

Technical and economic comparison of different electric bus concepts based on actual demonstrations in European cities

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Abstract: Battery-powered electric buses are increasingly being used around the globe. This work investigates four technological concepts for the rollout of electric buses from a technical and economic perspective: very fast and moderate opportunity charging, overnight charging and trolley hybrid buses (power supply via catenary/battery). The investigations fund on real demonstrations in four European cities. They were carried out in direct cooperation with the respective public transport operators to obtain realistic results. The focus of this work is on an economic comparison based on the total cost of ownership (TCO), including all investment and operating costs in the bus service. Thereby, the battery represents a major asset and is examined more closely, especially with regard to the expected service life. The TCO of corresponding electric and diesel buses, scaled up to a complete line, are directly compared. This includes penalty costs for the emissions of noise and pollutants. Sensitivity analyses on the most relevant variables are conducted to take into account risks and uncertainties. It shows that electric buses can nowadays already be economically competitive under favourable assumptions, regardless of the concept. Trolley hybrid buses turned out to be the most cost-effective variant in their respective country.

1 Introduction

The rollout of (battery) electric buses plays a major part in the reduction of hazardous emissions [most importantly CO₂, NO_x, particulate matter (PM), noise], which are caused by the operation of diesel buses in urban areas. The use of an electric bus makes it possible to obtain potential emission savings that could be achieved by replacing at least 30 internal combustion passenger cars with electric cars [1]. The emission of fine dust by mechanical braking is also reduced in general comparison to vehicles with combustion engines, since a large part of the kinetic energy can be recovered electrically (regenerative braking). To promote electrified public transport, alongside practical operation in daily road traffic, the economic perspective is of major significance. Within this work, four different technological concepts of electric buses, already driving in European cities, were directly compared and evaluated regarding their economic efficiency compared with diesel buses.

In recent years, tests with electric buses have been launched in a large number of European cities. An important major research project was the EU funded *ZeEUS* [2]. As an important result, the 'E-Bus Report' [3] provides a comprehensive overview of the projects implemented and of manufacturers/products available in Europe (as of the end of 2017). Topics relating to the cost-effectiveness and reliability of the new systems were also dealt with, but they were not published for various reasons. The technical maturity of the demonstrations was often not yet finalised, resulting in unsatisfying results.

Furthermore, the investigations took place in a strongly evolving market environment, in which the publication of sensitive data had to be approached with caution. In the context of another EU funded project named *Eliptic* [4], an outlook was given on possible business cases for electric buses. This was based on actual demonstrations and was intended to show whether and how the operation of electric buses can be economically viable in the future. The most important findings are presented in this paper, which is

an extension of the work presented at the IEEE VPPC 2017 conference [5].

The impact of two different charging concepts (overnight (ONC) and opportunity charging (OC)) on life cycle costs (LCC) has been investigated in [6]. The study was based on simulations of routes in Finland and California, taking cost data from the literature. The results showed that the LCC of electric buses were on average still higher than those of diesel buses. In some scenarios; however, they came very close to profitability. This was especially true for 'end station' concepts, where the (fast) charging stations are located at the respective terminal stops of the routes. A comparison of the economic efficiency of diesel and battery-electric buses including prospects was summarised in an extensive analyst report by *Bloomberg* [7]. It was based on general assumptions without reference to a specific application and already stated a greater economic efficiency of the electric bus in medium and big cities in the USA. The capital costs of the vehicle were the highest asset. It turned out that the electric bus had lower-energy and operating costs. These included aspects such as 'labour, insurance, repair and maintenance'. The profitability increased with the annual mileage. The results of a stakeholder survey on different e-bus charging technologies in northern Europe (including inductive charging) have been presented in [8]. Advantages and disadvantages of the operation were quoted. A theoretical cost comparison of different charging infrastructure (CI) concepts can be found in [9]. A distinction was made between stationary and in-motion recharging, either conductive (trolleybus) or inductive, as well as battery swapping stations. Here, too, cost information from the literature was used, e.g. for the charging stations.

Interestingly, the battery swapping stations had the lowest total costs in the investigated scenario (Orange Line, Los Angeles Metro). The authors also describe the reasons why these are not used anyway. These include the lack of interoperability between manufacturers and problems with different battery degradation. The line was characterised by a high vehicle frequency (16 vehicles/h). A comparison to combustion engine propulsion buses

Battery concept \ Charging concept		Low capacity / high power	Medium capacity / medium power	Large capacity / low power
Opportunity charging	Public grid	Scenario „Very fast opportunity charging“		
	Tram/ Metro grid		Scenario „Moderate opportunity charging“	
Overnight depot charging				Scenario „overnight charging“
Charging in motion (Trolley hybrid)			Scenario „Trolley hybrid“	

Fig. 1 Classification of technological concepts

was not made. The identification of the most relevant key performance indicators and the general evaluation of three European electric bus projects (EBSF, *3iBS* and *ZeEUS*) were dealt with in [10]. This comprised financial, environmental, social and safety issues, among others. The economic advantages of the application of trolleybuses were already illustrated in the middle of the last century [11]. This was probably also the main reason for their extensive worldwide deployment, which, however, experienced a decline in the past years due to more attractive alternatives. The use of powerful traction batteries on these vehicles is a logical step. A study in Zurich (Switzerland) showed that up to 20% of energy could be saved by equipping the trolleybuses with batteries [12]. The replacement of diesel buses by trolley hybrids was discussed in [13]. The trolleybus was presented as the most economical variant, especially on longer distances (number of departures).

In comparison to the studies mentioned above, which are often based on purely theoretical approaches and data, we presented the results of four real demonstrations in this paper. These have fundamentally different approaches, which are classified in Chapter 2. To make a meaningful economic assessment, we have carried out extensive simulations. These also take into account the load profiles and corresponding service lives of the most important technical components such as the battery. Especially, the battery was part of a more detailed investigation. Where possible, we performed an ageing prediction and considered different battery lifetime scenarios. To make a meaningful national economic comparison, which is lacking in many studies that are limited to the business part only, we have directly integrated the environmental costs for electric and diesel buses. The basic methodology is presented in Chapter 3. The input parameters, especially in terms of cost, and the results have been obtained from and validated by the respective public transport operators (PTOs) in a set of workshops and meetings over 3 years. The collected data and results of our economic investigations for each scenario can be found in Chapter 4. We excluded a direct cost comparison of the different concepts. We aimed to provide a realistic insight into the actual application of electric buses in our partner cities, which is the reason why we took as much realistic data as possible. Since the examinations took place in different countries with different wage levels and energy prices, this impeded a direct comparison. Nevertheless, it was important for us to give an overview of the current economic efficiency of electric buses by providing realistic figures. Chapter 5 discusses this issue, as well as the results and outlook of the various concepts.

2 Technological concepts

As mentioned before, the studies in this work are based on actual test operations conducted in four different European cities within the frame of the European project *Elliptic* [4]. Fig. 1 shows a basic classification. A distinction is made between the applied charging and battery concept.

Regarding charging, we investigated opportunity charging, overnight charging and charging in motion. In the first case, a distinction is also made about the grid connection. In this case, the use of existing (AC or DC) infrastructure of the local tram/metro network was possible. The corresponding batteries are roughly divided into high-power, medium-power and high-energy (low-power) packs.

A more detailed description of the projects, which is not possible here for capacity reasons, can be found in [14, 15].

2.1 Scenario ‘very fast opportunity charging’

The project took place in Barcelona (Spain). It examined the operation of two articulated electric buses (18 m) on the H16 line. The recharging was performed using fast-charging stations at the respective terminals. The rated electrical charging power was 400 kW. One charger was connected to the municipal medium-voltage grid (AC). This necessitated the installation of a new transformer. At the other terminal, the charging power was drawn from the existing underground infrastructure (auxiliary network, AC).

This intended potential savings to be made on electrical components during installation. In this case, however, it led to costly construction measures and cable laying. Also, overnight charging was enabled by two smaller units with an electrical output of 50 kW. The concept of regular intermediate charging at the terminal stops made it possible to keep the traction batteries relatively small. This was supported by the premise that the buses are charged at the terminals without exception.

The batteries consisted of cells with a lithium-titanate-oxide (LTO) anode instead of the most commonly used graphite (C). Owing to the high-power density and the associated high charge/discharge rates of this cell chemistry, the 125 kWh pack could be dimensioned comparatively small in energy terms [16, 17].

2.2 Scenario ‘moderate opportunity charging’

The connection of fast-charging stations to the existing DC tram network was being investigated in Oberhausen (Germany). For this purpose, two standard electric buses were purchased, each of which started operation on one line. In addition to being charged overnight in the bus depot, an electrical output of 220 kW can be regularly drawn at the respective terminal stops. The electrical connection is made either directly to the overhead line or to the busbar of a substation. The advantage of this implementation is the use of the existing infrastructure. This potentially saves space and costs. When considering this scenario, it must be borne in mind that it was a technical first demonstration. For this reason, a final evaluation was not possible yet as the technology used is still partly subject to development. The 200 kWh battery pack, manufactured by a Polish supplier, consisted of lithium iron phosphate (LFP) cells from *A123 Systems* [18]. These are characterised by a higher-energy density compared with LTO cells, but still offer an acceptable power density to allow moderate opportunity charging.

2.3 Scenario ‘overnight charging’

The testing of a pure overnight charging approach took place with a standard electric bus in Bremen (Germany). The concept was characterised by lower infrastructure and higher battery costs.

The 230 kWh battery was recharged in the depot using a type 2 plug with up to 50 kW. The energy was drawn from the medium-voltage grid of the local electricity supplier. To ensure a daily range of 230 km without interim recharging, the passenger compartment was heated with a small diesel generator in winter. This enabled energy savings of up to 50% compared with an operation with electrical heating. This allowed the comparatively compact dimensioning of the energy storage, which consists of LFP cells. The manufacturer pursues a concept, in which only the strongly aged cells are successively replaced and not the entire battery pack.

This should bring a cost advantage, which still has to be verified in real operation (see Section 4.3).

2.4 Scenario 'trolley hybrid'

The application of trolley hybrids, i.e. trolleybuses equipped with traction batteries was investigated in this scenario. Trolleybuses operate since the middle of the last century. The combination with modern batteries increases the operational flexibility, as it allows driving on routes without an electrical supply grid. The demonstration took place in the Hungarian city of Szeged. The examined bus line, having a circulation length of 13.3 km of which 5.8 km run under catenary, is in fact a diesel bus line. During the test period, it was served with electric buses. For this, two 18 m trolleybuses have been equipped with an additional traction battery. The usable energy of the 81 kWh Li-ion battery pack, having a Nickel-Manganese-Cobalt (NMC) based cathode and graphite

anode, is limited to 36.2 kWh. This was due to ageing constraints. Recharging took place during operation under catenary using an 80 kW onboard charging device.

Table 1 summarises the most important parameters. The yearly vehicle mileage, which refers to 100% availability (a value which is not reached in real operation), and passenger capacity are important factors. To gain comparability, the costs are referred to them in the following. For more detailed information (exact route profile, detailed description of the buses) of the demonstrations, see [15].

3 Proposed simulative approach

To assess the technological concepts and their economic benefits, we have carried out detailed simulations involving all pertinent technical components. We have a special focus on the battery and our approach allows us to predict the ageing of the battery during operation. The simulation was implemented in *MATLAB/Simulink*. In a first step, the load profiles of all technical components (especially battery, power electronics, connectors etc.) were calculated. This was done for each scenario. The current vehicle plans and technical configurations served as the basis. Subsequently, the total cost of ownership (TCO) were calculated. For capacity reasons, a detailed description cannot be given here, but the most important elements are presented (namely, the TCO calculation and composition). For more information on the simulation process and its input parameters, the authors refer to [14] (Chapter 2.2).

3.1 TCO calculation and composition

We applied the net present value (NPV) method to calculate the TCO. The calculation of present values enabled us to compare arising cash flows, which differ in amount, timing and duration. The NPV of an investment is defined as the total of all cash flows (CF_{*t*}) over a set period (*T*) discounted by the discount rate (*r*) to the starting date (*t* = 0) [19]

$$NPV = \sum_{t=0}^T CF_t(1+r)^{-t} \quad (1)$$

The TCO includes all costs/revenues for the pertinent technical equipment, arising during the investigation period. It was 12 years for the battery-electric buses and 18 years for the trolley hybrid bus. Table 2 provides a classification of the considered costs. From the PTOs point of view, the transition to electric buses is not yet taking place primarily for financial reasons. Therefore, environmental aspects [external costs (ECs)] play an important role in overall economic consideration. In addition to avoiding CO₂ emissions that promote the greenhouse effect, an important goal of electric mobility is the local reduction of air pollutants, especially in densely populated areas. These cause damage to health and the environment, which is ultimately a financial issue from a national economic point of view. The quantification of the consequential damage is reflected in correspondingly high environmental costs, which were analysed and determined in reports by the Federal Environment Agency ("Umweltbundesamt", UBA, [1]) and the European Commission [20] (see Table 3).

PTOs do not have to pay for these costs, making diesel buses still an economical alternative. Nevertheless, a business case can already be generated today via politics with appropriate subsidies for clean buses.

4 Simulation results/economic assessment

The economic assessment of the four demonstrations/technological concepts includes four steps:

(i) TCO calculation of the initial scenario (operation as described in Chapter 2). This includes a consideration of the external/environmental factors. To compare 12 and 18 m buses in a meaningful way, the value is referred to in €/passenger km.

Table 1 Main parameters of the four scenarios

	'Very fast opportunity charging'	'Moderate opportunity charging'	'Overnight charging'	'Trolley hybrid'
city of demonstration	Barcelona (Spain)	Oberhausen (Germany)	Bremen (Germany)	Szeged (Hungary)
number of lines/buses	one line/two buses (articulated)	two lines/one standard bus each	one line/one standard bus	one line/two buses (articulated)
passenger capacity	110	70	80	120
distance per vehicle	200 km/day~73,000 km/year	240 km/day~87,000 km/year	155 km/day~57,000 km/year	240 km/day~90,000 km/year
battery	125 kWh/Li-ion (NMC/LTO)	200 kWh/Li-ion (LFP/C)	230 kWh/Li-ion (LFP/C)	81 (36.2 usable) kWh/Li-ion (NMC/C)
charging power	2 × 400/50 kW	2 × 220/20 kW	1 × 50 kW	80 kW
power supply grid	metro aux./public (both AC)	tram (DC)/public (AC)	public (AC)	trolleybus grid (DC)
route characteristics	low speed/high traffic	medium speed/low traffic	medium speed/low traffic	medium speed/low traffic

Table 2 TCO composition

ECs	- penalties for the emission of noise and pollutants in inner cities - production not regarded
energy (E)	- diesel (/l; incl. taxes and excise taxes) - electricity (/kWh; incl. subsidies and taxes) - grid utilisation fees (/kW and /kWh)
CI	- charging devices [asset and maintenance (maintenance charging infrastructure (MCI))] - coupling devices (asset; stationary part) - grid connection costs (one-time expenses) - constructional measures (one-time expenses)
Battery System (BS)	- cells, packaging, system components (asset) (BS1) - cell/pack replacement (BS2)
maintenance (vehicle)	- maintenance costs (/km) - insurance costs (annual costs)
vehicle	- vehicle (asset; incl. e-machine/diesel engine) - coupling device (asset; onboard part) - no BS (see above)

Table 3 ECs for pollution in urban areas per weight and km (noise)

Pollution type	CO ₂	NO _x	PM ₁₀	Noise
costs [Germany] [1]	€145/t	€10.300/t	€36.300/t	€0.0968/km
costs [EU] [20]	€30/t	€4.400/t	€87.000/t	€0.0768/km

Table 4 General simulation parameters

General parameters	
discount rate	4%
period under review	12/18 years (trolley hybrid)
electricity price trend	+ 50% within 12 years
diesel fuel price trend	+ 50% within 12 years
average passenger load	40%

Table 5 Involved suppliers and cost parameters

Technology	Company	
battery-electric buses (18 m)	Solaris Bus & Coach S.A. [3]	
pantograph	SCHUNK GmbH	
charging devices	Ekoenergetyka	
cost type	E-Bus per unit	diesel bus per unit
vehicle (w/o bat.)	€532,000 (12 years lifetime)	€350,000 (12 years lifetime)
maintenance T_0	€4500/quarter	€4500/quarter
battery	first: €187,500 and second: €144,000	—
energy/diesel T_0 – T_{end}	€0.06/0.1– 0.09/0.15/kWh	€0.93–1.40/l
CI OC T1 – connected to the public grid		
transformer + construction	€60,000	
installation costs	€95,000	
construction costs	€75,000	
coupling system	€18,500	
charging station	€170,000	
CI OC T2 – connected to the metro grid (aux.)		
installation costs	€400,000	
construction costs	€75,000	
coupling system	€18,500	
charging station	€70,000	
CI depot – connected to the metro grid		
installation costs	€15,000 initially	
charging station	€35,000/unit	

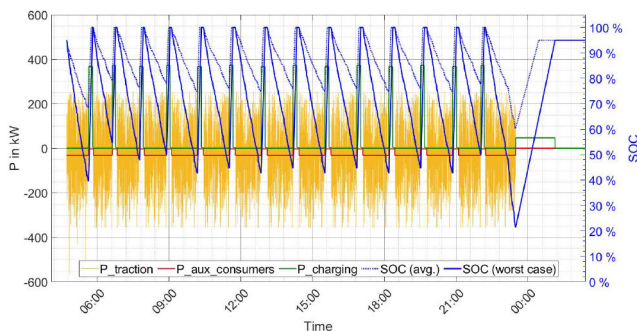


Fig. 2 Simulated worst-case operation on weekdays (4.5 kWh/km specific energy consumption; 2 kWh/km in average case)

- (ii) Scaling the number of electric buses in operation→consideration of a complete line electrification.
- (iii) Comparison to diesel buses (EU6).
- (iv) Sensitivity analysis on the most important parameters (impact assessment).

Table 4 states the general simulation parameters. About 12 years were assumed to be the standard service life for a bus (of course this depends on the country and PTO) and 18 years for a trolleybus (due to the lower wear of the electrical components).

Predicting the development of electricity and diesel prices over a longer period is impossible. Therefore, we chose for a conservative approach assuming a price increase of 50% for both in the period under consideration. The cost per passenger kilometre is a suitable measure for comparing different buses. For this, we have assumed an average passenger load of 40% in all scenarios.

The final NPV is calculated according to (2). It is composed of the investment costs (i) for vehicles (V_i), the initial battery systems ($BS1_i$), and the CI incurred at the beginning of the period under consideration. The annual running costs (a) for the maintenance of the vehicles (MV_a) and infrastructure (MCI_a), as well as energy (E_a) and ECs (EC_a) are added to this. Furthermore, in scenarios with battery replacement, the costs for an additional pack ($BS2_i$) are included. The residual value (rv) of the first pack ($BS1_{rv}$), which amounts to 5% of the initial costs, is subtracted from these. The residual values of the vehicles (V_{rv}), battery systems ($BS1_{rv}$, $BS2_{rv}$) and infrastructure (CI_{rv}) are deducted at the end of the period. In the case of diesel buses, the costs for CI and BSs are omitted.

$$\begin{aligned}
 NPV = & V_i + BS1_i + CI_i \\
 & + \sum_{t=0}^T (MV_a + MCI_a + E_a + EC_a) \times 1.04^{-t} \\
 & + (BS2_i - BS1_{rv}) \times 1.04^{-(t=t_s)} \\
 & (V_{rv} + CI_{rv} + BS2_{rv}) \times 1.04^{-(t=t_{end})}
 \end{aligned} \quad (2)$$

4.1 Scenario 'very fast opportunity charging'

Table 5 lists the manufacturers involved and the main cost parameters of the demonstration in Barcelona. A more detailed list can be found in [14]. The vehicle and battery assets are high. This results in more than twice the investment costs for one electric bus compared with a diesel bus. Owing to lacking long-term experience and the initial need of adaptation of the workshop and staff, diesel and e-bus maintenance are assumed to be equal first, but with a distinct decreasing trend for the electric system. This accounts for all scenarios we investigated in this paper. The installations of the fast-charging stations at terminals 1 and 2 (T1 and T2) make up a comparatively big part of the initial investment. This is explained by major efforts for constructional work such as opening the walkway to install a transformer underneath it at one terminal. This was necessary to withdraw the energy from the municipal power grid. The other terminal is connected to the subway's auxiliary network. Owing to the long distance of a few kilometres, there was a great effort involved in laying the cables, which resulted in high costs. Owing to the required high performance, the prices for charging stations are correspondingly high.

Fig. 2 shows the electric power [traction (yellow), aux. consumers (red), charging (green)] and battery state of charge (SOC) (blue) curves for simulation under worst-case conditions [full passenger load (110) and auxiliary power (25 kW)]. Negative power values indicate a discharge of the battery and positive values indicate a charge. It shows optimisation potential regarding the battery sizing/design, as there is still the unused capacity of the 125 kWh battery. On the other hand, the oversizing provides a safety buffer and reduces the cycle depth, which extends the service life of the battery.

Fig. 3 shows the expected cyclical lifetime of the LTO battery ('Wöhler curve') [21]. During average operation (2 kWh/km consumption), the cycle depth/depth of discharge (DOD) is ~25%. This translates to around 16,500 equivalent full cycles (EFCs) that are executed on the battery within the 12 years of operation (dotted green line). For this reason, we assume that the end of life of the battery is determined by calendar ageing. This depends strongly on the average SOC and the temperature. These parameters are

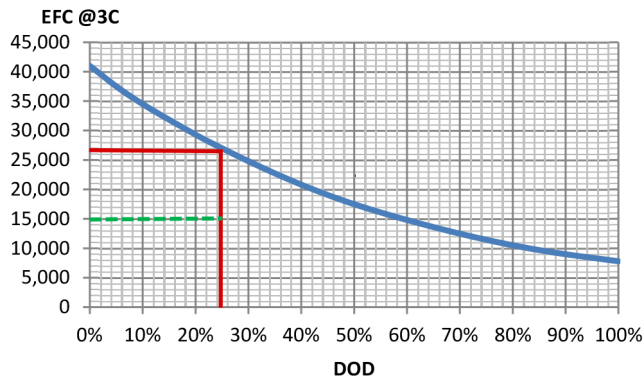


Fig. 3 Expected cycle lifetime of NMC/LTO cells in average operation

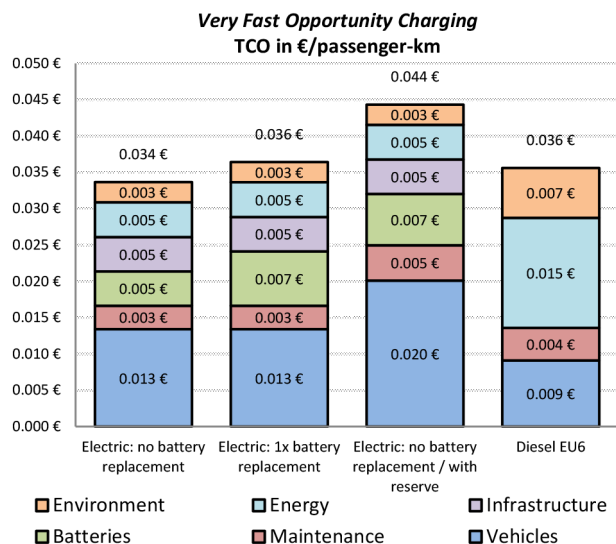


Fig. 4 TCO comparison: very fast opportunity charging

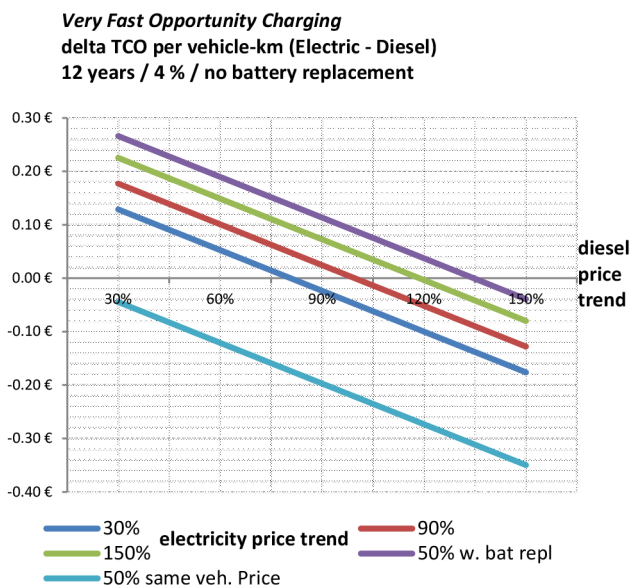


Fig. 5 Sensitivity analysis in €/vehicle-km (same reliability): very fast opportunity charging

difficult to estimate from the outside. Therefore, we assume two scenarios in the following: without and with (after 6 years) battery replacement.

Fig. 4 shows the final TCO, stated in €/passenger km. It has four bars, of which the three bars on the left-hand side represent the electric bus under different assumptions. The leftmost states a full line electrification (eight electric buses in operation instead of two) without a battery replacement within the 12 years' timeframe and an operational availability equal to that of the diesel bus. The

second bar corresponds to the first one, but includes the battery replacement after 6 years. Taking past price trends into account, the second battery is thereby assumed to have around 25% reduced invest costs compared with the first one, which is given a rest value of 5%. The third bar shows a scenario that seems most realistic at the moment. Owing to a lower technical reliability of the electric bus system at the beginning, diesel bus reserves have to be maintained, which are expressed in an increased vehicle price (factor 1.5). By including external aspects (orange bar), the economic efficiency of a line electrification can be displayed. The costs of the electric bus scenarios with comparable availability are equal or even lower than for the diesel bus. However, this requires a comparable (high) reliability of the electric bus system, which should be achievable in the coming years. The cost reduction, which compensates the high investments, is mainly caused by the distinctly lower-energy costs (around €0.10/kWh and ~2 kWh/km consumption compared with around €1.20/l and ~60 l/100 km for diesel). This case shows that by the expansion of the service, electrified public transport can be realised at competitive costs.

To counteract uncertainties of some assumptions and estimations, important parameters are reviewed more deeply. Two of the most uncertain factors are the price trends of fuel and electricity. While both are assumed to grow by about 50% during the period under review, the variation of the price trends between 30 and 150% is performed. This intends to cover different price development scenarios and evaluate their influence on the economic efficiency of the systems.

Fig. 5 shows the results. We can see that, under favourable conditions, an economic efficiency can be achieved for all electricity price trends (negative TCO difference). Assuming an increase in electricity prices of 30% (blue line), the electric bus, assuming no battery replacement, becomes economical from a diesel price increase of about 80%. For 150% (green line), the corresponding diesel value is 120%. Here as well, the strong dependence of the diesel price is evident. It is apparently the most relevant factor from a financial point of view. The repurchase of batteries is impactful, but not overall decisive. It further reduces the efficiency of the electric bus (purple line) by around 10 cents/km. Although battery replacement is planned to increase reliability and to ensure a trouble-free operation of the buses, the necessity of more than one battery per bus over 12 years is, as stated before, uncertain. Assuming the same vehicle price, a scenario that should appear realistic in the future due to growing production figures, the electric bus would be economically viable across all energy price influences (light blue line).

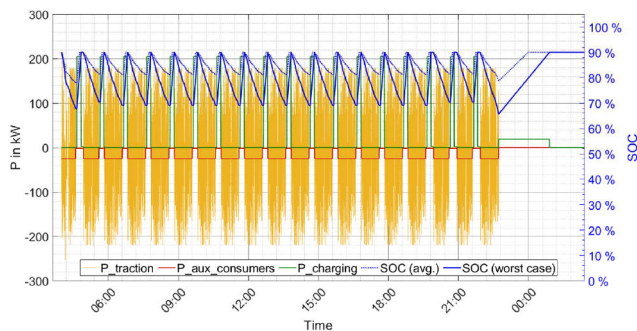
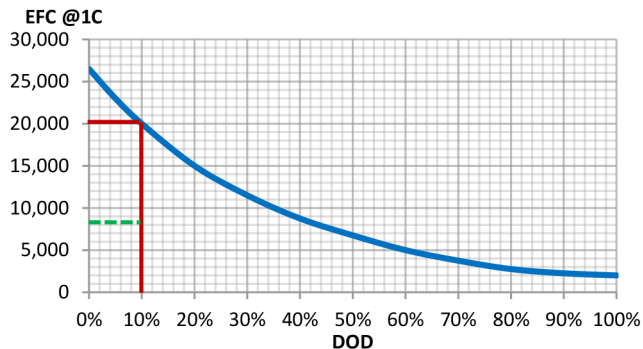
4.2 Scenario 'moderate opportunity charging'

Table 6 lists the most important cost parameters and manufacturers involved. Here, too, the investment costs for a standard electric bus with battery are about twice as high as for a diesel bus. The technical feasibility of connecting two fast-charging stations to the local tram grid (DC) was to be demonstrated in this scenario. Although this prevented a new connection to the medium-voltage grid, the investment costs were nevertheless quite high compared with a 'standard' grid connection. This was caused by the necessary work for a direct connection to the overhead line. Furthermore, comparatively expensive DC chargers had to be installed, which had to be galvanically isolated and have to operate with a strongly fluctuating input voltage.

Fig. 6 shows the simulation results of the worst-case operation, which is characterised by an auxiliary power of up to 25 kW during operation. The DOD of the battery is up to 20%. This resulted in a buffer of more than three round trips. Thus, it was quite obvious that the capacity was oversized even under permanent worst-case conditions and caused (too) high initial costs for this project. As already mentioned, however, this is a technical first demonstration, which should not be assessed solely on the basis of economic factors. In this case, the oversizing allowed a longer battery life to be guaranteed (lower cycle depth and current rates), which was seen as a more important point. Fig. 7 underpins this statement [18]. We assumed a cyclic lifetime of 20,000 EFCs at a DOD of 10%, which is the cycle depth for an average operation. Having 19

Table 6 Involved suppliers and cost parameters.

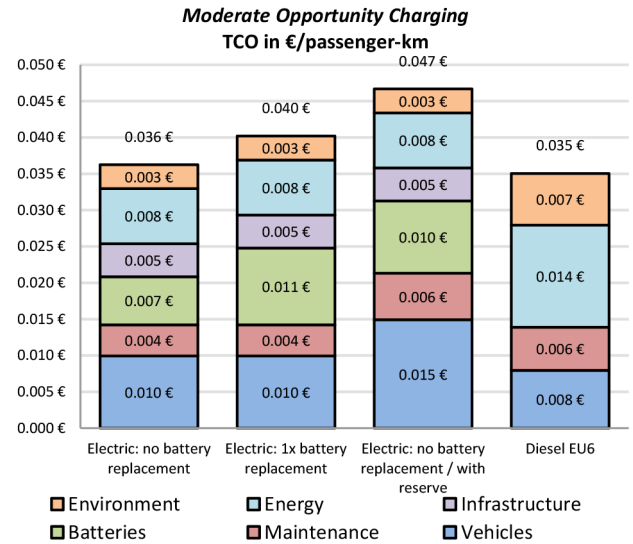
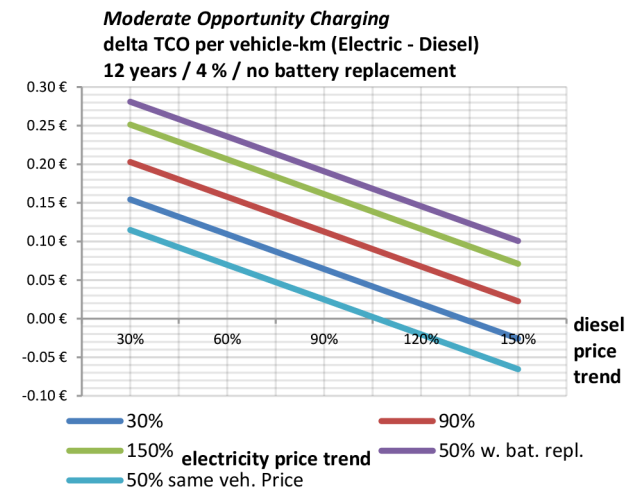
Technology	Company	
battery-electric buses (12 m)	Solaris Bus & Coach [3]	
battery cells	A123 Systems Inc. [18]	
pantograph	SCHUNK GmbH	
charger	Ekoenergetyka	
CI	Siemens AG	
cost type	E-bus per unit	diesel bus per unit
vehicle (w/o battery)	€300,000 (12 years lifetime)	€240,000 (12 years lifetime)
maintenance T_0	€4500/quarter	€4500/quarter
battery	first: €200,000 and second: €125,000	—
energy/diesel T_0 – T_{end}	€0.15–0.225/kWh	€1–1.50/l
CI		
installation costs OC	€367,000	
installation costs depot	€1000	
coupling system OC	€18,500/per unit	
charging station OC	€90,000/per unit	
charging station depot	€16,000/per unit	

**Fig. 6** Simulated worst-case operation on weekdays (2.6 kWh/km specific energy consumption, 1.3 kWh/km in average case)**Fig. 7** Expected cycle lifetime of LFP/C cells in average operation

cycles/day, this results in around 8300 EFCs over 12 years (green dotted line). This is again, far below the critical limit. As in the scenario before, it is presumable that the battery end of life will be determined by calendric ageing.

Fig. 8 shows the final TCO, stated in €/passenger km. The bars are analogous to the previous scenario. Again, approaching profitability of electric buses can be depicted, when we include economies of scale to the calculations (operation of three buses per line instead of only one), assess external aspects and assume same reliability (bars 1 and 2 versus 4). Despite the high initial costs, the almost competitiveness of the electrical system is achieved, as in the previous scenario, by the lower-energy costs (€0.15 ct./kWh and ~1.3 kWh/km consumption compared to €1/l and ~38 l/100 km for diesel in year zero).

In the last step, the price trends for fuel and electricity are subjected to a sensitivity analysis. Both are estimated to grow by

**Fig. 8** TCO comparison: moderate opportunity charging**Fig. 9** Sensitivity analysis in €/vehicle-km (same reliability): moderate opportunity charging

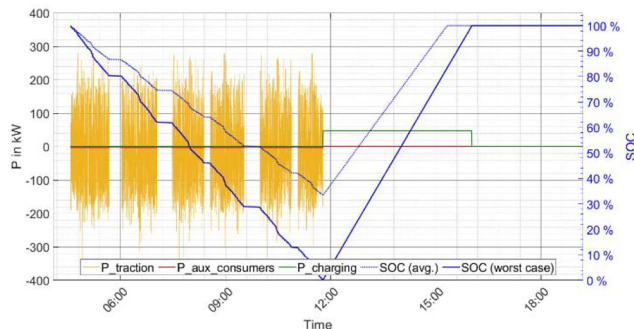
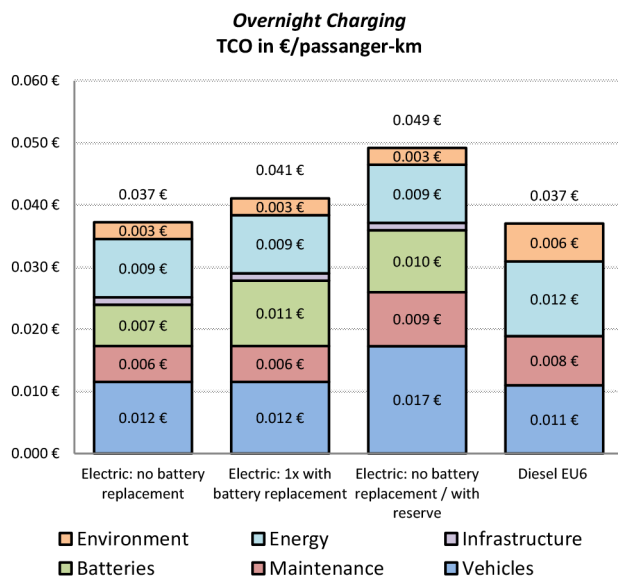
around 50% over the next 12 years, which are seen as high, but decent numbers. Nevertheless, for the sensitivity analyses, both trends are again varied between 30 and 150% to identify the dependency of the TCO on the prognoses. The results are displayed in Fig. 9, stated in €/vehicle km. A positive value [delta TCO (electric–diesel)] means a more economical operation of the diesel bus.

While the cost difference between the trends (60% step width) for electricity is around €0.05/km for each solution, the corresponding cost difference for diesel amounts up to nearly €0.09/km. This is caused by the higher-energy consumption of the combustion engine. However, only under the most favourable forecasts (30% electricity and 150% diesel trend), the electric bus can achieve economic efficiency (deep blue bar). Another uncertain factor, which is still part of broad scientific research, is the durability of battery cells used in electric vehicles.

The initial simulations assumed that a replacement of the LFP batteries would probably not be necessary during the period under review, especially concerning cyclic ageing (Fig. 7). The repurchase of the batteries after 6 years is analysed (violet graph, repurchase costs see Table 6). With this assumption, the electric bus will not yet become economical, even with the most favourable energy cost developments. A further sensitivity was carried out on the vehicle price (light blue line in Fig. 9). Assuming equal cost for electric (chassis including powertrain without battery) and diesel buses, the profitability is already evident from a diesel price increase of about 105% over 12 years (at an electricity price increase of 50% and no battery replacement).

Table 7 Involved suppliers and cost parameters

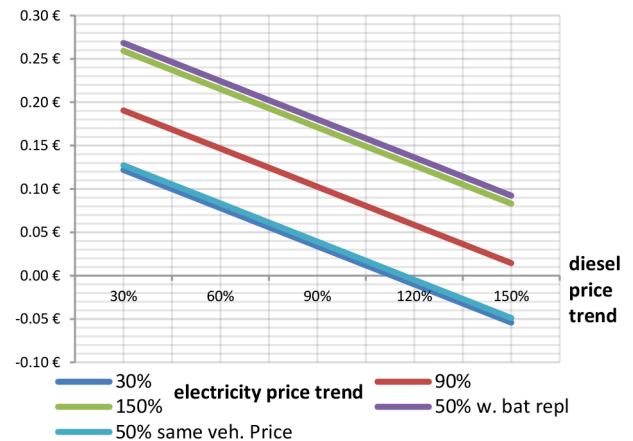
Technology	Company	
battery-electric bus and equipment (12 m)	Bozankaya/Sileo GmbH [3, 22]	
cost type	E-Bus per unit	diesel bus per unit
vehicle (w/o bat.)	€280,000 (12 years lifetime)	€240,000 (12 years lifetime)
maintenance T_0	€4500/quarter	€4500/quarter
battery T_0	€138,000	—
energy/diesel T_0	€0.22/kWh	€1/l
CI (depot)		
installations	€10,000	
charging station	€40,000/unit	

**Fig. 10** Simulated worst-case operation on weekdays (1.5 kWh/km specific energy consumption, 1 kWh/km in average case)**Fig. 11** TCO comparison: overnight charging

4.3 Scenario 'overnight charging'

Table 7 summarises the most relevant investment costs. The infrastructure assets are rather low for the concept of pure overnight charging, especially for only a small number of electric buses. A bigger fleet would necessitate a more extensive depot reconstruction. This is not considered here. The vehicle and specific battery costs are the smallest of the four concepts/scenarios presented. Since recharging takes place at comparatively low current rates, comparably cheap Chinese LFP cells are used, compared with the rather expensive cells in the previous scenarios. However, they have disadvantages in terms of performance, energy and service life. These are reflected in our investigations in increased maintenance costs for the battery of around €1000/year, which is to be regarded as a fairly small value. In this case, the prediction of ageing is difficult because we had no more precise

Overnight Charging
delta TCO per vehicle-km (Electric - Diesel)
12 years / 4 % / no battery replacement

**Fig. 12** Sensitivity analysis in €/vehicle-km (same reliability): overnight charging

information about the cells. We considered a scenario with/without battery replacement, too.

Fig. 10 shows the simulated worst-case operation of the test operation. It can be seen that under these conditions the battery is completely discharged. The required power of the auxiliary units is comparatively low, as fossil fuels are used to heat the passenger compartment. Without this additional heating device, the achievable range would be significantly reduced.

Fig. 11 shows the final TCO related to passenger's kilometres. Even under favourable assumptions (same reliability of electric and diesel bus and a small share of battery replacement costs), the electric bus cannot compete from a business perspective.

Only when we consider the external aspects, a close to cost parity can be depicted for the best case electric scenario (leftmost bar). This is mainly caused by the comparably high electricity price of €0.22/kWh the operator currently pays for taking energy from the public power grid. The sensitivity analysis in Fig. 12 underlines the statement. In this scenario, the electric bus only becomes economical under the most favourable assumptions (dark blue plot: 30% price trend for electricity and more than 120% for diesel, light blue: same vehicle acquisition costs and 50% electricity/120% diesel price trend).

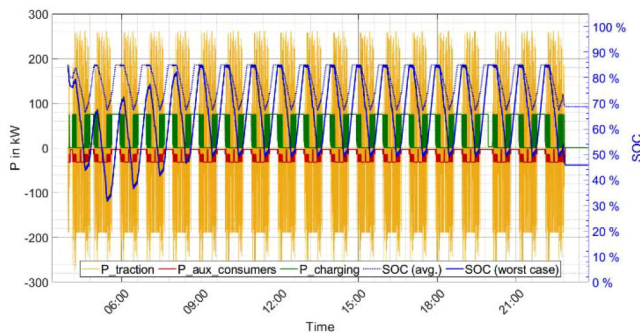
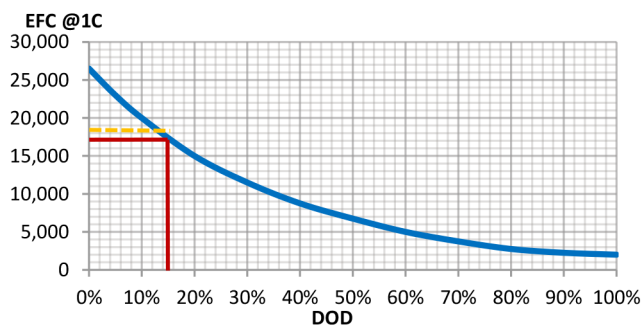
4.4 Scenario 'trolley hybrid'

Table 8 shows the major cost parameters of the 'trolley hybrid' scenario, examined in the Hungarian city of Szeged. Here, too, the electrical system (vehicle incl. battery) is more than twice as expensive as the diesel bus. As said before, it is assumed that the maintenance costs for the diesel and electric buses are the same, taking into account the additional BS, which should cause higher costs for the first time. In general and for future studies, maintenance costs for a trolley hybrid bus are expected to be significantly lower than for diesel. In Hungary, the electricity prices are around 30% less than in Germany and the diesel costs are around 10% lower. This has a significant impact on the overall profitability. The installation costs of a catenary system (including substations) are included in the calculations, varying from €300,000 to 900,000/km. The first value applies to non-complex straight lines. Depending on the type and complexity of the track (number of bends, crossings etc.), it can rise to a level of €900,000/km or more [13, 23].

Fig. 13 shows the simulated worst-case operation on the demonstration route. The battery SOC falls below 40% in the first cycles, which would be a critical value since the BS is restricted to an operation between 40 and 85% SOC (see Table 1). In real operation, the battery management system should be able to allow the operation in such exceptional situations, as they outweigh a potentially minimal increased ageing. Fig. 14 shows the expected cycle life of the NMC/C battery [24]. During average daily

Table 8 Involved suppliers and cost parameters

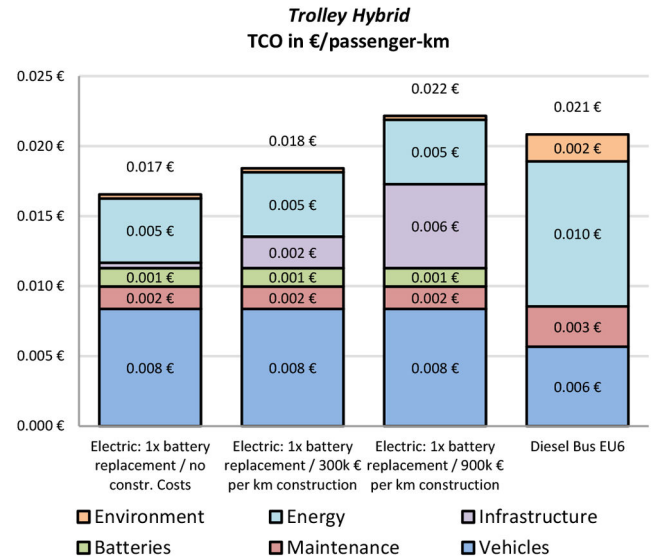
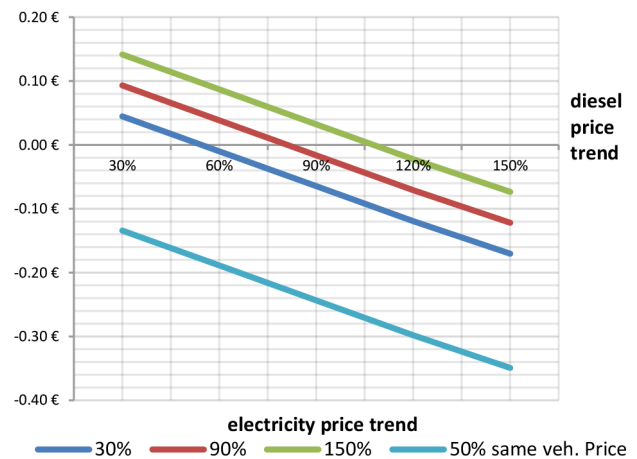
Technology	Company	
trolleybuses (18 m)	Ikarus Skoda TR187.2	
battery cells	Kokam [24]	
charger	onboard	
CI	trolleybus grid (DC)	
cost type	E-Bus per unit	diesel bus per unit
vehicle (w/o bat.)	€680,000 (18 years lifetime)	€350,000 (12 years lifetime)
maintenance T_0	€2500/quarter	€2500/quarter
battery T_0	€60,750	—
energy/diesel T_0-T_{end}	€0.10–0.18/kWh	€0.9–1.49/l
CI (depot)		
installation trolley grid	€0–300,000–900,000/km	
maintenance grid	€1000/month (proportionately)	

**Fig. 13** Simulated worst-case operation on weekdays (3.7 kWh/km specific energy consumption, 1.7 kWh/km in average case)**Fig. 14** Expected cycle lifetime of NMC/C cells in average operation

operation, the battery is charged with 19 cycles at a cycle depth of around 15%. This translates to 2.8 EFC/day around 18,400 EFCs within the 18 years of operation. This value is only a bit above the expected limit, which again indicates that the battery end of life would be determined by calendric ageing. We assumed one obligatory battery replacement as the most realistic scenario and included it in our calculations.

Fig. 15 presents the final TCO, stated in €/passenger km. The bars show a cost comparison of the trolley hybrid demonstration without and with (€300,000 respective 900,000/km) infrastructure construction costs (first, second and third bars) as well as the respective diesel bus operation (fourth bar). In contrast to the previous investigations, a period of 18 years is considered here, as this is the usual service life of a trolleybus. It is assumed that the diesel buses will be replaced after 12 and the battery will be replaced after 9 years.

It includes, as in the former investigations, scaling effects of infrastructure (operation of five buses on this line instead of two) and external/environmental aspects of operation (production not regarded). These are very low here, as they are mainly caused by CO₂ penalty costs (the EU value, which is used here, is significantly smaller compared with the German, applied in the first three scenarios, see Table 3). CO₂ emissions from electricity

**Fig. 15** TCO comparison: trolley hybrid**Trolley Hybrid delta TCO per vehicle-km (Electric - Diesel)**
18 years / 4 % / 2x battery replacement / 300k €/km**Fig. 16** Sensitivity analysis in €/vehicle-km (same reliability): trolley hybrid

generation are also lower due to the high proportion of nuclear power in the electricity mix.

Trolley hybrids are the most economical option for existing infrastructure (leftmost bar). However, also the new installation represents an economical alternative to the diesel bus. This is especially due to the significantly lower-energy costs of electric buses (light blue bar).

The sensitivity analysis (Fig. 16) shows the TCO difference (electric–diesel), stated in €/vehicle km. It relates to a scenario with €300,000/km costs for the construction of a new trolleybus grid including two battery replacements (6 and 12 years). While the cost difference between the trends for electricity (60% step width) is around €0.05/km for each solution, it is correspondingly up to almost €0.10/km for diesel. This is caused by the higher-energy consumption of the combustion engine (60 l/100 km versus 17 kWh/100 km).

It can be seen that, depending on the different cost developments, the trolley hybrid bus can still be economical, even if infrastructure had to be constructed.

The vehicle price has a very big influence on the TCO of electric bus projects. Assuming that the purchase price of the electric vehicle (chassis with powertrain, but without battery) approaches that of the diesel, a distinct economic efficiency becomes clear, regardless of all energy price developments (light blue curve).

5 Discussion

As mentioned in Section 1, a direct comparison of the four scenarios makes no sense due to different energy and wage prices. This accounts especially for a comparison of the German/Spanish projects with the Hungarian trolleybus.

From a mere business perspective, only the Trolley hybrid concept is beneficial against the operation of diesel buses in its country (see Fig. 15) This applies if the infrastructure already exists or can be set up cost-effectively (€300,000/km). In general, this scenario is by far the most cost-effective. This is due to several factors:

- (i) The long depreciation period of trolleybuses (18 years) and the electricity grid (30 years) play a major role. The installation of 3 km of catenary infrastructure is distributed over an average of five buses. This number is still very small, assuming that the installation is in the city centre and can potentially be used by many lines. The share for the infrastructure (including its maintenance) in the TCO loses thus clearly in weight.
- (ii) Compared to Germany/Spain, the electricity costs are quite low at comparable diesel prices. There are almost no ECs, as CO₂ emissions mainly cause these. These are low in Hungary due to the electricity mix (big share of nuclear power) and are distributed over the largest number of passenger kilometres. The environmental damage caused by the use of nuclear power is not taken into account in this calculation.
- (iii) Furthermore, the maintenance costs of the vehicles are also lower, as the trolleybus is an established system with decades of experience. Also, wage levels in Hungary are well below those in Spain and Germany.

Despite these obvious advantages, the concept does not receive a predominantly positive response. The main reason is that the installation of new overhead lines is politically and from an urban planning perspective difficult to enforce. This is especially true for cities that do not have catenaries nowadays such as Aachen (Germany), the current residence of the authors (a city with comparable size with Szeged).

Taking the Hungarian Trolley hybrid out of consideration, and looking only at the remaining three electric bus concepts, it emerges that the gap to profitability is already quite small (requirement: same availability as the diesel bus). It can surely be surmounted shortly by reducing the investment costs for electric buses, which are currently about twice as high as for a comparable diesel bus. When external factors were included, namely CO₂ emissions, noise and air pollution in urban areas, as well as the assumption of a long (but realistic) battery lifetime, the electric bus system could already be outlined as overall beneficial in all cases. This is mainly due to significantly lower-energy costs. The vehicle and battery accounted for the major part of the TCO in all scenarios. Owing to a large number of vehicle/passenger km, the infrastructure costs were greatly reduced. This is an important statement, as the high initial costs often act as a deterrent. The results are consistent with comparable studies [6, 7], which also state the today's economic efficiency of the electric bus in favourable, but not unrealistic, scenarios.

The 'very fast opportunity charging' scenario was characterised by disproportionately high vehicle and infrastructure costs. It successfully deployed the fast-charging concept, which is important for line operation with short pause intervals and high daily mileage. The 'overnight charging' was characterised by the smallest battery price and its replacement concept, which still has to prove in real operation. A disadvantage was the small daily range and the necessity of a fossil auxiliary heating to guarantee passenger comfort in winter. 'moderate opportunity charging', however, seems to be practical for urban lines and less densely populated areas with fewer passenger expectancy.

In conclusion, it must be said that all investigated scenarios were pioneer demonstrations, and thereby still suffered from minor problems and risks, mainly caused by not finally mature technology of buses and CI. This fact was taken into account by including a vehicle reserve. It currently makes the electric bus

uneconomical. However, reliability differs greatly between manufacturers and cities. Fleets with very high reliability (95%) are already in operation, e.g. in Eindhoven (Netherlands) [25]. At this point, it is the task of the big manufacturers to provide fully developed and mature system solutions for the electric bus.

6 Conclusion

Four different concepts for the introduction of battery-electric buses were successfully demonstrated. The opportunity charging of battery-electric buses, taking the energy (also) from the local public transport grid has been successfully demonstrated in Barcelona (Spain) and Oberhausen (Germany). The concept of overnight charging, which is considered to be the most comfortable solution, since infrastructure investments are rather low, was tested in Bremen (Germany). It is generally preferred by many cities, but suffers from the disadvantage that a very large battery or an additional fossil heating has to be installed to achieve the required range, especially in winter. In Szeged (Hungary), the operation of Trolley hybrid buses on a former diesel bus line has been successfully demonstrated.

The investigations were performed for small fleets and only one, respective two lines. The conversion of a whole bus fleet from diesel to electric will be a more complex task, as there have to be profound changes in the depot and its power supply. Besides, scaling effects will have more impact and further reduce the cost of electric buses/vehicle and passenger km.

The combination of different approaches can be advantageous for other projects. To name an example, the presented overnight charging scenario could benefit from the adaptation of aspects from the opportunity charging concepts. Thus, the purchase of energy from the local tram/metro network (if available, as in this case) represents a potentially cost-effective alternative.

To determine the costs of larger bus fleets is of further interest. The cases examined concerned only a few electrically operated buses. Owing to the small number, they can obtain their energy from the public or tram/metro power grids without major upgrading measures. However, supplying an entire fleet with more than 100 buses could require connection to a high-voltage grid to enable simultaneous charging, especially overnight. Such a concept could nevertheless prove profitable as the infrastructure costs are spread over a large number of vehicles.

7 Acknowledgment

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