

Bus 4.0: On the path to zero tailpipe emissions, low noise and highly energy efficient public Transport - experiences and results from the operation of public transport buses with hybrid and battery electric drivetrains in Germany

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Summary

For bus based public transport recent developments show a variety of options for fuels and propulsion technologies. To determine the fuel/ propulsion system technology which is most beneficiary for the community and the bus operator, the involved stakeholders need to understand a wide range of aspects, such as the current status of the available technologies and its performance with regard to e.g. energy efficiency, environmental impact, total cost of ownership, requirements with regard to skill level of maintenance personnel etc.. To provide these learnings and information a consistent and transparent assessment framework for the evaluation of electric driven urban city buses and its underlying monitoring scheme is presented, including selected results and conclusions from multiple lighthouse projects where it was applied.

Keywords: BEV (battery electric vehicle), bus, cost, emissions, energy consumption, HEV (hybrid electric vehicle), public transport

1 Introduction

Where bus fleets of local public transport (PT) are concerned, diesel-powered buses have been the industry standard for decades. However, against the backdrop of increasing challenges regarding air quality, noise reduction and climate protection in inner cities there is a growing interest in alternative drive trains powering the people's ever-growing mobility needs. In big cities in particular, intensive efforts are being made to reduce the tailpipe emissions of public transport bus fleets. To this end, in Hamburg, for example, the city administration took the decision that only emission-free public service buses will be purchased from 2020 onwards. In the process, the (partly) electrification of the drive trains of local transport buses represents a promising technological option for a low emission or emission-free future for the road-bound local public transport networks.

Nowadays numerous transport companies have introduced respectively are introducing buses with diesel hybrid, fuel cell and electric drives as part of sponsored projects. The results and experience gained in the process are being documented and evaluated as part of a joint taskforce initiated by the German federal ministries of Transport (BMVI) and for the environment (BMUB) entitled "Innovative Drivetrains for road-bound urban public transport" (Working group (WG) Bus). It serves as a platform for the exchange of information and experiences between transport companies, manufacturers, research institutes and the founding federal and also state ministries. The WG Bus is pooling the results of both the individual research

projects and the federal programme supporting the market entry of alternative drivetrains for urban buses. The various research and monitoring activities, which have been carried out, aim at evaluating the technological readiness level of the (partly) electric drivetrain technologies. They also are intended to verify the actually achievable environmental and climate-protection benefits that will come with a wide spread introduction of these technologies.

The focus of the WG Bus has so far been on diesel hybrid and battery electric buses, however in light of their open approach for all technologies, it is envisaged to also include other electric drive technologies such as fuel cells and hybrid trolleybuses in future.

2 Evaluation Approach

The analyses of WG Bus are based firstly on the long-term collection of data from the daily operation of the monitored buses that is used to track the status of the deployed technologies and to monitor how they developed over time since January 2013. Secondly, dedicated measurements on fuel consumption, emissions and noise were carried out under specific test conditions, e.g. within the framework of the EFBEL project¹. In addition, the data is being supplemented by the individual accompanying research activities of the various R&D projects of the different funding ministries. In order to evaluate the innovative technologies they are benchmarked against an established reference technology, which is the diesel internal combustion engine. Hence it is of great importance to correlate the data with that of corresponding diesel reference vehicles.

From January 2013 to December 2015, data from a total of 219 local transport buses from 24 operators was collected. These comprise 151 diesel hybrid, 3 plug-in hybrid and 16 battery buses. 49 diesel buses were also included in the study as conventional reference vehicles. For the diesel hybrid buses there were three types of drive technology in use: serial, parallel and power split hybrid drives in both rigid buses (12m) and articulated buses (18m)². In terms of the electric buses there were 4 midi buses with overnight charging capability as well as (newly introduced in 2015) 8 rigid and 4 articulated buses, which are recharged several times en route (opportunity charging). Opportunity charging is predominantly done contact free, i.e. via induction. However there are various conductive charging systems employed alongside this.³ In total there is operating data for over 24 million kilometres for the various bus systems (see Figure 1). For the hybrid and diesel buses in particular there is a solid and extensive body of data. The distance driven by the battery electric buses highlight in a way the still limited experiences with this rather new drivetrain technology in comparison to the diesel hybrid buses.

¹ EFBEL: “Extended Research Supervision for the Deployment of Energy-Efficient Public Service Buses in the Rhine-Ruhr Transport Authority”. Coordinated by ika, RWTH Aachen, sponsored by BMVI, 2013 - 2016.

² Serial hybrid: 20 rigid (12 m), 51 articulated (18 m); power-split hybrid: 10 articulated; parallel hybrid: 56 rigid, 17 articulated

³ As well as conductive opportunity charging en route, conductive overnight charging in the depot is also carried out via plug connection, usually with a lower power level compared to the opportunity charging.

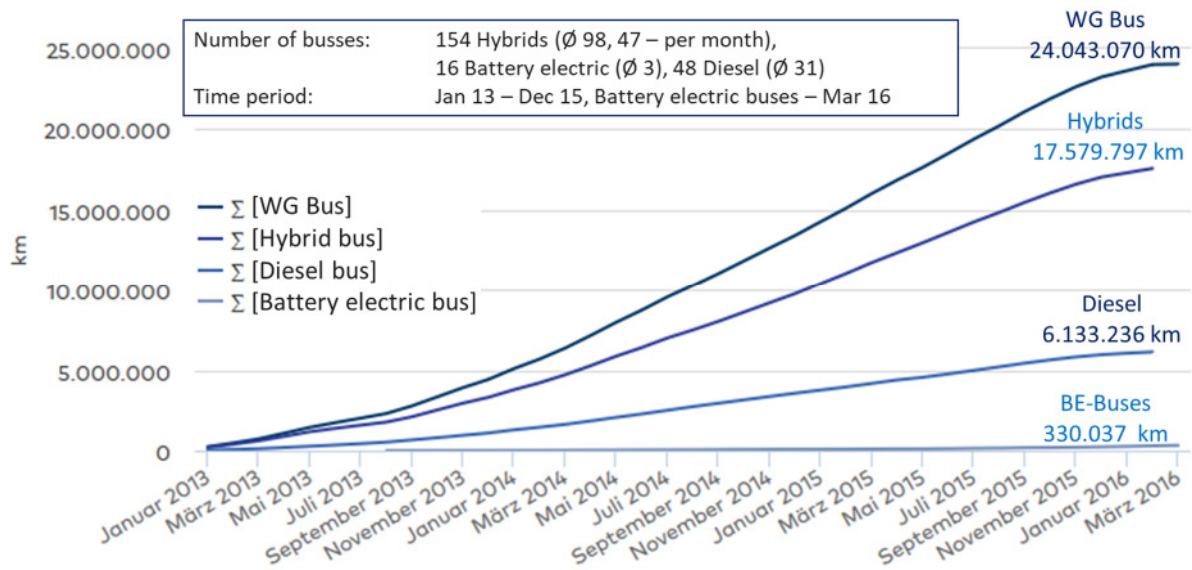


Figure 1: Driven distance of the different monitored bus types [8]

The innovative bus systems are evaluated across five categories which have been mutually decided by the participants of WG Bus and which cover the most relevant topics for a prospective market launch. By means of the evaluation criteria selected for each assessment category (see Figure 2), the technical and operational performance as well as the environmental effects of the buses are evaluated in comparison to conventional diesel buses.

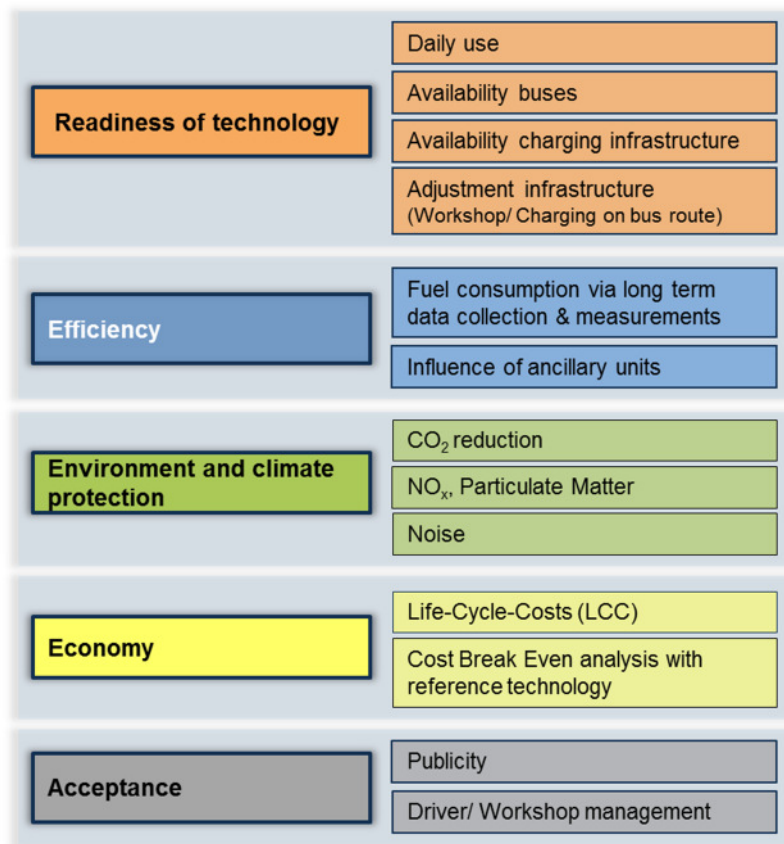


Figure 2: Assessment categories and evaluation criteria of WG Bus [2]

Profitability is currently only being considered for diesel hybrid buses. For battery electric buses it is too early to make any reliable assertions on the matter as the technology is still at a relatively early stage. While the first results on reliability, energy efficiency and operational performance (see below) can already be presented, the learning curves still have to be established over increasingly longer periods of operation for the battery electric buses. This is also true with regard to the costs of vehicles, infrastructure, operation etc. meaning that the initial focus here is on achieving a higher level of technological maturity so that more reliable assertions with regard to profitability can then be made on that enhanced data basis.

Alongside the techno-economic criteria, the employees' (drivers and workshop employees) acceptance of the operational changes related to the new drive technologies (e.g. the introduction of opportunity charging in regular operation), the general operating procedures (e.g. the deployment of the buses only on certain selected lines) and employee qualifications (esp. with regard to high-voltage technology) are being investigated.

3 Technological readiness

Diesel hybrid buses have been in operation for the past 5 years and can now be regarded as tried-and-tested vehicle concepts, which by and large cover the demands of the regular route services. Across the various drive technologies their availability⁴ over the last few years has continually increased, and their numbers are increasingly approaching those of conventional diesel buses at an average of 83%, while the availability number of rigid parallel hybrid buses, for example, is at 92%, which is fully comparable of their conventional diesel counterparts. By contrast, other vehicle systems such as serial articulated buses, with an average availability of 74%, exhibit potential for further improvement.

It is worth noting that causes of outage are predominantly found in conventional vehicle parts (10% loss of planned operating hours) and not in the hybrid drivetrain (5% downtime with reference to the planned operating hours).

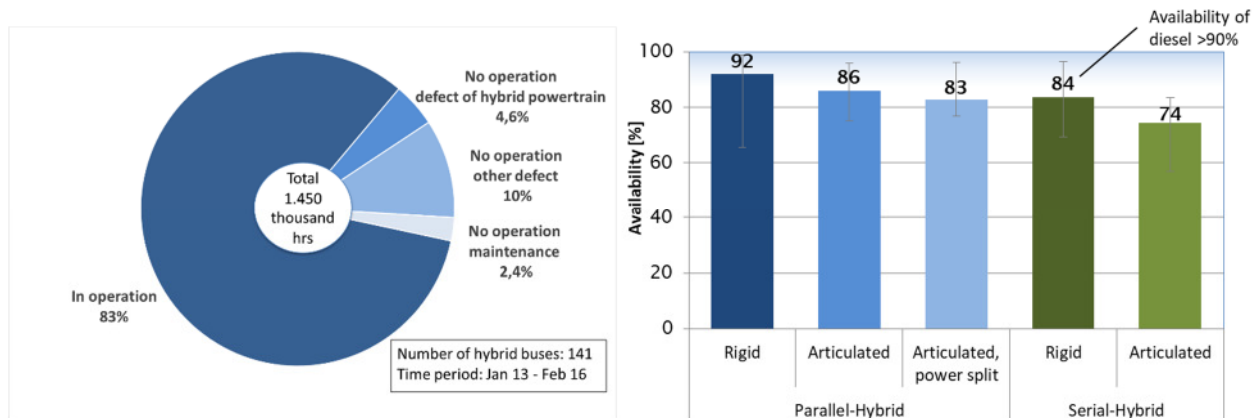


Figure 3: Availability of diesel hybrid buses by operational status and drive train technology [8]

As can be seen from Figure 4, it is apparent that after a service life of more than five years in some cases, there has been no noticeable decline in availability as a result of ageing.

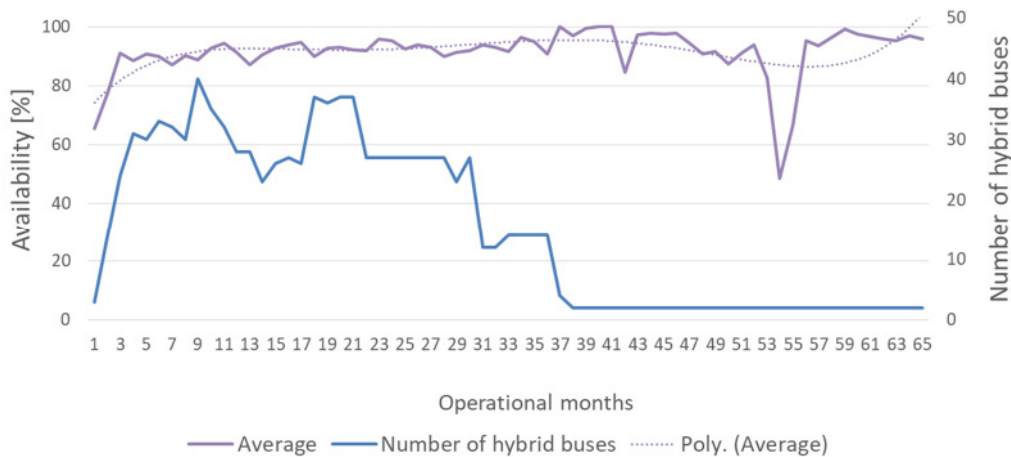


Figure 4: Availability of diesel hybrid buses over operational service time – example of rigid parallel buses [8]

With respect to preceding observations [see 1; 4; 6] a further improvement in the average availability of hybrid buses can be observed, and accordingly the monthly distance driven of diesel hybrid buses is

⁴ Availability is calculated using operating hours performed (actual operating hours) in relation to planned operating hours. Defects and servicing come under the heading of “not available”. Accidents and damages caused by vandalism are not taken into account when calculating availability.

developing positively and currently stands at 4,700 km / month at an average of 23 service days per month. In comparison the distance driven of the observed diesel reference buses adds up to around 5,300 km / month with 25 service days per month.

As regards to battery buses, midi-buses with overnight charging show an average availability of 71% for the period from August 2013 – March 2016 (see Figure 5). If one observes the last 18 months, the achieved average availability of almost 80% amounts to a clear improvement in availability. For the 12m and 18m buses with inductive charging continuous data is now available from regular route services since July 2015. As of March 2016 the mean availability of the 12m buses is around 76%, while the 18m buses are displaying a comparable level of availability.

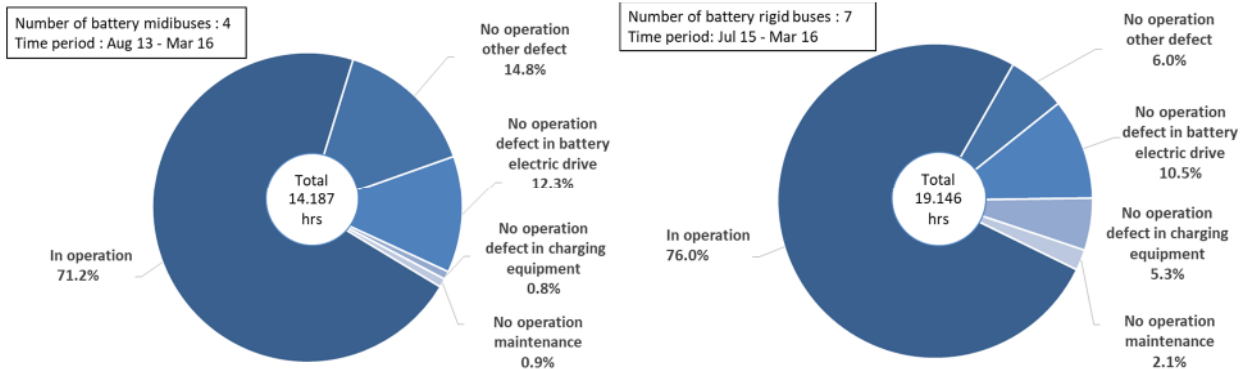


Figure 5: Distribution of availability of battery electric midi- (< 12m, left) and rigid (12 m, right) buses [8]

These availability values also include downtimes due to defects in the loading infrastructure (1% for midi-buses or 5% for rigid buses). Defects in the battery electric drive are responsible 10% respectively 12% of outages, depending on the bus type. The reliability of the charging process also needs to be improved. Initial experiences have shown that the percentage of successful charges is not yet at the required level for continuous and stable route service. With the new technology and the low vehicle numbers, issues such as the insufficient availability of replacement parts are to be expected and consequently result in higher downtimes.

Due to the lack of top-up charging and the resulting limited range, the daily driving distance of midi buses with only 103 km / day, are lagging behind rechargeable buses which travel an average of 149 km / day. The monthly driving performances are accordingly lower at 1,760 km / month (midi-buses) and just under 2,600 km / month (rigid and articulated battery electric buses). Battery electric buses are currently deployed for 17 or 18 days per month, predominantly on demonstration routes, which have been specifically selected for the buses with opportunity charging due to the required recharging facilities which are to be installed along the route.

The low distance driven of battery electric buses illustrates the still existing gap of the new technology compared to diesel hybrid buses. On a positive note, two operators are already deploying the battery electric buses on a daily basis and are achieving driven distances of up to 4,600 km / month which is comparable to that of conventional diesel buses. Depending on the respective operating experiences, the plan is for the remaining operators to accordingly increase the daily service time of their battery electric buses.

4 Energy Efficiency

The potential to increase energy efficiency and to save fuel are key motivations for the use of (partly) electrified drivetrain technologies in urban transport buses. By the possibility to recover part of the braking energy by means of regenerative braking and by electrifying auxiliary units (e.g. air compressor, power steering pump, compressor for air conditioning) it is possible to significantly increase the vehicles' energy efficiency.

In light of the fact that the achievable fuel savings are in general heavily dependent on the given operating conditions (topography, route characteristics, climatic conditions) and by the type of hybrid bus in use, an average fuel saving of almost 13% could be achieved across all monitored buses and operating conditions

for the period under review. Depending on the drive technology and bus size, average consumption savings of between 4 and 23% are attainable (see Figure 6), where the indicator bar in each case shows the bandwidth of fuel savings which have been achieved for each individual route. Accordingly, the consumption savings for rigid and articulated buses with parallel-hybrid drive (the latter also includes values for articulated buses with power-split hybrid drive) are on average a good 10% to well over 20%. The serial articulated buses in operation still have room for improvement with regard to the energy demand for the heating of the passenger cabin which (over)compensates for fuel savings in the drivetrain at low external temperatures and in some cases even results in over-consumption; this is elaborated in more detail in Figure 7.



Figure 6: Average fuel savings achieved by different diesel hybrid bus types [2]

Detailed investigations into the operating conditions [see 2; 5] proved that in the case of diesel hybrid buses, topography has the biggest influence on fuel savings. Here, in particular, the amount of longer, uninterrupted stretches with steep downhill or uphill slopes, is relevant. Apart from parallel hybrid buses with battery storage devices which were only marginally influenced by uphill stretches, hybrid buses should primarily be deployed on routes with as few steep inclines as possible (maximum 20 % of the route with a gradient of > 25 m / km) because in the case of demanding topographies the achievable fuel savings in comparison to conventional diesel buses are negated to a significant degree compared to routes with short up- and downhill stretches. On the other hand, the influence of the mean cruising speed on fuel savings proved to be much lower, while higher savings tend to be achievable on routes with a lower average cruising speed.

Based on the monthly mean temperatures, the influence of the external temperature on relative fuel savings was investigated. In Figure 7, using the example of serial articulated hybrid buses on various routes, it is apparent that with regard to diesel fuel consumption and, where applicable, additional diesel separately used for heating, the highest savings are made at mid-range temperatures. By contrast, mean ambient temperatures of over 20°C lead to a clear decline in possible fuel savings, while very low temperatures in particular can, in some cases, result in over-consumption by the hybrid buses. The reasons for this are the reduced contribution of the main diesel engine towards passenger cabin heating due to the lower usage of waste heat, as well as the additional fuel consumption by the auxiliary heaters which were installed to combat this effect and which usually are not freely controllable. As a result, there is significant potential for an improved efficiency through the optimisation of passenger cabin heating in the winter months.

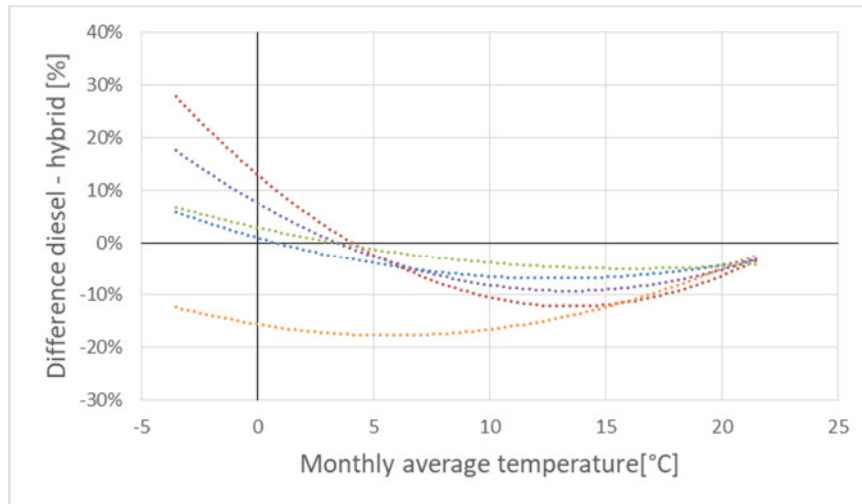


Figure 7: Relative fuel consumption of serial articulated hybrid buses vs. conventional diesel buses on different routes as a function of the monthly average ambient temperature, IVI [2]

For a variety of operational reasons there is currently no directly comparable consumption data available between battery electric buses and diesel buses yet. However, using the available consumption measurements it was possible to analyse the influence of the ambient temperature on energy efficiency. For battery electric buses the heating of the passenger cabin presents a challenge in the winter months. Due to the lack of waste heat from the non-existing combustion engine, the energy required to heat the passenger cabin during the winter months is of the same magnitude as the energy required for the mechanical propulsion, as can be seen in Figure 8, which shows the example of battery electric bus with a diesel-powered auxiliary heating system. Also in this example the additional energy requirements of the electric air conditioning (32 kW output) for July 2014 as well as for July and August 2015 can be clearly seen by reference to the increased energy consumption. However with an over-consumption rate of close to 20%, it is still much lower than the heating energy requirements during winter times.

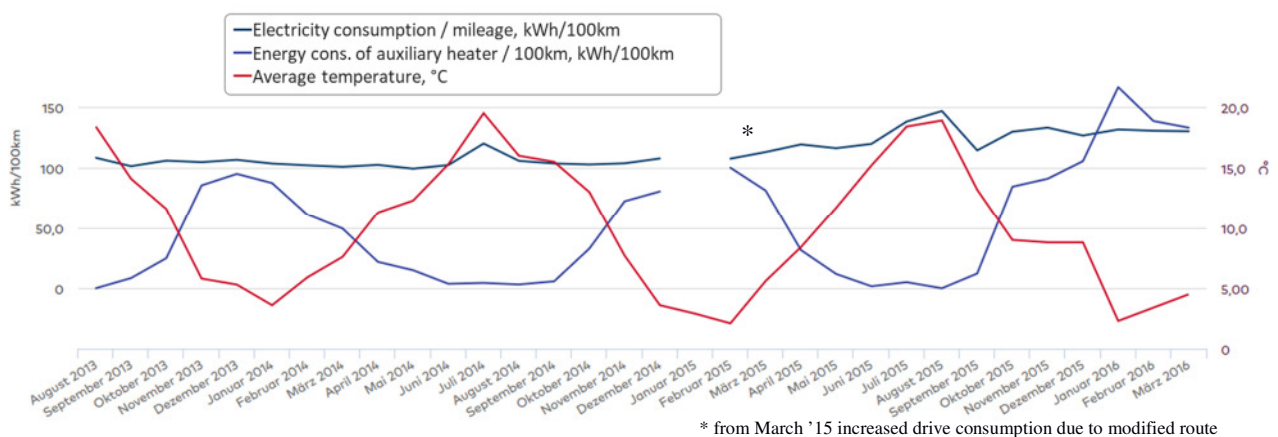


Figure 8: Energy consumption of battery buses with diesel fired cabin heating as a function of ambient temperature [8]

The first available electricity consumption data for battery electric buses with an electrical heating system for the passenger cabin in Figure 9 also shows an increase in overall energy consumption of around 60% for the (very mild) winter months of 2015. As the passenger cabin in these buses is not air-conditioned, their energy consumption above approx. 15°C ambient temperature remains rather stable.

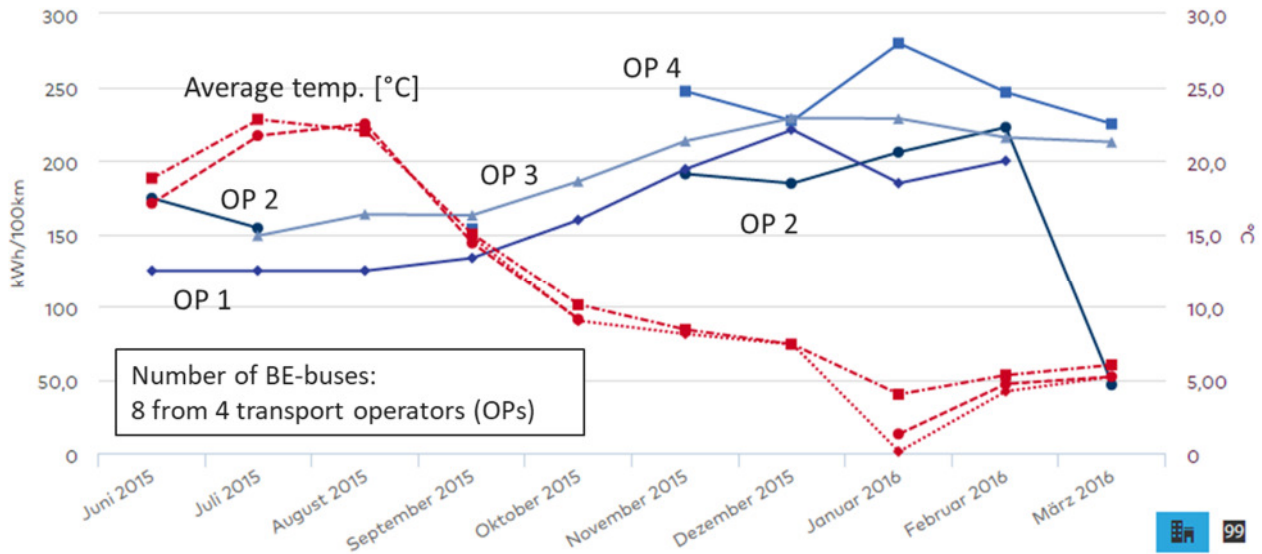


Figure 9: Energy consumption of battery electric buses with electrical cabin heating as a function of ambient temperature (measured on mains side, i.e. incl. charging losses) [8]

The charging efficiency of the inductive and conductive charging systems in operation is currently around 90% and 92-95% respectively, measured between the mains connection to the grid and the battery input terminal.

A more detailed analysis of the route characteristics and the average speed on the energy consumption of battery electric buses is not yet possible with the currently available database. A preliminary analysis of the available data points to the fact that in the case of battery electric buses the route characteristics seem to have a lower influence on energy consumption than it was the case for diesel hybrid buses. This may be due to the increased potential for recovering braking energy thanks to the higher energy capacity of the high-voltage batteries that are used in battery electric buses.

5 Ecology and Climate Protection

With regard to the targeted reduction of CO₂ emissions in the transport sector and compliance with EU limit values concerning air and noise pollution in inner cities, the use of innovative low-emission or emission-free drives in buses in local public transport networks offer a viable contribution to the .

From the beginning of 2013 to the end of 2015, WG Bus saved around 1 million litres of diesel through the operation of its 154 hybrid buses, so in climate protection terms around 3,000 tonnes of greenhouse gas emissions (GHG in CO₂ equivalents) were avoided. The potential of the technology can be illustrated by means of a rough estimate (see Figure 10). If hybrid buses made up 10% of the city bus fleets in Germany, there would be an annual savings potential of around 40,000 tonnes of CO₂ which is the equivalent of the greenhouse gas emissions of a town with 5,000 inhabitants.

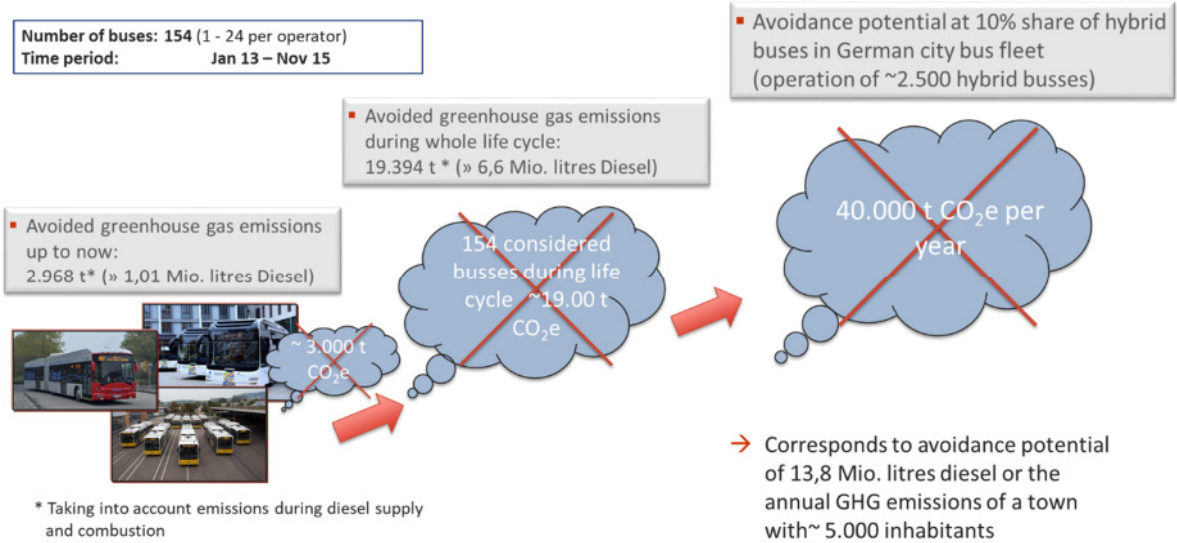


Figure 10: Fuel savings and greenhouse gas emissions of diesel hybrid buses [2]

As there is no comparable consumption data available for comparing battery buses to diesel buses, an analysis of the greenhouse gases avoided by their use has not yet been possible. However, initial basic studies were already able to be carried out. Alongside energy consumption, the greenhouse gas balance of electric buses in particular is directly dependent on the supply of the electrical energy used, because electricity from renewable resources exhibits a much lower intensity of greenhouse gases and pollutants than electricity from fossil fuels such as coal or natural gas. The German electricity mix in 2014 had a GHG intensity of 576g CO₂e / kWh, while the production of electricity via renewable sources in the German electricity mix (wind, water, photovoltaic etc.) produced around 54 g CO₂e / kWh.

For the conventional diesel bus, at an assumed fuel consumption of 40 l / 100 km across the entire life cycle, around 129 kg of greenhouse gases are produced per 100 km. Over the entire life cycle of a diesel bus (12 years, 720,000 km) around 929 tonnes of greenhouse gases are produced. For the purposes of a sensitivity analysis the energy consumptions in each case have been varied according to the values shown in brackets in Figure 11. In this way, starting from a base value of 40 l / 100 km, the fuel consumption of the diesel bus was varied between 35 and 45 l / 100 km.

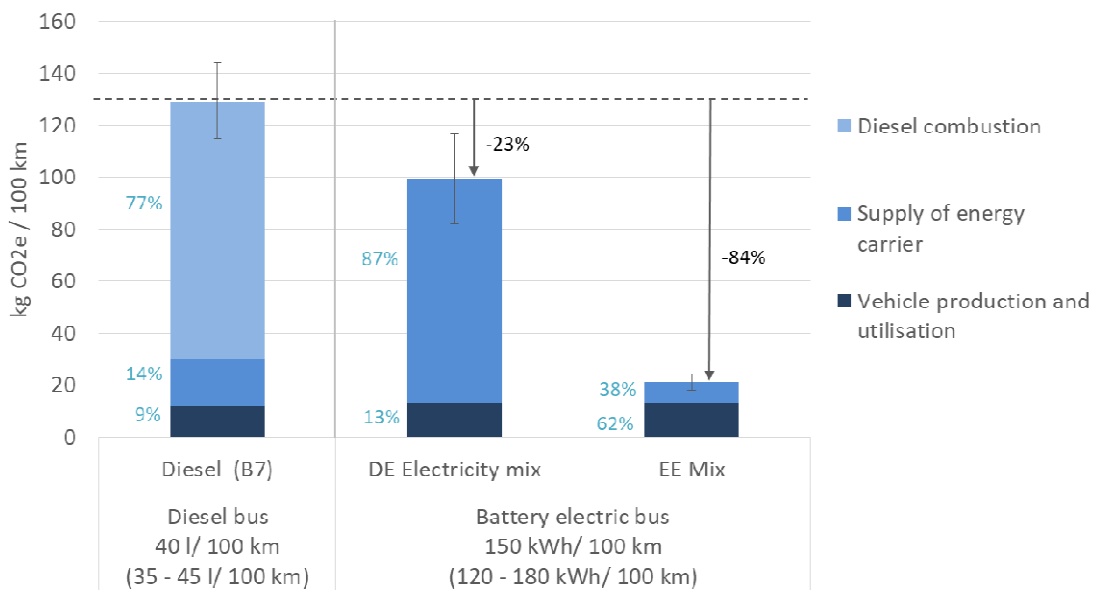


Figure 11: Example of greenhouse gas emissions for diesel and battery buses [2]

In a similar manner a basic consumption value of 150 kWh / 100 km has been assumed for the battery bus and varied between 120 and 180 kWh / 100 km. The respective results have been presented by means of indicator bars in Figure 11. With a view to its greenhouse gas balance, within the assumed consumption values it is apparent that where the use of electricity from the German electricity mix is concerned, the battery bus is at least comparable or may even display initial potential for savings. If electricity from the renewable energy mix is used there is a significant savings potential to the tune of 80%.

Regarding the relevance of the individual life cycle phases, in the case of the diesel bus the useful life dominates, as expected, at almost 80%. The energy carrier supply – in this case the supply of diesel fuel – is 14%, while vehicle production and utilisation amounts to 9%. Depending on the source of the electricity used, the percentage for vehicle production and utilisation rises to up to 62% for the battery bus. For the battery bus, depending on the electricity used, the electricity supply is responsible for almost 40% to 90% of greenhouse gas emissions.

Regarding the emission of pollutants, in the case of nitric oxide emissions in real-life test runs by TÜV Nord, a considerable reduction in emissions was achieved through the use of hybrid drives. In this way, when compared to the Euro V / EEV diesel reference vehicles, the Euro VI parallel hybrid with SCR catalyst and urea injection exhibits a NO_x reduction of 96% and a reduction of 91% when compared to the Euro VI diesel vehicle. The rise in emissions at low speeds that is typical of conventional vehicles can be almost completely avoided with hybrid drives as the electric drive is employed in particular for the start-up procedure and emission-free driving at low speeds (see Figure 12).

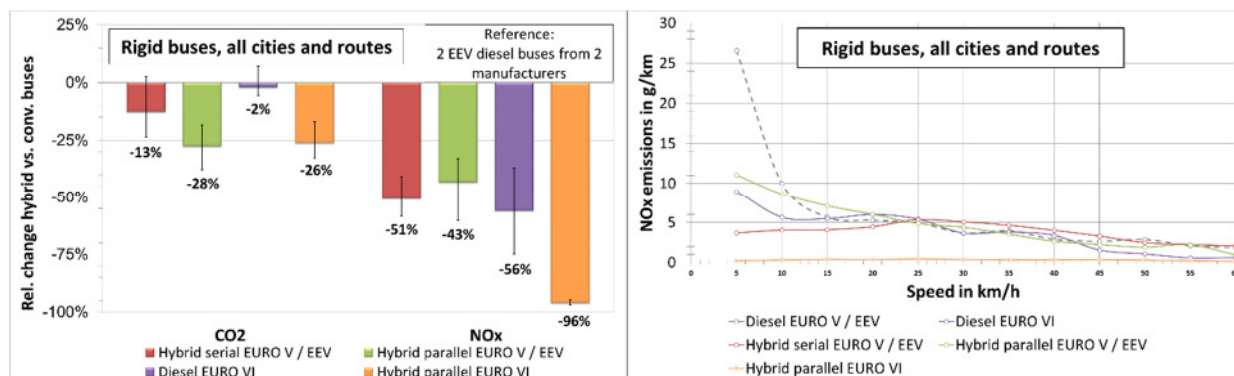


Figure 12: Change in CO₂ and NO_x emissions (left) + NO_x emissions classified by driving speed (right) (rigid buses, 8 different routes in Rhine-Ruhr area), TÜV Nord [2]

Alongside the emission of pollutants, traffic-related noise emissions are also significant, especially in residential areas. The measurements carried out by ika, RWTH Aachen as part of the EFBEL project showed that even in hybrid mode with the diesel engine running there was a notable reduction in the noise emissions of hybrid vehicles to less than half of the loudness⁵ of conventional reference vehicles. The battery electric rigid bus which was also measured displayed even lower exterior noises. As expected, even when starting at full throttle it was able to achieve a reduction in loudness of 2/3 or more (depending on the diesel reference vehicle).

As already mentioned, because hybrid buses have the possibility of running in fully electric mode, particularly when in an idle state or when starting, e.g. at bus stops or traffic lights, they can make a significant contribution to local noise and pollutant reduction. Depending on design, the serial hybrid buses exhibit a higher potential for the amount of purely electric driving when compared to buses with a parallel hybrid drive. With serial hybrid buses the size of the energy storage determines the electric range, while in the case of parallel hybrids fully electric mode, if provided at all, is limited to certain driving situations such as the start-up procedure, for example. The proportion of time in purely electric mode across the various speed ranges for the bus systems is accordingly varied (see Figure 13). At low speeds in particular, the combustion engine in serial hybrids is turned off for well over half of the time. However, various tests carried out within

⁵ As an indicator a more precise representation of the psycho-acoustic correlations was chosen and applied. In place of evaluated sound pressure levels, the linearly scaled loudness of the noise events was calculated.

the framework of WG Bus showed that with regard to the ambitious local emission-reduction scheme “Zero Emission Mode” this is generally not ideal for the overall energy efficiency of the hybrid drives.

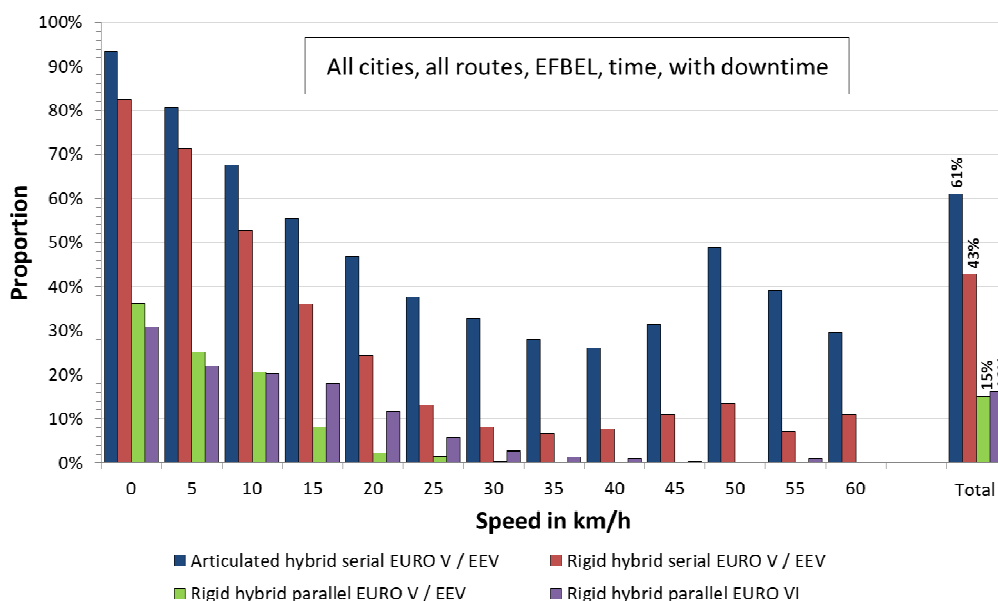


Figure 13: Diesel hybrid buses: proportion of operating time in zero emission operation mode, TÜV Nord [2]

6 Cost Effectiveness

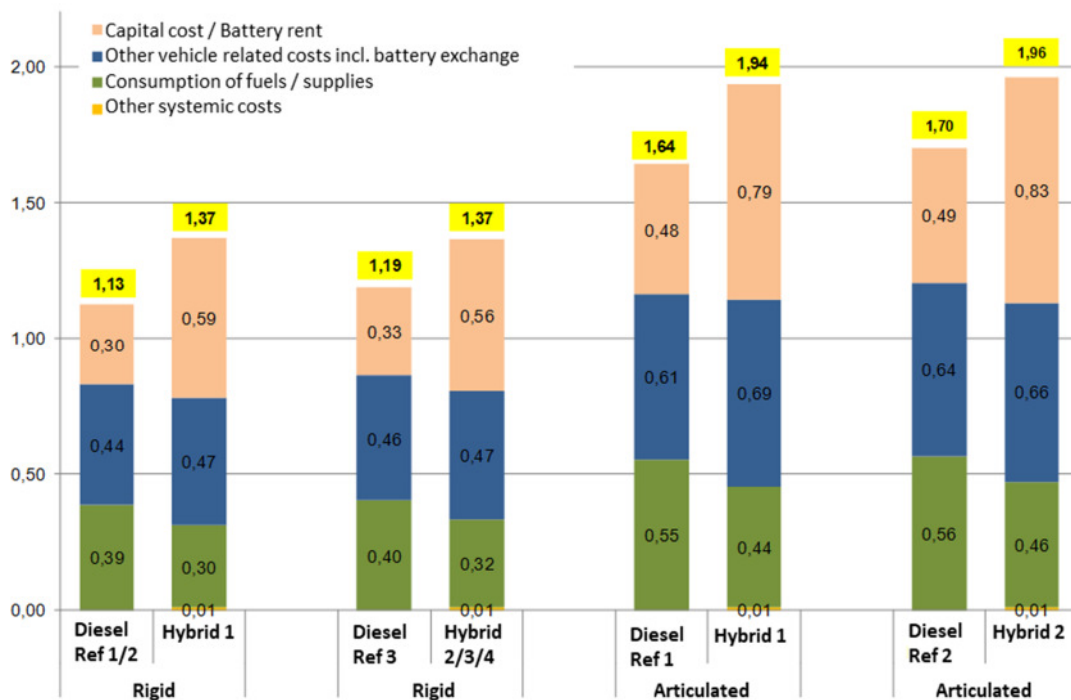
For a successful market launch the costs of the innovative drive technologies over the life cycle of the buses and the possible future growth in profitability are considerable factors. As a benchmark the costs of the hybrid buses on route services are compared to those of the diesel reference buses. As hybrid buses have only been in operation for a maximum of 5 years now and because there is definite potential for further optimisation along with a corresponding reduction in costs, only an approximate ascertainment of costs is possible. For a profitability assessment a distinction is made between vehicle-related and system-induced costs. In particular the following cost types are considered:

- Servicing costs with typical expenditure on vehicle maintenance (cleaning, refuelling etc.);
- Fuel consumed in practice operations;
- Capital costs;
- Other vehicle-related costs; and
- System-induced additional costs (e.g. standby vehicles, workshop equipment, employee training).

12 years of service and a yearly driven distance of 60,000 km are taken as a basis for the calculation.

In comparison with the cost analyses carried out by the BMU in 2012, over the last four years the additional costs of rigid hybrid buses have fallen to 17 – 23 cent / km (-20%) while those of articulated hybrid buses have fallen to 25 – 29 cent / km (-15%). The reduction in costs can by and large be traced back to lower investment needs⁶ and higher fuel savings.

⁶ e.g. between 2011 and 2014 the price of an articulated hybrid bus fell by €20,000.



Costs (standardised to 60 tkm p.a. and a service life of 12 years, without funding)

Figure 14: Comparison of the life cycle costs of hybrid and diesel reference buses, BbA [2]

From a purely economic point of view, however, the cost reductions achieved up till now still fail to offer enough incentive to employ the innovative hybrid technologies. Continued support for market penetration is required, for example by means of the funding of additional purchasing costs, e.g. as part of various funding programmes by the BMVI and the BMUB. In the long-term, however, the challenge rests with the vehicle manufacturers to reduce the purchasing and running costs (e.g. through a further reduction in energy consumption) to such an extent that the technology can compete and establish itself in the market.

As mentioned at the outset, the current state of development of battery electric buses and the associated charging infrastructure does not yet allow for any reliable assertions to be made with regard to profitability. For a start, it is necessary to further increase the technical maturity while also identifying and implementing financial improvements. Because of the considerably higher investment costs of vehicle and charging infrastructure at present, electric buses are not yet competitive from a purely economic point of view. These are precisely the reasons why the various research and development projects as well as the first demonstration projects for electric buses are being funded.

7 User Acceptance

Whether the implementation of an innovative technology will be successful depends not least on its general acceptance, especially among the affected employees (driving and workshop staff) and users (passengers), but also among the other parties concerned (e.g. local residents). In a variety of surveys the expectations and experiences of the various interest groups was evaluated.

In the previous acceptance studies among drivers and passengers the smooth starting and the lower noise levels of the buses in particular were rated positively. On topographically demanding routes the dynamic driving behaviour of the drivers is also rated. Among the riders and the public in general the new bus technologies are getting predominantly positive ratings as well. However, with regard to the various recharging systems in use for battery electric buses, several concerns were raised about the high costs, the reliability and possible health risks.

8 Summary

The experiences and learning gained from, in some cases, over 5 years of service, attest to the high reliability and road capability achieved by diesel hybrid buses. Their use on appropriate routes allows savings of 20% and more compared to conventional diesel buses. Concerning air pollutants (NO_x, particulate matter) and noise there is an even bigger potential for reduction, in particular in fully electric mode when pulling out and arriving at bus stops, as well as when in an idle state at traffic lights or bus stops. From an economic point of view the diesel hybrid buses are not yet competitive, at least currently, because of their 15 – 20% higher life cycle costs.

Battery electric buses, with certain exceptions, have only recently been deployed on prative runs or on single demo routes and as a result are still at the beginning of their development phase and learning curve. Their advantage lies in locally emission-free and less noisy operation. In terms of the use of electricity generated from renewable energies, electric buses exhibit a potential to reduce greenhouse gases by 80% and more. However their operation comes with certain challenges due to the necessity of charging infrastructure. At present there are various concepts being tested for charging in the depot and/or en route. Because they are currently at a pilot stage, cost effective operation is not feasible yet. The next trial stage involves running several routes and (partial) networks to appraise the operational stability and flexibility (e.g. seasonal influences on energy requirements and consequently the operating range, the effects of delays or diversions at charging points en route etc.)

A high level of acceptance for the new technology can be achieved by getting operator staff (drivers and workshop employees) involved early and through targeted public relations work right from the onset when deciding to introduce buses with innovative drivetrain in public transport. With this the bus-based public transport is serving as a very good lighthouse project with a broad impact for the introduction of innovative drive technologies. By currently operating more than 350 hybrid buses as well as around 100 purely electric buses (battery buses, trolleybuses, fuel cell buses) part of the German federal government's originally targeted number (1 million electric vehicles by 2020) has already been reached in the German city bus fleet and is used on a daily basis by hundreds of thousands of citizens.

Acknowledgement

The results presented here originate from various projects funded by the federal transport (BMVI) and the federal ministry for environment (BMUB) as well as other federal and state ministries whose funding initiatives contribute considerably towards the market preparation and launch of these innovative drive technologies in public transport buses. An overview of the funded projects can be found in [3] and at <https://www.vdv.de/ebus-projekt.aspx>.

The findings of the topics, as well as a variety of questions, were compiled by a large number of research institutes and industrial enterprises and made available within the framework of the WG Bus. Thanks is due to the authors, in particular the BbA - Dr. Bruns & Fetzer Management Consultancy, the Fraunhofer Institute, the ika at RWTH Aachen, TÜV Nord and the VCDB.

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