of the battery electric bus in the respective application context), the additional vehicle demand can be kept as low as possible. The H_2 provision costs play a significant role, especially for the FC bus, but also for the FC REX. On the other hand, a rising CO_2 price for fossil diesel can reduce the cost gap for all e-bus systems.

Currently, battery electric bus and fuel cell bus systems can only approach cost parity or feature additional costs in the range of less than 15%, if subsidies are used and under certain conditions. Additional efforts are required, whether through further technical developments or through economies of scale, in order to reduce the additional costs for the use of e-buses. This is especially important as funding agencies are wanting to reduce the currently high funding intensity once a self-supporting market been established.

Source: Mainzer Mobilität 2021

The battery electric bus with opportunity charging turned out to be the most favourable technology option under the assumptions made for the profitability analysis of the sample fleet. However, before individual technologies are favoured solely based on the profitability analysis, it should be pointed out that it is necessary to examine the operational and structural feasibility of the respective energy supply infrastructure for the local emission-free drive concepts under consideration. Especially for the opportunity charging bus, the operational feasibility must be specifically examined in each individual case. It must be clarified whether the vehicle scheduling with the planned turnaround times allows reliable recharging of the buses on the route. It must also be determined if it is possible to implement one or possibly several charging points for regular recharging of the opportunity charging buses at these points in the route network in terms of space, construction and power supply. The performed sensitivity analysis clearly illustrates once again that the additional costs of the individual drive technologies depend on various factors under the specific conditions of use, as already outlined above. These factors include: operational (e.g. additional vehicle requirement), regulatory (e.g. reduction of the EEG levy [green power surcharge]) and economic (e.g. vehicle price, energy procurement costs).

As a result, the economic effects on future budget and departmental planning for road-based local public transport can be indicated for the examined e-bus systems.

4 Outlook

What will be the drivers for the further development and spread of emission-free drives in local public transport?

In order to achieve the desired goal of converting bus-based public transport as much as possible to alternative drive systems as a contribution to climate and environmental protection, it is necessary to stabilise and further intensify the already initiated market ramp-up for locally emission-free buses. This requires continued and sustainable support and reinforcement of the various stakeholders developing innovative solutions which further technical development and the ongoing optimisation of operational processes and infrastructure.

In the short term, the factors leading to regulatory hurdles need to be reduced. Lengthy planning and approval processes must be simplified and investment security must be ensured. If companies want to switch to alternatively powered vehicles today, they must have long-term assurance that the basis of their profitability analysis will not be impaired by short-term changes in the subsidy scheme and unclear exemptions from statutory levies (e.g. EEG levy) during the term of the project. The temporary exemption from grid fees and other levies are examples of corresponding political fields of action. These are described in detail in the report on funding programmes and political parameters, available in the 'Electromobility starter kit'[62],. It is important to constructively support the development of a self-sustaining market that has already begun.

62 Available at https://www.durchstarterset-elektromobilität.de/OPNV/

Specific proposals for political fields of action to support the ramp-up of low-emission drive technologies are presented in chapter 4.1 ‘Options for action’. In addition to ensuring the legal requirements are conducive to the desired market ramp-up, it is also important to further improve the acceptance of alternative drive technologies among transport companies and their customers.

Based on the analysis of operational requirements and additional data, chapter 4.2 ‘Further technical development of components’ presents a perspective for the development of energy storage systems and shows options for minimising the energy demand. The possibilities of synergies through the shared use of existing rail infrastructures by battery electric buses and trolleybuses are evaluated and the effect of standardisation activities on the spread of emission-free drives is analysed.

Chapter 4.3 ‘Market potential’ discusses the question of how the market potential for renewable drives will develop in the medium term with regard to specific technologies. A conclusive forecast cannot be made today. As the analysis in chapter 4.2 shows, almost 20% of the routes at the TCs are longer than 300 km. Fuel cell buses can already meet this requirement, but in some cases they have even higher additional costs than battery electric buses, which cannot reach this range. It is therefore still necessary to promote battery and fuel cell buses in a way that is open to all technologies.

Finally, chapter 4.4 ‘Sector coupling’ looks at the long-term significance of emission-free drives in the context of the energy transition. For example, the batteries of buses, as mobile electrochemical storage units (or as stationary units in their ‘second life’), represent a short-term storage option for fluctuating generation of renewable energies. Technically, this is already possible, but there are still a number of regulatory hurdles to overcome (see chapter 4.1).

For fuel cell buses, the transformation of fluctuating renewable energy into hydrogen leads to a temporal decoupling of electricity procurement for hydrogen electrolysis and refuelling of the buses. By using electricity quantities that are absorbed by large hydrogen production plants (e.g. during windy periods), the overall efficiency of a renewable energy-oriented energy system can thus be increased. However, the combined efficiency losses of the individual fuel cell buses and H_2 generation are higher than those of the battery electric bus.

4.1. Options for action

Based on the results and findings of the accompanying research on buses, there are various options for action for policy-makers to facilitate the further spread of zero-emission drives. They can be implemented at the Federal and State level.

The following fields of action were identified in the area of electromobility in local public transport with regard to the future establishment of a self-sustaining market:

- Funding opportunities: Creation of financial incentives for the procurement of emission-free bus systems (vehicles and infrastructure), studies/concepts, R&D projects, etc.
- Environment, regulations & processes: Define minimum requirements for the use of buses in local public transport, which in turn are incorporated into regulations (e.g. CVD), control procurement processes via legal and regulatory requirements (e.g. CVD), simplify the processes for applying for subsidies for the procurement of vehicles and energy supply infrastructure
- Knowledge transfer and acceptance: Accumulation and dissemination of knowledge regarding alternative drive technologies and infrastructure systems of electric bus systems to increase the acceptance of the technologies among transport companies, public authorities and passengers

Funding of vehicles and energy infrastructure

Funding of vehicle procurement

With regard to the financial support of transport companies through state subsidies, it is important to strengthen and stabilise the market development and the market ramp-up. As shown in the profitability analysis, due to the additional costs of the use of zero-emission drive technologies now and in the near future, support for the necessary investments in vehicles and infrastructure (energy supply, workshops, possibly additional parking spaces) is still necessary. Thus, in addition to the funding of the additional purchase costs of emission-free and clean buses, the promotion of extended warranty services on key components can also play a role.

With regard to the vehicles, funding of the additional acquisition costs for zero-emission and clean buses should be continued and expanded as an investment cost subsidy. A funding guideline by BMDV was published in Q3 2021. Funding has been available from the BMUV since 2018. Particularly in light of the impact of the current pandemic situation, local public transport is in an uncertain situation due to lockdowns and contact restrictions, which makes long-term investment decisions even more difficult. Therefore, it is necessary to provide funding that is as comprehensive as possible, and continued over the longer term in order to ensure the switch to emission-free drive technologies in the long term and to succeed in establishing a self-sustaining market. At the same time, there is a demand on the part of the funding providers to reduce the future funding quotas after the expiry of current funding programmes, some of which have very high funding intensity. This leads to the challenging task that the providers of zero-emission buses and the associated charging infrastructure (see next section) have to achieve relevant cost reductions in the medium to long term.

Funding of infrastructure procurement

The funding of infrastructure, e.g. for acquisition costs, must also be considered in addition to vehicle funding. Special attention should be paid to separating the coupling of infrastructure funding from the funding of vehicles. This will make it easier to account for planning of the infrastructure for a broader future demand ramp-up beyond local public transport. For hydrogen, it is considered expedient to seek or create local and (supra-)regional synergies through the broadest possible use of hydrogen and the associated supply infrastructure (pipelines, H_2 refuelling stations, etc.), since such economies of scale make H_2 supply affordable. Thus, H_2 supply for other sectors besides local public transport must be approached in parallel, e.g. to supply other mobility applications (passenger cars, light and heavy commercial vehicles, rail, etc.) as well as other sectors such as industry, commerce/trade/services or private households via the existing gas infrastructure. In order to take into account increasingly complex hydrogen logistics and to be prepared for possible market scenarios at an early stage, the promotion of feasibility studies and initial pilot applications is a good way of evaluating the implementation of such an H_2 infrastructure both economically and technically.

The same logic applies to the larger-scale development of a hydrogen infrastructure as to the upgrading of the various electricity grid levels to supply local public transport and other users from other areas and sectors with electrical energy.

Funding research and development

Parallel to the funding of investment costs, there is still a considerable need for research and development of components and their integration into the overall system consisting of vehicle and energy supply infrastructure (charging/tank infrastructure).

The further technical development of components in terms of service life, assembly space, weight, production costs, etc. and the optimisation of their most efficient control and networking can play an important role in the future development of emission-free drives. Special attention must be paid to energy storage systems and the minimisation of energy requirements, both on the vehicle and infrastructure side.

Regulations and processes, environment

Clean Vehicles Directive

The CVD, which will come into force in August 2021, will create demand for these technologies through binding minimum procurement quotas for zero-emission buses (at least 22.5% by the end of 2025, and at least 32.5% from 2026). Further demand can be created by increasing the level of ambition with regard to the share of zero-emission buses within the framework of the future awarding of transport services by the local public transport authority

Consideration of full social costs/CO_2 price

Especially from the perspective of the public transport authorities, the external environmental costs (CO_2, pollutants, NOx, particulate matter, noise, etc.) should also be considered in the economic evaluation of the offers received and thus in the awarding of contracts. So far, these elements have been left out of a pure operating cost analysis. With the definition of a CO_2 price that actually has to be paid, a first step in this direction has been taken by policy-makers. However, the sensitivity analysis of the economic viability calculation shows that the current price level is not yet sufficient to have a real impact.

Simplification and acceleration of funding application processes

A simplified solution should be sought to reduce the current lead times and processes for applying for and disbursing subsidies. The current effort and time required to obtain funding are still a barrier to the increased use of zero-emission drive technologies. These application processes must precede the usual tendering process for the procurement of vehicles and infrastructure by the transport company (see also chapter 2.1.2). One option here would be that the application for funding and the tendering process for procurement can run simultaneously or at least partially overlap in time. This ‘parallelisation’ could result in a time reduction potential of up to 6 months.

Consideration of required lead times in awarding contracts

The public transport authority must consider lead times of at least 18–24 months for the application for subsidies when tendering for transport services, the planning and procurement of the vehicles as well as the construction of the necessary energy supply infrastructure. However, the current award practice sometimes only allows for 6–9 months lead time until the start of line operation. Much more lead time needs to be provided.

Extending contract periods for bus transport services

It would be desirable to extend the contract award periods in the light of the additional costs that result from the use of zero-emission drive systems for the transport company or the contracting authority as the purchaser of the transport service. This would enable the transport company to depreciate the not inconsiderable investments in vehicles, and especially in the necessary energy infrastructure over longer periods than the usual timeframes of up to 10 years as currently required by EU regulations. For example, analogous to rail transport, use could be made of the possibility under Regulation (EC) 1370/2007 to extend the term of the public service contract by a maximum of 50%, taking into account the amortisation period of the assets. This would allow the contract period for bus transport services to be extended to 15 years. This would require working towards an increase in the permissible depreciation periods for vehicles and charging infrastructure.

Adaptation of energy supply regulation

The regulatory framework for energy supply in particular needs to be further harmonised and adapted to the broadest possible use of the electricity and hydrogen energy sources in various applications and sectors. One example is the multiple use of charging infrastructure by buses, cars and city rail. Today, this leads to regulatory challenges. By making bus and car charging points accessible to third parties, e.g. provision of the rapid charging infrastructure at the ZOB by one transport company for use by opportunity charging buses of another transport company. As a result, the transport company that operates the charging infrastructure becomes the electricity supplier with all the consequences for its energy and tax classification. The energy-economic parameters do not yet reflect the sector-coupling processes of an integrated energy and transport transition that will be necessary in the future. One example is the use of existing DC electricity infrastructure, e.g. a streetcar or metro, for recharging BEV buses. Several individual stakeholders (e.g. Federal Grid Agency, DSO and TSO) still need to be coordinated for the acceptance of measurement and billing concepts for DC charging points, since, for example, no meters that comply with statutory measurement and calibration specifications are yet available for the DC input.

Another example of the need for standardisation or simplification of regulations results from the grid-serving operation of energy storage systems, as planned in the GUW+[63] project. The currently applicable, high regulatory requirements of electricity trading mean that economic operation of such a decentralised energy storage system is not possible.

63 See the overview of the contents of the R&D projects funded by the BMDV, which is available as a detailed report in the 'Electromobility starter kit'.

Source: Verkehrsbetriebe Hamburg-Holstein GmbH

Current technological developments and framework conditions must also be reflected in guidelines and specifications. For example, the licensing requirements for the storage of H_2 in a depot with 65 buses with an average H_2 tank size of 40 kg H_2, which provide for stockpiling of the average daily requirement of 20 kg per bus for 2 days, falls under the Hazardous Incident Ordinance according to the 12th BImschV, which is currently applicable from a storage quantity of 5 t H_2. In the upcoming revision of the EU Directive 2012/18/EU (Seveso III Directive), a corresponding increase in the limits for H_2 storage quantities should be requested.

Knowledge transfer and acceptance

In addition to the legal requirements and funding opportunities, attention should also be paid to the acceptance of the technologies among the general population, i.e. among the customers of the transport companies, as well as among the transport companies themselves. For the intended rapid market ramp-up, the topic of knowledge transfer and knowledge building among the various stakeholders (transport companies, public transport authorities) is therefore also a success factor that should not be underestimated.

This can be supported by target group-oriented information offers as well as through feasibility studies in the local context.

In order to strengthen acceptance and interest, it is also important to explain the environmental benefits of the use of low-emission buses. This way, the positive effects of lower emissions can lead to greater acceptance among the population and contribute to achieving global and local climate goals.

4.2. Further technical development of components

Statements on further technical advancements and market potential need to be based on analysis of operational requirements. In addition to chapter 2.1.1, about 2,800 schedules from 20 different transport companies stored in the in-house database IVIdat were analysed. Assuming the requirement to allow no or only insignificant changes in the operating procedures, the requirements for the ranges shown below are the result.

FIGURE 78 **Classification of operating distance into operating distance classes – solo buses** (basis: approx. 2,800 schedules)

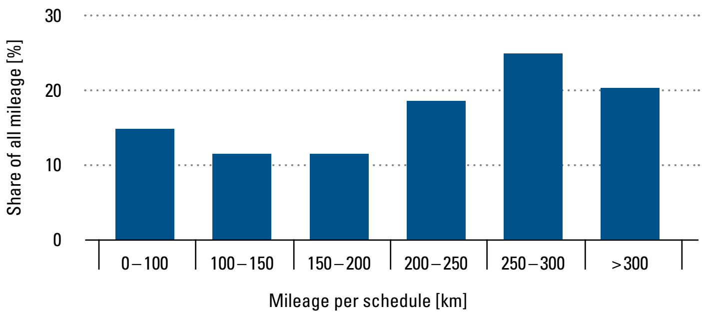
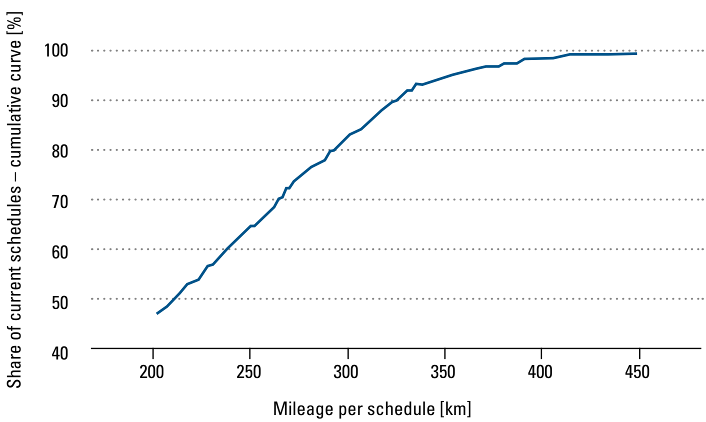


FIGURE 79 **Distance driven as a cumulative curve (excerpt) – solo buses** (basis: approx. 2,800 circulation schedules)



Vehicle schedules with a service length of more than 300 km account for almost 20% of all vehicle schedules. Only about 5% of all vehicle schedules have an operating distance of more than 350 km (Figure 79). The majority is below these requirements.

The operational requirements and the need to be able to use the batteries, which are still very expensive to purchase, for as long as possible result in various approaches for further developments that focus primarily on minimising the energy demand and monitoring batteries.

Due to their design, battery electric, fuel cell and hybrid trolleybuses are particularly suitable for the application of intelligent energy and power management systems. Such operating strategies are primarily aimed at

- the reduction of energy consumption through auxiliary units,
- the reduction of power peaks during the storage and retrieval of electrical energy, and
- reducing the energy throughput in the vehicle's batteries.

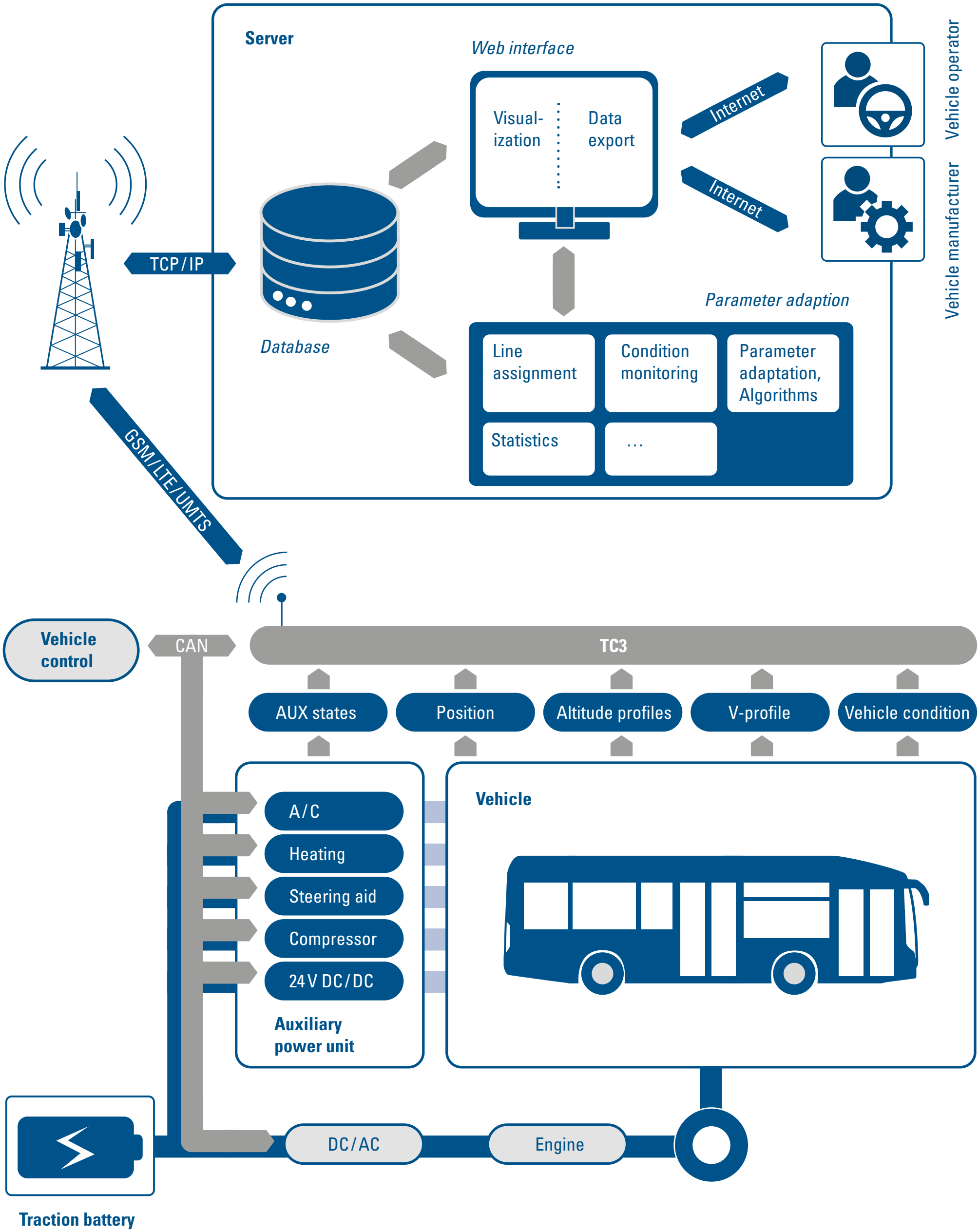
This results in increased ranges and a longer service life for batteries. For fuel cell buses, an additional target criterion is the stabilisation of the fuel cell, i.e. the avoidance of highly dynamic changes in performance, which in turn increases its service life.

There are also so-called range assurance functions (RAF), which initiate appropriate measures to reduce energy consumption in the event of a predicted failure so that a planned vehicle schedule can be achieved.

The basic structure of intelligent energy and power management systems is shown in Figure 80. Important for the understanding of such systems is their status as a so-called comfort or add-on function, which gives recommendations to the vehicle control, but leaves the control over all functions to the vehicle control systems, especially if they are safety-oriented.

The basic approach is based on the main operation of various auxiliary units when there is an excess of electrical power in the vehicle (braking, driving downhill). This avoids or minimises losses attributable to the storage and retrieval of electrical energy or its conversion into heat in braking resistors.

FIGURE 80 **Basic structure of intelligent energy and power management**

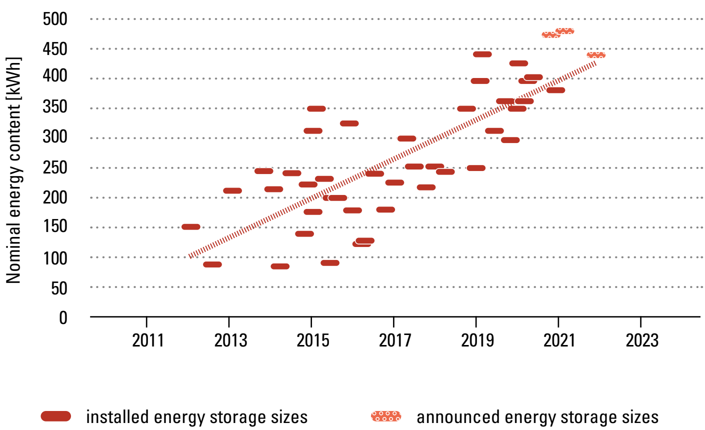


In order to be able to achieve the most energy-efficient operation of the auxiliary units, algorithms calculate suitable switch-on and switch-off points. The vehicle itself is able to determine its current geographical position and the scheduled route on its own and independently adjusts the vehicle control according to the optimised strategy.

Figure 81 below shows the development of HV batteries in solo battery electric buses based on the installed or announced battery sizes, expressed in their storage capacity (kWh).

Due to one-time effects (e.g. increase of the permissible total weight for battery electric buses), extrapolation of the values is not possible. However, if one assumes further, albeit less dynamic, development of battery cells based on today's dominant lithium-ion technologies, storage capacities of up to 550 kWh can be expected by the year 2025 and storage capacities of about 650–750 kWh by the year 2030. If new cell technologies such as solid-state batteries with even higher energy densities enter the market, even larger amounts of energy can be expected. However, their market maturity is not predicted until the second half of the decade, which is why vehicle and application concepts should be oriented towards an evolutionary expansion of existing cell technologies for the time being.

FIGURE 81 **Already installed (red) and announced (orange) HV battery sizes in solo battery electric buses**[64]



64 Source: IVI*dat*

HV batteries account for approximately a quarter to a third of the total investment costs for battery electric buses. If a replacement battery is included, the investment cost share increases to about half. In order to improve the economic viability and further reduce the environmental impact, it is necessary

- to increase the service life of the HV batteries or
- to put them to a second use.

Monitoring of HV batteries is necessary in order to detect problems with individual cells at an early stage and, if necessary, to replace them individually or in modules as early as possible.

Secondary use, e.g. as buffer storage in charging stations or in depots, requires seamless monitoring as well as a binding evaluation procedure adapted to the cell technology in order to be able to determine the degree of damage or ageing during use in vehicles.

Therefore, the development of monitoring systems with standardised and binding evaluation parameters (e.g. damage or wear indices) is essential.

Further considerations, which will not be dealt with in detail here, were made for

- Heating and air-conditioning systems (increasing energy efficiency)
- Compressed air systems (elimination in electrically driven buses, if possible)
- Vehicle control units with increased computing power for the implementation of CPU-intensive performance and energy management systems
- Drive motors (modular systems)
- Fuel cells (increased service life and cost reductions)
- Single-wire systems for hybrid trolleybuses (automation when stationary).

Rail infrastructure synergies

Synergies in the shared use of rail infrastructure are possible in the operation of battery electric buses, and theoretically also trolleybuses.

Almost 60 companies operate tram or light rail networks with a DC system in German cities. Moreover, there are four cities with a separate underground train system, two cities with a separate suburban railway system and three cities with trolleybuses. In these cases, 600 and 750 V direct current dominate as nominal voltage. The Wuppertal suspension railway and various funicular railways are also operated with direct current.

Direct use of an unregulated DC voltage is possible, but it requires a different vehicle architecture that, among other things, sets the charging current required by the battery management system (BMS). This is not a standard vehicle architecture based on charging current control on the infrastructure side.

Nevertheless, there are applications in which DC grids are used for recharging battery electric buses (e.g. in Hanover, Vienna or Prague).

In order to assess the potential in cities with massive rail DC grids, the grids in Dresden (DVB), Hanover (üstra) and Leipzig (LVB) were analysed with regard to the connectivity of charging stations to be installed at relevant terminal stops to the rail DC grid.

The investigated networks are transport companies with a relatively large share of light rail and tram services. They were deliberately chosen in order to limit the potential upwards. The lower potential in cities without railways with direct current supply is given anyway.

Source: Reutlinger Stadtverkehrsgesellschaft mbH

The following conclusions can be drawn from the results:

- Even in cities with a large light rail or tram network, only a small part of the lines can have all the charging stations needed for vehicle recharging connected to the DC supply of the light rail or tram.
- The potential for connectable charging stations is at least sufficient so that charging stations with DC voltage on the input side have a market potential.
- Vehicles designed purely for direct recharging at unregulated DC voltage sources have practically no market, provided the vehicles are operated according to the principle of opportunity charging.

Standardisation

Charging infrastructure/battery electric buses

Standardisation is deeply enshrined in various institutions at national, European and international level.

The charging infrastructure for battery electric buses and hybrid vehicles is well advanced with respect to standardisation which allows the following conclusions to be drawn about market development.

For the foreseeable future, there will be a mix of conductive charging systems that meet different requirements depending on the operating concept.

The conductive charging plug-in systems (see Figure 82) and docking systems (see Figure 83) have whole system standardisation with the exception of the pending standardisation of the available pantograph solutions (stationary and vehicle-mounted). The steadily increasing battery capacity for full chargers will also require a higher charging capacity in the future in grids with extended service periods in order to ensure the availability of the vehicles. For recharging at the depot, there is still the option of supplying the charging energy via an underfloor contact system as an alternative to plug-in or pantograph systems.

FIGURE 82 **Overview of standardisation of conductive charging via plug-in system**

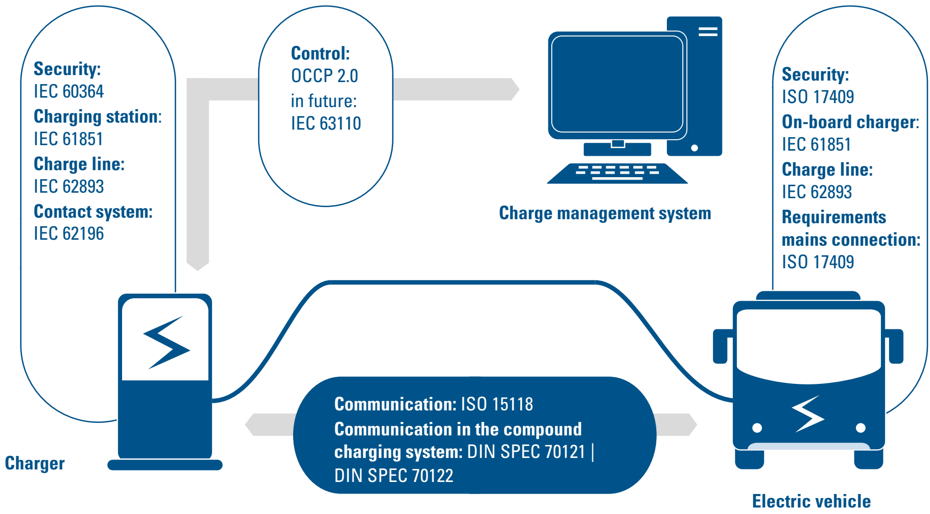
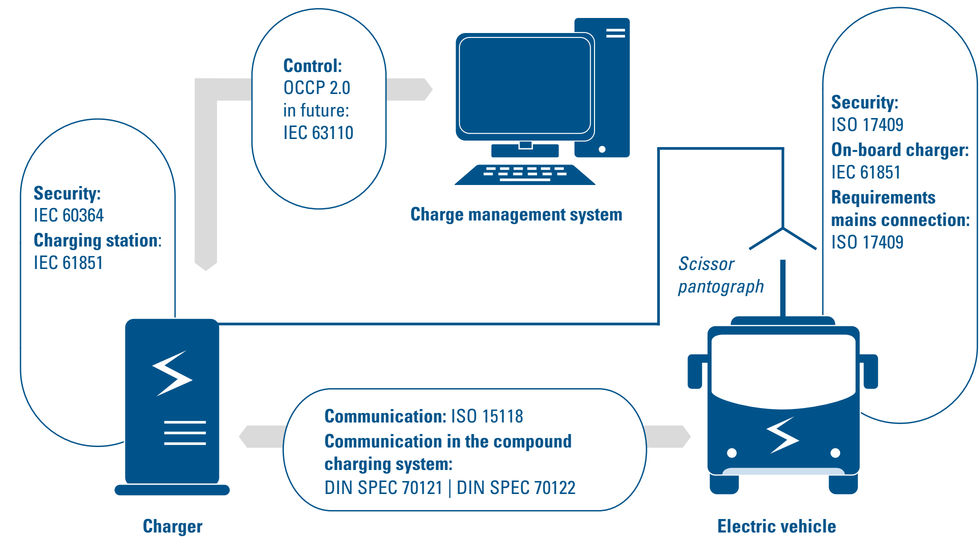


FIGURE 83 **Overview of standardisation of conductive charging via docking system**



More detailed information can be found in the detailed report on the standardisation of the energy supply infrastructure.

The overhead contact system (pantograph) can currently still be considered a niche market. However, it will play a more important role in the future due to the introduction of hybrid vehicles in this sector, which is why additional standardisation efforts may be necessary beyond the existing standardisations.

Inductive charging did not become established and will not play a significant role in the future. Further information on overhead line systems and inductive charging can be found in the detailed report on the standardisation of the energy supply infrastructure.

The currently very active development of depot and charging management systems (BMS) with accompanying standardisation efforts of the interfaces to charging infrastructure and vehicles indicates that uniform functional scopes are to be expected for the above-mentioned charging systems in the future, regardless of the charging system used. The docking system is better suited for processes in the depot that may need to be automated in the future (driving movements, charging processes), which would have to be controlled by the BMS.

Battery storage charging infrastructure
Source: Heidenheimer Verkehrsgesellschaft HVG (Transdev GmbH) 2019

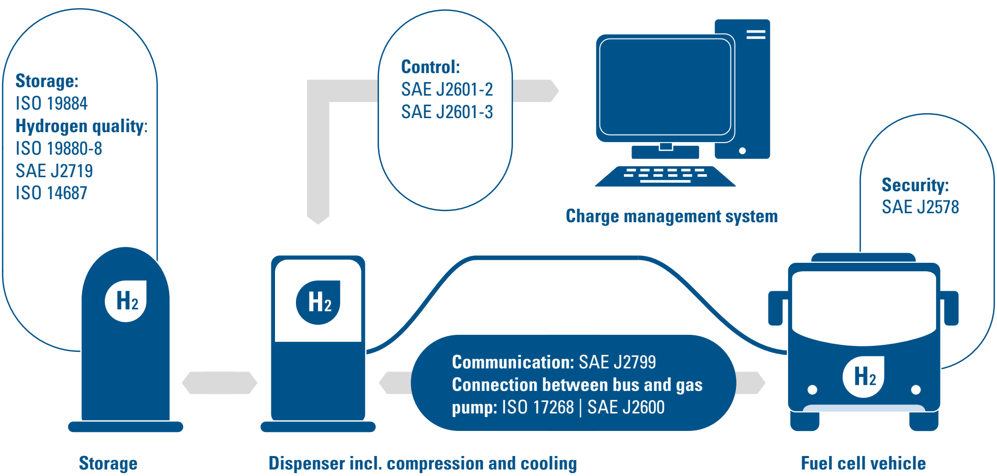
Hydrogen tank infrastructure/fuel cell buses

The advancing standardisation of hydrogen technology (see Figure 84) for refuelling buses allows the following conclusions to be drawn with regard to market development:

- A relatively advanced state of standardisation enables the planning of hydrogen infrastructure systems in compliance with standards.
- The existence of technical standards facilitates the development of technological solutions in accordance with technical guidelines and thus enables more system suppliers to enter the market.
- Documentation of system specifications becomes more comparable.
- Access to standards potentially reduces development costs and facilitates coordination with competent authorities.

The cost reduction effects associated with standardisation and the related increase in market partici-pants move hydrogen technology more rapidly towards more acceptable cost structures (see also detailed report on the standardisation of energy supply infrastructure for more information).

FIGURE 84 **Hydrogen Fuelling Standardisation Overview**



4.3. Market potential

The market demand for emission-free buses, especially for electrically powered vehicles, is increasing due to the increasing climate protection requirements. It is supported by the Clean Vehicles Directive and its procurement requirements, which are now enshrined in German national law. Since many smaller and medium-sized transport companies will shy away from a one-third mix (e.g. diesel, biogas and battery electric buses) when they are choosing the drive technology, an annual procurement quota of at least 50% for buses with zero-emission drive technologies can be expected from 2025 onwards.

How the resulting market will be distributed among battery, fuel cell and (hybrid) trolleybuses is mostly defined by the respective costs. For more information, please refer to the profitability analysis in chapter 2.5 .

In addition to the pure cost consideration, however, other barriers to entry for the transport companies can also be observed. They are mostly of a subjective nature and are primarily caused by the necessary infrastructure required in addition to a new drive technology.

From the authors' point of view, the market for zero-emission buses in Germany will be largely divided between battery and fuel cell buses. The split will essentially be determined by five factors in addition to the respective investment costs:

- Cost of hydrogen
- Availability of a public hydrogen refuelling infrastructure accessible to the transport company
- Acceptance of fuel-powered auxiliary heaters in battery electric buses
- Range of battery electric buses with or without purely electric heating determined by battery development.
- Opportunities for sector coupling (see 4.4)

In the medium to long term, so-called full chargers will prevail for battery electric buses, which will only be charged at depots. For opportunity charging buses, there will be a transitional phase, which, in addition to battery development, will mainly be determined by political requirements regarding purely electric heating. In all likelihood, advancements in battery development will make it possible to serve longer and more demanding routes with depot charging buses in the future. Ideally, they will be using a purely electric heating concept for the battery electric bus in order to enable entirely locally emission-free operation.

From today's perspective, hybrid trolleybuses will remain a niche drive technology in Germany, at least in the short to medium term, although it is a robust and proven technology. The main reason for this is the often unacceptable overhead line infrastructure in urban planning and the associated implementation periods of at least 5–7 years, in some cases even longer. The possibility of hybridising trolleybuses to operate sections without overhead lines offers new opportunities for a broader acceptance of the technology.

4.4. Sector coupling

One of the great challenges of the energy transition is the fact that wind and solar energy are variable. This variability becomes a greater issue and must be balanced even more as the share of renewable energy in the power supply increases. If possible, this needs to be done without fossil power plants. To ensure a constant supply, short-term storage (such as electrochemical batteries) and long-term storage (such as pumped storage power plants and hydrogen storage) must then balance generation and demand. The key to managing this fluctuating electricity production from renewable energies is the possibility of sector coupling. This means using renewable electricity outside the energy sector, for example to decarbonise transport or even entire industries or heat production.

The batteries of buses as electrochemical storage units represent such a short-term storage option. However, since they are primarily intended as energy storage devices for driving, the timeframe for grid- and system-serving storage work is limited to the charging timeframes. Since these must be sufficiently long, this will only be an option for depot charging buses. Longer rest times, even during the day, may arise for buses, e.g. in regional transport, with pronounced peaks of use in school transport in the morning and midday hours, so that participation in the energy market outside these timeframes can be considered. The basic prerequisite for this is an appropriately equipped charging infrastructure that enables such participation in the energy market (e.g. bidirectionality, flexible controllability). To this end, some standards still need to be created or refined (e.g. bidirectionality). These standards are currently being addressed in the national and international standardisation committees.

This is also one of the reasons why, in practice, only positive charge control has been used so far, although it would technically also be possible to feed power back into the grid from the vehicle batteries. Generally, the required load and charging management must be able to control the charging power. In the future it must also control the feed-in power depending on various parameters such as vehicle disposition, local grid load, correlating renewable energy input or price signals from the energy markets.

The charging timeframes of the opportunity charging buses on the route, on the other hand, are deliberately as short as possible and therefore do not allow for controlled charging that could also compensate for the volatility of power generation. Energy is needed here when drivers' break times allow for recharging. This schedule cannot take account of the origin and quantity of the electricity that is supplied. As long as the majority of electricity generation is not yet based on renewable energies, this charging behaviour may even lead to a higher share of fossil-based electricity generation.

In some cases, stationary second-life storage facilities are being built. They are traction batteries that no longer have sufficient capacity for driving, but still have sufficient storage capacity for pure storage operation. The use of stationary batteries can have a supporting effect in capping peak loads in depot operation. However, significant additional investments are still necessary today to integrate the discarded traction batteries of the buses into stationary battery storage systems. Therefore, the economic viability of such a solution is currently still in question.

Through controlled charging of the buses in the depot, load peaks can be smoothed and additional grid capacities for pure peak power can be optimised accordingly.

Operators sometimes offer load management as part of their non-regulated third-party business, jointly with the operation of the charging infrastructure, for example if this is not regulated by the local internal electricity market grid directives.

The grid-serving operation of a depot charging infrastructure is also already possible today from a technology perspective. However, the regulatory instruments that enable the operator of the charging infrastructure to generate additional revenues through grid charging management are lacking. From the perspective of the distribution system operator, however, there is no need for this yet, even in the medium term. This is different for the transmission system operators (TSOs), for whom there is a developed balancing energy market.

Battery-electric and hydrogen-based bus systems differ considerably at this point, as the flexibility is much more strongly determined by the operating parameters of the battery electric bus and the charging time than for a fuel cell bus supplied by a grid-serving electrolysis system. In this case, hydrogen, which is much easier to store than electricity, represents a decoupling element.

Generally, hydrogen production through electrolysis can be managed so that it is mainly produced when more renewable electricity is available than is needed in the grid. These amounts of electricity have so far been curtailed, with operators of the renewable energy plants compensated for not producing electricity but rather for switching off their plants. As long as the hydrogen production plants are directly connected to the renewable generation plants or are at least on the same side of a grid bottleneck area, hydrogen production can contribute to an optimised utilisation of the plants and thus to an indirect economic cost reduction.

The supply source for delivered hydrogen that is used in the economic viability calculation assumes centralised hydrogen production, which is directly connected to corresponding wind and solar parks.

The implementation of the German Hydrogen Strategy and the projects currently submitted as part of the European Hydrogen IPCEI Programme stipulate that a large number of larger hydrogen production sites will be established in Germany in the near future.

For transport companies, the supply chain for green hydrogen will therefore become much more attractive in the future. In turn, projects planned in the region will increasingly approach transport companies, as a sufficiently large fleet of fuel cell buses represents an attractive hydrogen requirement for the economic viability of a hydrogen production plant. Very interesting synergies can especially arise in areas, where municipal companies operate the transport companies and the renewable energy production. Within the HyLand programme, there are various consulting and funding offers that municipalities and transport companies should examine for themselves.

5 Annex

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List of Abbreviations

AC	Alternating current
ARe	Accompanying Research
BAFA	German Federal Office of Economics and Export Control (Bundesamt für Wirtschaft und Ausfuhrkontrolle)
BattG	German Battery Legislation (Batteriegesetz)
BEHG	German Fuel Emission Trade Act (Brennstoffemissionshandelsgesetz)
BEV	Battery electric vehicle
BEV DC	Depot charging bus (the loading process takes place at the depot)
BEV OC	Opportunity charging bus
BImSchG	German Federal Immission Control Act (Bundes-Immissionsschutzgesetz)
BMDV	German Federal Ministry for Digital and Transport (formerly BMVI) (Bundesministerium für Digitales und Verkehr)
BMUV	German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (formerly BMU) (Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz)

C	Charge rate [kW charge power / kWh battery capacity]
Capex	Capital expenditures
CCS	Combined charging system
CGH_2	Compressed gaseous hydrogen
CIS	Charging infrastructure
CMS	Charge management system
CNG	Compressed natural gas
CVD	Clean Vehicles Directive of the European Commission
DC	Direct current
DMS	Depot management system
EEG	German Renewable Energy Sources Act (Erneuerbare-Energien- Gesetz)
EFBEL	Extended accompanying research for the operation of energy-efficient city buses (2013 – 2016) (Erweiterte Forschungsbegleitung für den Einsatz von energieeffizienten Linienbussen)
EnWG	German Energy Act (Energiewirtschaftsgesetz)
FC	Fuel cell
FCH JU	Fuel Cell and Hydrogen Undertaking, Public-Private Partnership between the European Commission and Industry
FC REX	Fuel cell range extender
FZV	German vehicle-registration-ordinance (Fahrzeugzulassungsverordnung)
GHG	Greenhouse gas
GtL	Gas to Liquids
H_2	Hydrogen
HOBus	Hybrid Trolleybus (Overhead catenary bus with battery storage which allows operation without catenary)
HP	High pressure
HRS	Hydrogen refuelling station
HPC	High power charger
HV	High-voltage
WG bus	Working Group 'Innovative drivetrains for buses'
KBA	German Department for motor vehicles (Kraftfahrtbundesamt)
KSG	German Climate Change Law (Klimaschutzgesetz)
LH_2	Liquid hydrogen
LIB	Lithium-ion battery
LNG	Liquified Natural Gas
LP	Low pressure
LPT	Local public transport
LSV	German Charging Station Ordinance (Ladesäulenverordnung)

LTO	Lithium-titanium-oxide
MP	Medium pressure
NIP II	National Innovation Programme Hydrogen and Fuel Cell Technology Phase II of the federal German Government
NMC	Nickel-manganese-cobalt
NOW	German National Organisation Hydrogen and Fuel Cell Technology (Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie)
NOx	Oxides of Nitrogen
OBus	Trolleybus (Overhead catenary bus)
OEM	Original equipment manufacturer
Opex	Operating expenses
OS	On-site
PV	Photovoltaics
PEM	Proton exchange membrane
PM	Particulate matter
PPA	Power Purchase Agreement
R&D	Research and development
RED II	Renewable Energy Directive II of the European Union
SoFi	Sphera’s web-based software tool for collecting and analysing vehicle operating data
SORT	Standardised on-road test cycles
StromStG	German Electricity Tax Act (Stromsteuergesetz)
StromStV	German Electricity Tax Ordinance (Stromsteuerverordnung)
T	Trucked-in hydrogen
TC	Transport company
TCO	Total Cost of Ownership
TRL	Technology readiness level
VDV	Association of German Transport Companies (Verband deutscher Verkehrsunternehmen e. V.)
WG	Working Group

6 Further Information

This final report and the following publications of the accompanying research on buses can be found on NOW's electromobility starter kit at https://www.starterset-elektromobilität.de/

Publications from the accompanying research on buses and the working group 'Innovative drivetrains for buses'

Project overview 2020/2021 of zero-emission buses in Germany funded by BMDV and BMU

Market / funding overview Bus 2020/2021

Guide for buses with alternative drive systems

https://www.starterset-elektromobilität.de/Bausteine/OEPNV/

eBusTOOL

Online decision-making aid for transport companies for the selection of buses with alternative drive systems, taking into account the specific operating conditions on site.

https:// www.ebustool.de

Municipal electromobility concepts 2021

Legislative Map ‘electromobility in local public transport’ 2021

Electric bus projects in Germany

Project overview of the Association of German Transport Companies (VDV) on electric buses:

Available at:
www.vdv.de/e-bus-projekt.aspx

Project overview page of the BMU

https://www.erneuerbar-mobil.de/projekte

Further information and assistance for the Introduction of H_2/FC buses

Introduction of hydrogen buses in public transport

https://www.starterset-elektromobilität.de/Aktuelles/broschuere-einfuehrung-von-wasserstoffbussen-im-oepnv

Electric bus projects in Europe

- JIVE and JIVE 2
  current demonstration projects on H_2/FC buses co-funded by the FCH JU.

  JIVE: https://www.fuelcellbuses.eu/projects/jive
  JIVE 2: https://www.fuelcellbuses.eu/projects/jive-2

- Fuel Cell Bus Europe
  Information on H_2/FC bus projects in Europe incl. explanations on technology, driving data, etc.
  https://www.fuelcellbuses.eu/

- Clean Bus Europe Plattform
  Initiative of the European Commission to support the market ramp-up of zero-emission bus technologies under the Clean Bus Deployment Initiative coordinated by UITP as part of the APOLLO-EU project.

  www.cleanbusplatform.eu

- ZeEUS
  Demonstration project on BEV, trolley and plug-in hybrid buses, completed

  https://zeeus.eu/

  eBus Report #2,
  Available at:
  http://zeeus.eu/uploads/publications/documents/zeeus-ebus-report-2.pdf

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