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Introduction of Battery Electric Buses in European Cities – Economic Comparison of Novel Technological Concepts

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Abstract

Nowadays, the conversion of diesel fueled public bus fleets into those powered by electricity is one of the most important tasks for public transport operators. In the frame of European Commission funded projects ("Eliptic" [Commission, 2015], "ZeEUS" [Commission, 2014]), there are at the moment several demonstrations in different European (big) cities. Besides purely demonstrating the general technical functionality, finding Business Cases is also a crucial task, since the operation with the new technology should be at least not significantly more expensive than compared to Diesel, besides having clear societal and environmental benefits.
Within this context, the presented work focuses on the detailed comparison of two novel technological concepts of electric buses which are currently demonstrated in several European cities in the frame of the "Eliptic"-project:

1) Opportunity-charging of battery electric buses taking energy from local DC tram grid
2) Trolley-Hybrid buses (Buses being fed by overhead catenary and being able to cover parts of their routes by on-board batteries)

The investigations are based on already existing and potential future electric bus network and real operation in different cities and are performed in direct cooperation with the respective public transport operators to obtain meaningful results. A technical, economic and ecological presentation and comparison of the different approaches is the main target of the work.
For this purpose, detailed analyses are performed in order to calculate the Total-Cost of Ownership (TCO). This comprises all relevant technical investment- and running costs over a certain period under consideration. Sine it is representing an important cost-factor of the new system, the battery is particularly considered regarding the expected lifetime in different operation scenarios.

Keywords: Electric Bus, Business Cases, Battery, Trolley-Hybrid

1. Introduction

The introduction of (battery) electric buses has a great significance in reducing a large amount of emissions (most importantly CO2, NOx, particulate matter (PM), noise) produced by diesel buses in urban areas. Studies show, that by substituting the diesel engine, each electric bus would save absolute emissions equal to the savings that could be achieved by at least 30 electric cars combined [Schwermer et al., 2014]. Cities like London are introducing low (no)-emission zones in the inner areas, where only emission free vehicles are allowed to drive in the future. Besides the non-existent exhaust caused by a combustion engine, fine dust emitted by mechanical friction brakes can also be reduced in electric busses by converting mechanical energy into electrical energy (recuperation). For the promotion of such electrified public transport, alongside practical operation in daily road traffic, the economical perspective is of essential significance. Within this work, two different novel technological alternatives for electric buses are presented, evaluated regarding their economic efficiency against diesel and directly compared.

2. Scenario Description

The investigations are based on two actual demonstrations, taking place in the frame of the EU-funded “Eliptic”-project (www.eliptic-project.eu). The comparison of two different battery and charging concepts is in focus, namely the differences between on-route charging using Trolley-buses additionally equipped with batteries (hereafter called “Trolley-Hybrid”) and opportunity charging with pure battery electric buses. Both concepts are explained in the following.

2.1. Oberhausen

The project, which was started on 4th October 2015 by the transport association VRR (Verkehrsbund Rhein-Ruhr) and local transport operator STOAG (Stadtwerke Oberhausen GmbH), aims at examining battery-electric buses in practice and making them acceptable for everyday operations. The concept included the conversion of two bus lines (line 962 and line 966) by installing compatible infrastructure. On each line one electric bus has commenced operations. Besides charging overnight at the bus depot, regular recharging can be performed at the terminal stations by means of the already existing DC tram infrastructure. Therefore, the energy is taken either from the tram catenary at the train station ‘Sterkrade’ (bus line 962) or from the substation at the station ‘Neumarkt’ (bus line 966), as shown in Figure 1 [Thurm et al., 2016]. These solutions share the big advantage of using already available systems, presumably saving additional space and costs, instead of making new connections to the medium voltage grid, requiring the installation of new transformers.

Both buses need around 1 hour for a full circulation including a pause of 14 minutes respectively 19 minutes which are composed of a 3 minute buffer for reducing delays plus charging time. With a line length of 15.62 km the electric bus on line 962 reaches a daily distance of 310 km on weekdays, while the bus that operates on line 966 drives a daily distance of 170 km with a line length of slightly above 2 km less.

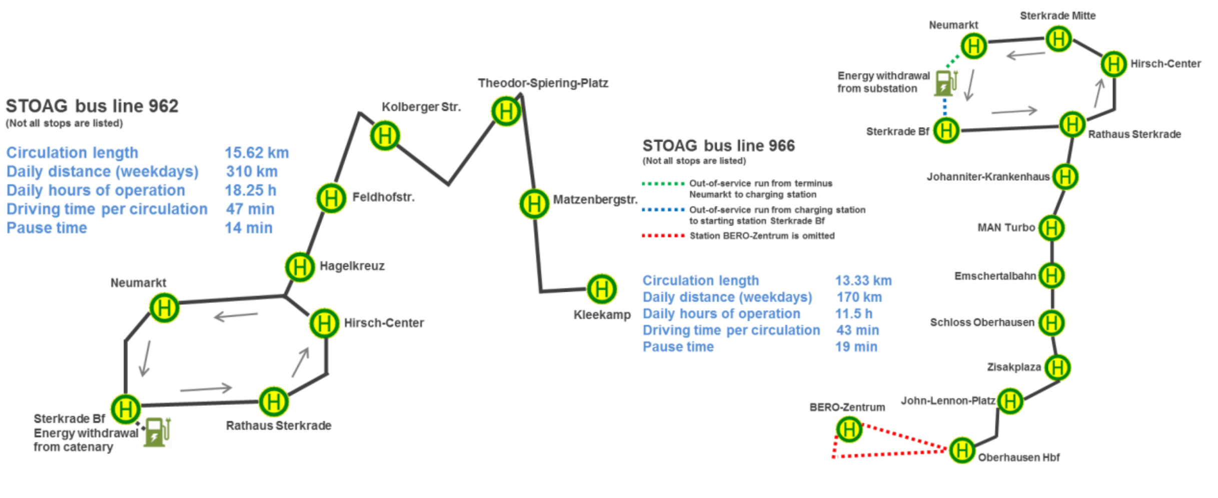


Figure 1 - Schematic sketch of the bus routes of lines 962 (left) and 966 (right) [Thurm et al., 2016]

The two charging devices at the terminal stations each provide charging power of 220 kW by means of the existing tram infrastructure, i.e. a catenary at line 962 respectively a substation at line 966 (Figure 2 [Thurm et al., 2016]). While the substation at “Neumarkt” is already equipped with required technology and, additionally, offers weather-protected positioning of the charger, the charging location at “Sterkrade” benefits from the nearby tram catenary and the sufficient space for devices and waiting positions for buses. Furthermore, a mast transmits the energy through a conductive pantograph which is placed on the roof of the bus.

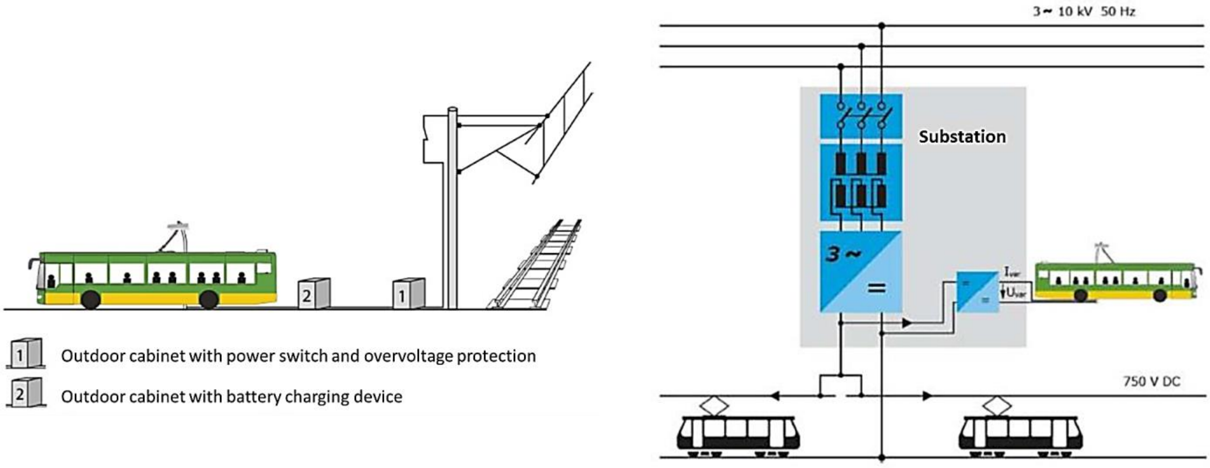


Figure 2 – Schematic sketch: charging from the tram catenary (left) and from the tram substation (right) [Thurm et al., 2016]

After service hours the batteries can be fully charged with a charging power of 20 kW at the bus depot overnight via plug-in. However, the installed charging units at each terminus enable the possibility of equipping the two buses with relatively small traction batteries without the requirement of charging during operation at the depot. Nevertheless, by dimensioning the storage capacity of each battery with 200 kWh, a big buffer has been considered to cover unforeseen events. More precisely, up to three charging cycles may be omitted which in turn leads to the relatively big battery.

While the chargers themselves are from polish company Ekoenergetyka which provides the appropriate devices for the buses manufactured by Solaris, the remaining equipment required for the energy transmission has been made available and installed by Siemens (Table 1) [Thurm et al., 2016].

Table 1 – Involved manufacturers and dimensioning in Oberhausen (Opportunity Charging)

Technology	Company	Dimensioning
Battery-electric buses	Solaris Bus & Coach S.A	Standard bus 175 kW el. machine, 25 kW AC/Heating (electr.) 70 passengers max.
Battery cells	A123 Systems, Inc. [A123_Systems,]	Li-Ion LFP/C
Battery pack	-	200 kWh
Pantograph	SCHUNK GmbH & Co. KG	-
Charger	Ekoenergetyka	2 x 220 kW / 2x 20 kW
Charging infrastructure	Siemens AG	-

2.2. Szeged

Szeged is located in the south of Hungary near to the borders towards Serbia and Romania. With a population of 169.000 inhabitants, it is the 4th largest city of the country. Due to the high amount of sun-hours per year (2100), it is also called the “city of sunshine”.
The first Trolley-Bus system has been introduced in 1979. The actual route structure has been built up in 1985, concentrating on the city center and the new constructions in the northeastern area.
In 2003, decisions for a modernization of the trolley- and tram system have been made followed by investments of around 100 Mio. € for new fleets, depots and power supply in 2008 [Naday et al., 2016].

Figure 3 shows the examined bus line 77A (left), which is in fact a diesel bus line but during the test also served with Trolley-Hybrids. The greater part of the line (7.5 km) is driven in battery mode. The battery is recharged under the catenary part of the route (5.8 km). One circulation takes around 46 minutes, followed by a pause of 14 minutes. The daily distance per vehicle amounts to 240 km.

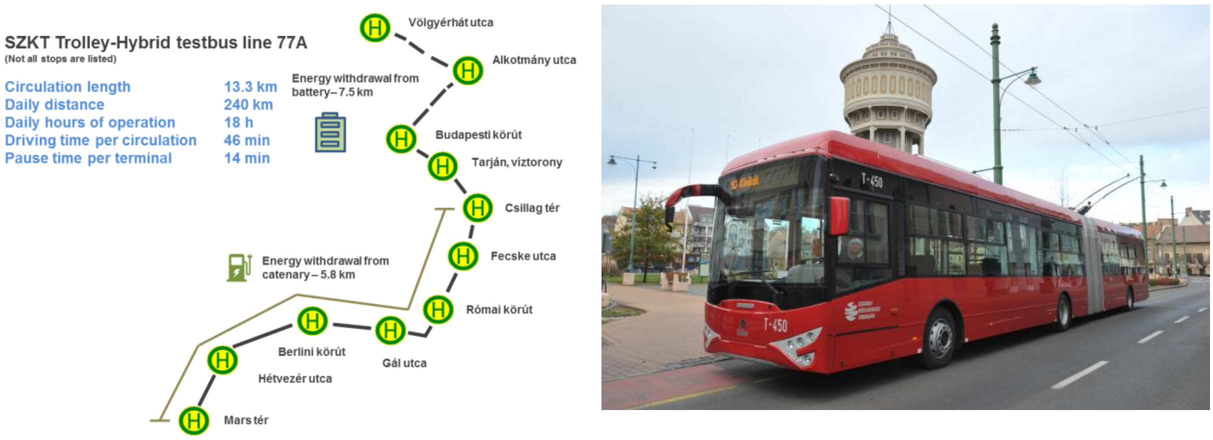


Figure 3 – (left) Schematic sketch of the bus route of test-line 77A, (right) Trolley-bus in Szeged (Photo by Dr. Zoltan Adam Nemeth)

Table 2 presents the involved manufacturers and the technical dimensioning. The 18m trolley-buses are manufactured by Ikarus Skoda and equipped with a battery system consistent of Kokam Li-Polymer cells [Kokam, 2017]. The usable energy of the battery pack is limited to 36.2 kWh. It is recharged during operation under catenary by means of an onboard charging device.

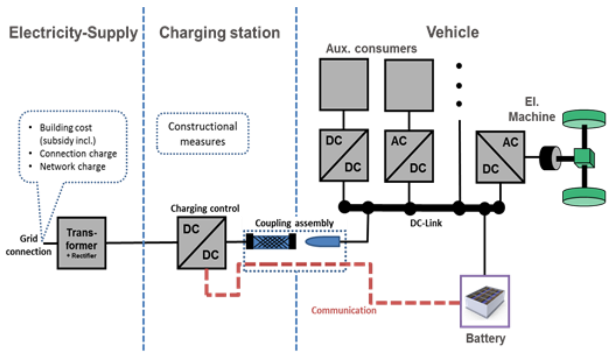
Table 2 - Involved manufacturers and dimensioning in Szeged (Trolley-Hybrid)

Technology	Company	Dimensioning
Battery-electric buses	Ikarus Skoda	18 m bus 275 kW electric machine 35 kW AC/Heating (electr.) 125 passengers max.
Battery cells	Kokam SLPB Large Cell [Kokam, 2017]	Li Ion NMC/C
Battery pack	-	81 kWh / 36.2 kWh usable
Charger	-	Onboard
Charging infrastructure	-	Substations + catenary

3. Investigation Approach

3.1. Simulative Approach / TCO calculation

In order to assess the technological concepts and their economic usefulness, detailed simulations, including all relevant technical components, are carried out. For this purpose, the energy consumption is calculated for different operating conditions. The simulation is based on the technical configuration proposed in Figure 4 and implemented in Matlab/Simulink. For each scenario, detailed load profiles for all technical components are calculated first, based on the actual vehicle schedules. Resting upon this and the local energy prices, the complete resulting costs (TCO – Total Cost of Ownership) for a 12-year period of operation are determined. Figure 4 (right) shows the composition of the TCO.



External Costs	- Penalties for Emission of noise and pollution in inner cities
Charging Infrastructure	- Charger (asset and maintenance) - Coupling device (asset; stationary part) - Grid connection costs (one-time expenses) - Constructional measures (one-time expenses)
Battery system	- Cells, packaging, system components (asset)
Energy	- Diesel (per litre; incl. taxes and excise taxes) - Electricity (per kWh; incl. subsidies and taxes) - Grid utilization fees (per kW and per kWh)
Maintenance (for vehicles)	- Maintenance costs (per km) - Insurance costs (annual costs)
Vehicles	- Vehicle (asset; incl. e-machine / diesel engine) - Coupling device (asset; on-board part) - No battery system (see above)

Figure 4 - (left) Relevant technical components under investigation/included in simulation; (right) composition of final TCO

In order to calculate the TCO, the Net-Present-Value (NPV) method is applied. It is used to calculate present values and gain comparability of all project-relevant cash flows which differ in timing and amount. The NPV is described as follows:

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

It is the total of all cash flows (CF_t) over a set time period (T) discounted by the discount rate (r) to the date t = 0 [Kruschwitz, 2011].

3.2. External costs

External aspects are key factor as the reasons for the transition to electric-driven vehicles are not primarily direct financial ones. One of the most important objectives of electro-mobility is the local reduction of health and environment harming emissions produced by diesel engines which is finally also a financial issue. The consequences of those exhaust gases are reflected in correspondingly high environmental costs which were analysed and determined in a report published by the Federal Environment Agency (UBA) [Schwermer et al., 2014] of Germany and presented in Table 3. Such costs may be less relevant from a business perspective since public transport operators do not have to bear them. However, an economic assessment enables to estimate the benefits of environmental policies which may prevent significant costs for national economies.

Table 3 – Used external costs to assess the savings in emissions by electric buses

Pollution type	CO2	NOx	PM10	Noise
Costs – Oberhausen [Schwermer et al., 2014]	145 €/t	10.300 €/t	36.300 €/t	0.0968 €/km
Costs – Szeged [Union, 2009]	30 €/t	4.400 €/t	87.000 €/t	0.0768 €/km

4. Simulation results and economic assessment

In the following, the two introduced technological concepts are investigated and then directly compared. All relevant cost parameters were obtained from the respective public transport operators. Table 4 summarizes the most important general parameters.

Table 4 – General parameters

Parameter	Oberhausen	Szeged
Discount rate	4 %	4 %
Period under review	12 years	18 years
Total mileage per vehicle	1.04 Mio. km	1.34 Mio. km

4.1. Oberhausen

Table 5 shows the most important cost parameters. Vehicle and battery costs for the electric bus are listed separately. The invest-costs for the standard electric bus (incl. battery) are around twice compared to a diesel bus. Maintenance costs are, due to lacking experience and the necessary adaption of workshop and staff, assumed equal for both systems first. However, the electric bus system is expected to be more cost efficient regarding maintenance. This is taken into account by a distinct decreasing trend over the investigation timeframe of 12 years. The biggest part of the infrastructure costs consists of installations, mainly the retrofitting of the substation (new cables, switching cabinet, protection systems etc.). Infrastructure costs for the diesel bus (mainly refueling station) are not considered here because of the very low cost effect per vehicle.

Table 5 – Cost parameters of Oberhausen scenario

Costs type	E-Bus per unit	Diesel Bus per unit
Vehicle (w/o bat.)	300.000 €	240.000 €
Maintenance T0	4.500 €/quarter	4.500 €/quarter
Battery T0	1.000 €/kWh	-
Energy/Diesel T0-T_{end}	0.15 – 0.22 €/kWh	1 – 1.50 €/l
Charging infrastructure (OC = opportunity charging)		
Installation costs OC	367.000 €	
Installation costs depot	1.000 €	
Coupling system OC	18.500 € per unit	
Charging station OC	90.000 € per unit	
Charging station depot	16.000 € per unit	

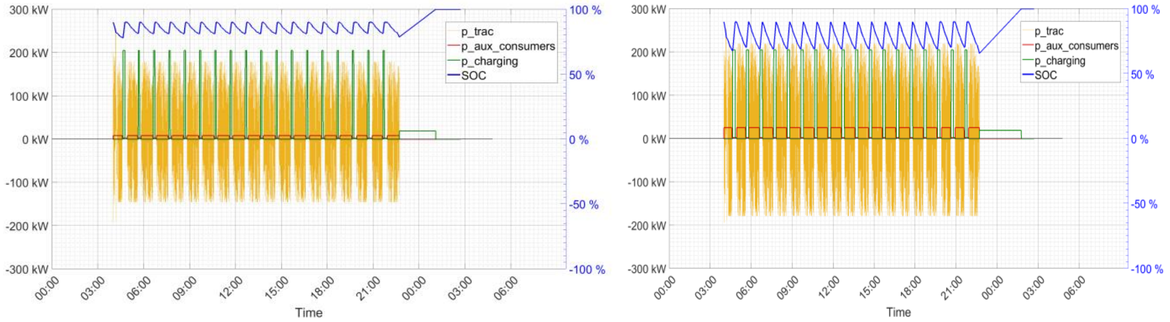


Figure 5 - (left) simulation results of line 962 on weekdays under average conditions. 1.3 kWh/km; (right) worst-case conditions, 2.6 kWh/km

Figure 5 shows the simulation results of the daily bus operation under average conditions. The State-of-Charge (SOC) curve of the battery is stated in blue, while the electric power is shown in yellow (traction, positive values = driving, negative values = braking), red (auxiliary consumers) and green (charging power). When looking at the SOC of the average (left) and worst-case (right), an oversizing of the battery is remarkable, translating to a buffer of more than three round trips in worst-case.

Figure 6 presents the final TCO (left), stated in € per vehicle-km, and its respective sensitivity analysis (absolute TCO difference between electric and diesel bus for the actual demonstration with battery replacement, stated in €) over diesel and electricity price trend (right).The bars present a cost comparison of the actual el. bus demonstration without and with battery replacement (1st & 2nd bar), an optimized configuration with smaller battery (3rd bar, 160 instead of 200 kWh) and a respective diesel bus operation (4th bar). The calculations include scaling factors of infrastructure (operation of 6 buses on this line instead of 2) and external/environmental aspects of operation (vehicle and battery production is not considered). The Sensitivity analysis (right) refers to the base scenario (actual demonstration with battery replacement) and is performed for diesel and electricity price trend, varying from +30 % to +60 %.

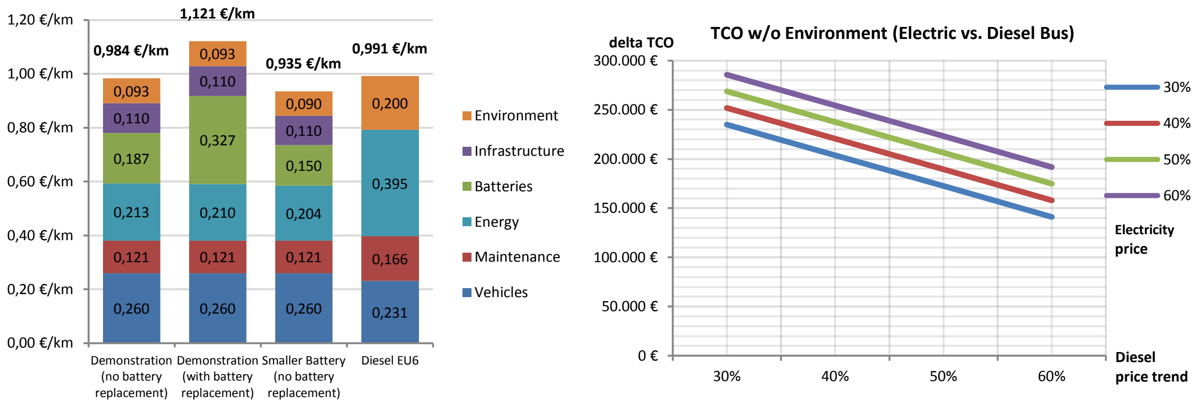


Figure 6 – (left) TCO comparison; (right) Sensitivity analysis of base scenario in Oberhausen

It can be seen that, under the presumptions made (same reliability of electric and diesel system, 50 % price increase for both electricity and diesel), the battery bus can already be cost-competitive, especially when external factors are considered and no battery exchange over the whole lifetime of 12 years is assumed, which is thoroughly possible due to the low depth-of-discharge (DOD) cycles for the battery in normal operation (see Figure 5 left, blue curve)[Schmalstieg et al., 2014]. Nonetheless, without environmental “costs” and on the assumption of one battery exchange, the TCO of the electric bus still amounts to 150.000 € more than the diesel TCO even under beneficial price trend developments (Figure 6, right, blue line).

4.2. Szeged

Table 6 shows the most important cost parameters of the Szeged use case. Again, the electric system (vehicle incl. battery) is more than twice expensive as the diesel bus. Vehicle maintenance costs are assumed to be equal here, giving respect to the additional battery system which should create more costs for the first time. In general and for future investigations, maintenance costs for a trolley-hybrid will probably be significantly lower than for a diesel bus. Electricity costs are around 30 % less in Hungary compared to Germany whilst diesel costs are around 10 % less. This has a significant effect on the general profitability. The installation costs for a catenary system (incl. substations) are considered in the calculations with 300.000 €/km. This is a comparatively small value, which was evaluated in direct talks with the operators, and applicable for non-complex straight routes. Depending on the route characteristics (amount of curves, crossings etc.) it can increase to the level of around 900.000 €/km [Heinz Schaden, 2004].

Table 6 – Cost parameters of Szeged scenario

Costs type	E-Bus per unit	Diesel Bus per unit
Vehicle (w/o bat.)	680.000 €	350.000 €
Maintenance T0	2.500 €/quarter	4.500 €/quarter
Battery T0	750 €/kWh	-
Energy/Diesel T0-T_{end}	0.10 – 0.18 €/kWh (+ 80 %)	0.90 – 1.49 €/l (+ 66 %)
Charging infrastructure		
Installation costs catenary (incl. subst.)	300.000 €/km	
Maintenance costs catenary	1000 €/month (proportionately)	

Figure 7 shows the simulation results of the daily bus operation, similar to the Oberhausen example. The left picture shows the average case (1.7 kWh/km) and the right one the worst-case (high passenger load and aux. consumption: 3.76 kWh/km). Again, an (energetic) oversizing of the battery is remarkable, to be seen from the battery SOC course (blue line) in both cases, but was chosen by the manufacturer to ensure maximal lifetime and provide sufficient power for propulsion.

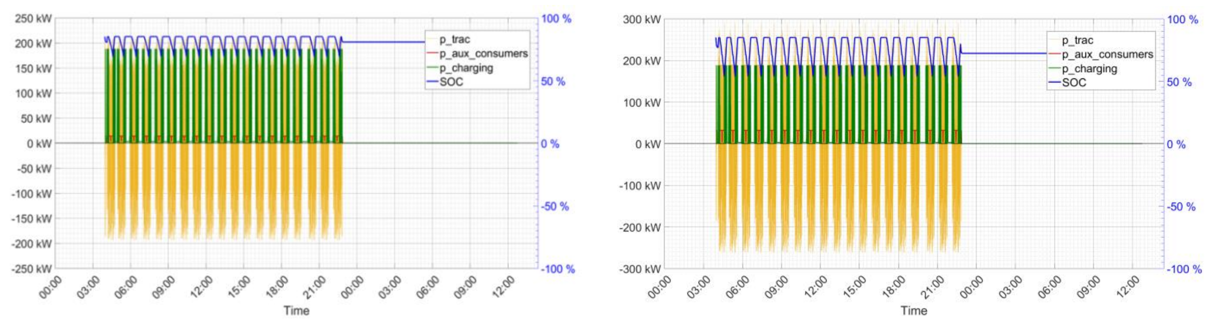


Figure 7 - (left) simulation results of line 77A on weekdays under average conditions; (right) worst-case conditions

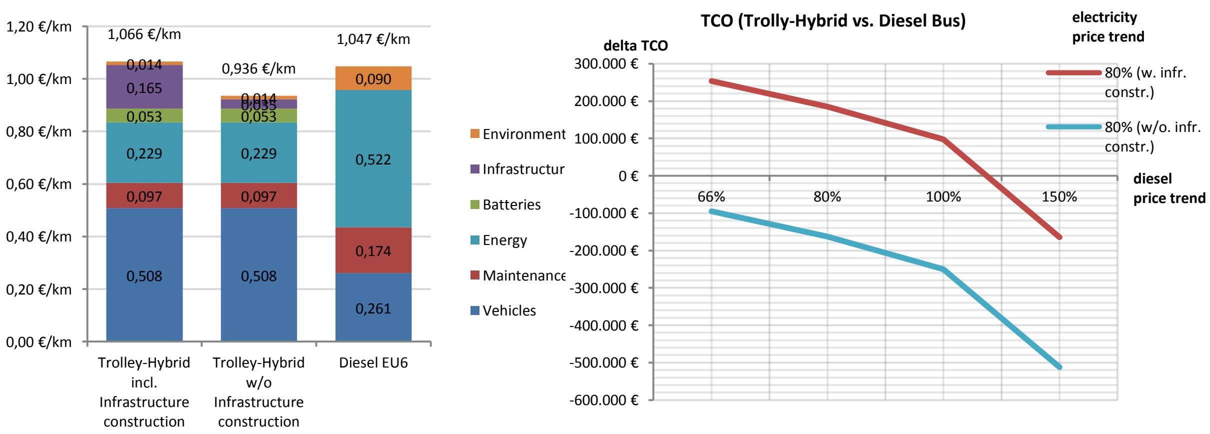


Figure 8 – (left) TCO comparison; (right) Sensitivity analysis of base scenario in Szeged

Figure 8 presents the final TCO (left) and its respective sensitivity analysis over diesel and electricity price trend (right), stated in € per vehicle-km. The bars show cost comparison of the Trolley-Hybrid demonstration with and w/o construction of infrastructure (1st & 2nd bar) and its respective diesel bus operation (3rd bar). It includes scaling effects of infrastructure (operation of 5 buses on this line instead of 2) and external/environmental aspects of operation (production again not regarded). The sensitivity analysis (right) shows the absolute TCO difference, stated in €, between the Trolley-Hybrid with and without construction of infrastructure and the corresponding diesel bus for the actual demonstration with battery replacement.
Once again it can be seen that, under the presumptions made (same reliability of electric and diesel system, 80 % price increase for electricity and 66 % for diesel within the 18 years), the trolley-hybrid bus can be cost-competitive, especially when the infrastructure already exists and solely has to be maintained. The battery has a lower influence on costs here, since its capacity can be rather small. External factors, which are determined with help of the values given by the EU-EC [Union, 2009], do not have a significant influence here. This is mainly due to the significantly lower costs for CO_2 emissions (see Table 3). Sensitivity analyses (Figure 8, right) shows that under beneficial presumptions (80 % electricity vs. 150 % diesel price increase) the final TCO of the trolley-hybrid with construction of infrastructure is less than for the respective diesel bus. Without construction of infrastructure, the Trolley-Hybrid system, assuming 80 % electricity price trend, is more cost efficient for all investigated diesel price trends.

4.3. Case Comparison

Figure 9 shows the direct comparison of the electric bus system in Oberhausen, Trolley-Hybrid system in Szeged (with and w/o. construction of infrastructure) and the respective diesel bus operations in both cities. For each electric scenario, at least one respective battery exchange is assumed. On the left, the TCO is stated in € per vehicle-km and on the right in € per passenger-km. For the passenger-km, an average passenger load of 40 % for each scenario is assumed. The vertical blue line marks the economically most cost efficient concept (including diesel, related to the direct costs for the operator, without external costs that are mostly societal). On the left, it can be seen that from a mere economic point of view none of the two electric concepts is competitive against the diesel bus, but that when external costs (which differ significantly between countries) are included they become better, even though not completely superior yet. Relating the TCO on the passenger-km leads to a clear advantage for the 18m buses in Hungary over the 12m buses in Germany. This fact is, besides the higher number of passengers (50 vs. 28) that are transported (what should be equalized through higher invest costs and energy consumption) mainly caused by the distinct lower energy costs in Hungary.

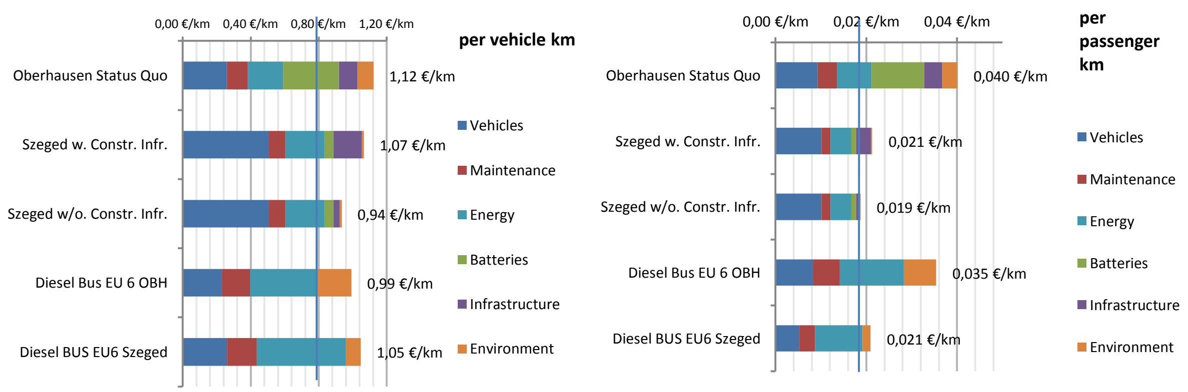


Figure 9 – (left) cost comparison, stated in €/vehicle-km; (right) cost comparison, stated in €/passenger-km

5. Conclusion and Outlook

The opportunity charging of battery electric buses, taking energy from the local tram grid has been successfully demonstrated in Oberhausen, whilst in Szeged, the operation of Trolley-Hybrid buses on a former diesel bus line has been successfully demonstrated, too.

The model based investigations show that the financial gap between electric and diesel buses is already fairly little, having same reliability as presumption. When including external factors and assuming a long battery lifetime, the electric bus system can already be outlined as overall beneficial. This is mainly due to significantly lower energy costs.
Nonetheless, the two investigated scenarios are pioneer demonstrations and thereby still suffer from minor problems and risks, mainly caused by not finally mature technology of buses and charging infrastructure. This fact has been neglected in the presented investigations by assuming the same reliability to show how electric buses can be a business case. At this point, it is the task of the big manufacturers to provide fully developed system solutions for the electric bus.

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, since 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 per vehicle- and passenger-km.

Acknowledgements

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