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TCO assessment of fuel versus electric heating for urban electric bus systems

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Summary

This paper presents a comprehensive cost assessment model based on a Total Cost of Ownership (TCO) approach for the currently most promising electric bus technologies, namely opportunity and overnight charging, taking operational and technology-related constraints into account. Therefor, the heating system as a potentially substantial energy consumer can significantly determine the electrification requirements. Thus, the cost assessment is conducted for different bus system configurations, respectively for a zero emission operation deploying a battery-powered heating system and a non-zero emission operation using a fuel-fired heating system, in order to quantify the impact on the system design. The results reveal that the electrification cost can be noticeably reduced for certain bus configurations by employing a fuel-fired heater.

Keywords: bus, heating, LCC, public transport, modeling

In the fact of stricter emission targets, e.g. the reduction of CO_2 by 60 % in 2040 in the European Union [1], "clean technologies" have to be developed and deployed. In order to evaluate the possible substitution of currently deployed conventional diesel buses, transport companies are intensifying electric bus trials [2].

However, replacing conventional diesel fleets faces several challenges for the vehicle procurement process. Firstly, electric buses – apart from trolley bus systems – only recently have become commercially available and they still need further technical improvements. Secondly, bus operators face several different options of electric bus and charging technologies. All options have specific assets and drawbacks concerning technological issues, capital and operational cost. Thirdly, for the electrification of bus networks an integrated approach, which considers vehicles, operation and infrastructure from a system perspective is required.

Therefore, transport authorities are challenged to implement appropriate evaluation tools for procurement to deal with the increased complexity and to take economic, environmental, as well as performance aspects into account. In particular, the cost assessment has to be adapted to the different cost structure of electric bus systems compared to conventional diesel buses to assure a cost-efficient technology selection. The cost-efficiency of a technology in turn depends on the optimal operational deployment. Vitally important for the adequate assessment is the modelling of full-day operation for each bus system and bus line in order to cover technology specific constraints such as range limitations and to reflect changing operational conditions.

In scope of this study, we introduce a cost assessment model, defined by a Total Cost of Ownership (TCO) approach, covering the expenses over the lifecycle of the deployed vehicle. Public transport networks are characterized by their inhomogeneous formation of different types of operation routes. The varying driving cycles of bus lines have significant influence on the economic evaluation [3]. Therefore, the TCO model also captures operational and technological data to determine the bus system requirements.

Within the scope of this article, we assumed that only the pure electric drive allows to cope with the environmental challenges cities are exposed. Therefore, hybrid options are not taken into account and have been excluded. Furthermore, cost assessments of fuel cell buses reveal that the expenditures, including the necessary hydrogen infrastructure, are significantly higher than that for battery-powered buses. The studies [4] and [5] predict an approximate cost parity for fuel cell and conventional diesel buses not before the year 2030; whereas, battery-powered buses are promising to achieve cost savings considerably earlier in time [6]. Hence, in this study the current latest battery-powered bus systems are examined such as electric buses following the opportunity (OC) and overnight charging (ON) concept. Both concepts are preferred options of transport authorities considering the number of electric vehicles in current operation [7].

As it has been investigated in several studies the heating ventilation and air-conditioning (HVAC) system is the most energy consuming auxiliary in an electric vehicle and therefore substantially affects the vehicle performance [8, 9, 10]. In case that the energy demand for the HVAC system is provided by the battery system, the vehicle energy consumption increases significantly, particularly when exposed to critical climate conditions, and hence limits the operating range of the electric bus. In order to overcome the vehicle range limitations caused by a battery-powered HVAC systems, many transport operators currently employ fuel heaters (no zero-emission operation possible). Addressing the implications of electric and fuel-powered HVAC systems, in this study the TCO assessment for the OC and ON concept is conducted respectively for both systems. In addition, the assessment is examined for a bus sub-network comprising 17 bus lines featuring different operational conditions and for a procurement in the year 2020 expecting cost degression and technological advanced vehicle components.

The reminder of this paper is organized as follows: In Section 2 the TCO model and its structure are explained, followed by Section 3 describing the case study and the respective assumptions and operational conditions on the bus network and the vehicle parameters. The results of the assessment are presented in Section 4 and the paper finally concludes with a summary and an outlook in Section 5.

1 TCO assessment model for line electrification

The following section focuses on the economic assessment of bus line electrification. In this chapter we merge the operational and technological aspects of electric bus service with economic figures in order to determine the total cost of electrification. The presented approach is based on a TCO model including all cost occurring during the lifecycle of a bus system. In this paper, the most relevant features of the model and data requirements are described. The comprehensive model description and further applications can be found in [3].

The assessment focuses on the individual evaluation of bus lines. As shown in Figure 1 the input data comprises three different data groups: operational, technical and cost data. The operational data represents relevant bus line specifications such as line lengths and velocity as well as the key figures of the vehicle schedules, like daily operation time, frequencies and dwell times. The second group comprises the technical data and parameters of each bus systems considered, whereby the respective input data is required for the vehicle and infrastructure. Further assumptions on the vehicle characteristics with regard to the heating and air-conditioning concepts and engine performances as well as charging efficiencies, energy densities and battery system strategy are to be determined. The cost parameters are assigned to the third group and contain figures on acquisition and operational costs.

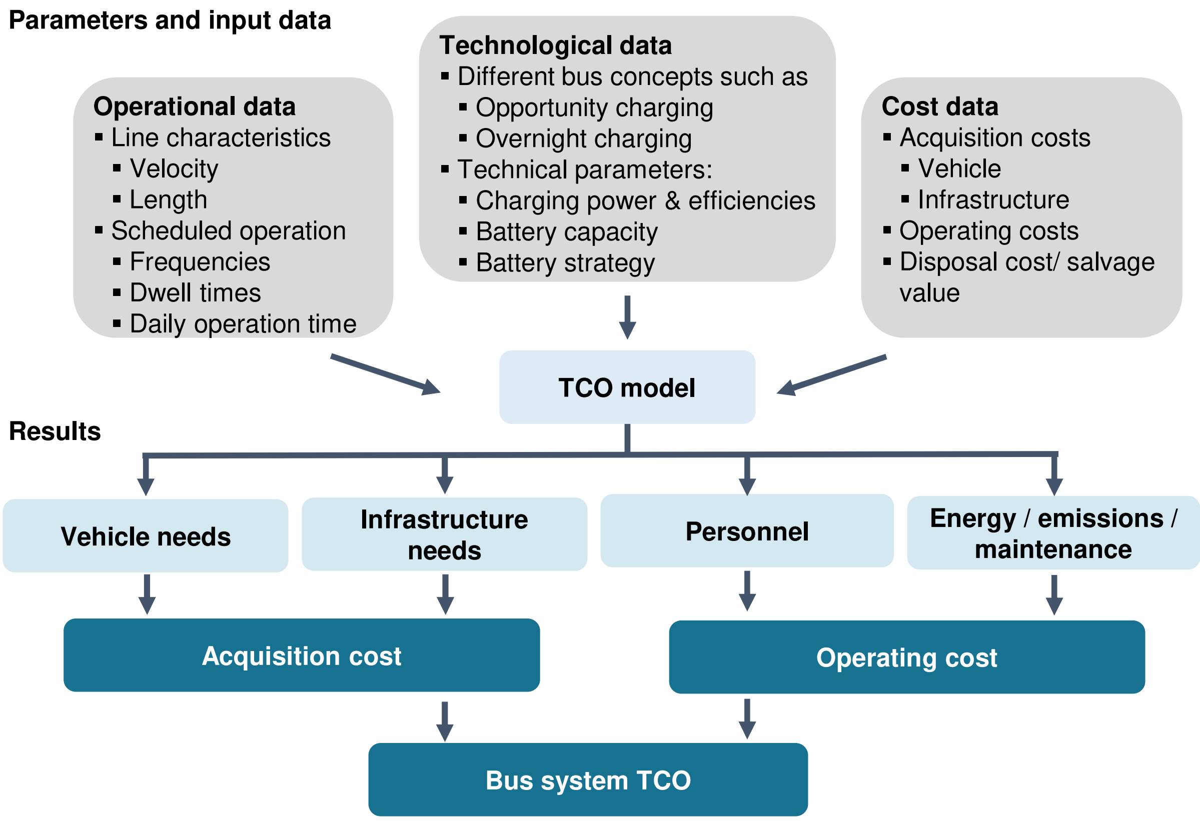

Figure 1: TCO model for the bus line electrification assessment

The electric bus system requirements are determined on the basis of the operational and technical input data. For this purpose, first the bus line and technology-specific energy consumption are determined in order to set the vehicle number and the infrastructure requirements such as required charging power and number of charging stations. The integrated consumption simulation is also the basis for the assessment of total energy demand during the entire operational phase as well as for the determination of the vehicle emissions. Additional operational cost such as for maintenance are also determined individually depending on vehicles and infrastructure configurations, so that different degrees of technology maturity can be reflected. Furthermore, personnel requirements are dependent on the operating data as well as on the technical constraints such as operating range.

Finally, the TCO model determines the individual financial ratios for bus line electrification. The bus system costs result as total costs over the service life. The approach ensures a monetary quantification of the technological and operational boundary conditions and allows for a clear technology preference by the amount of the TCO value.

2 Model application for a bus network

After outlining the main characteristics of the TCO model, the following section focusses on the boundary conditions and assumptions of the application case.

The TCO assessment for bus line electrification is conducted for a sub-network of the Berliner bus network. The sub-network consists of 17 lines which are mainly served from one bus depot with a total network of 381 km and 144 buses (conventional diesel buses at peak hours). Furthermore, the bus lines are operated by two different bus types, 12 m single-deck (SB) and 18 m articulated (AB), and feature a high degree of heterogeneity in terms of the bus line profiles. Thus, the route length as well as the average velocity observed on the lines varies significantly between 5 to 42 km and 15 to 25 km/h, respectively. The selection includes typical bus routes connecting the city center to the suburbs (e.g. L2), central interconnectors (e.g. L7), hybrid lines (e.g. M1), and rapid bus routes (e.g. X1 airport express). The operational characteristics of each bus line is listed in

Table 1.

Table 1: Relevant operational input data for TCO assessment

Bus line / Operation data	**Bus type**	**Route length (km)**	**Daily Operation time (h)**	**Average velocity (km/h)**	**Operation interval (min)**
L1	AB	18,1	20	18.4	10
L2	SB	19.7	19.5	19.5	20
L3	SB	5.4	19	22.2	10
L4	SB	42.3	20	21.6	10
L5	AB	29,9	20	18.1	10
L6	SB	11.5	19	18.2	10
L7	SB	13.0	14	15.5	20
L8	SB	31.4	20	17.3	10
L9	AB	14.0	20	15.7	10
L10	SB	18.2	20	17.6	10
L11	SB	17.4	20	19.0	20
L12	SB	7.8	16	16.0	20
X1[1]	AB	15.5	21	24.2	10
X2	AB	34.7	16,5	21.9	10
X3	AB	40.9	19	24.9	10
M1[2]	AB	30.0	24	18.2	5
M2	AB	31.2	24	20.9	5

For the assessment the boundary conditions and assumptions are derived from current experiences of the electrification projects in Berlin. In addition, a comprehensive literature review and interviews with operators and manufacturers were conducting to collect cost and technological data. As mentioned above the study distinguishes two different charging concepts of electric buses. Thus, the opportunity charging (OC) and the overnight charging (ON) concept is evaluated against the benchmark of conventional diesel bus operation. In case of OC bus systems we exclusively evaluate the conductive charging technology. The TCO model finally determines the electrification requirements such as battery size and charging infrastructure individually for each examined bus line based on real operational schedules. The overview of the most relevant input data on cost and technological assumptions are given in Table 2. All data are forecast for a procurement in the year 2020.

The operating cost for heating and cooling the cabin of the vehicle is determined based on the daily energy demand for a reference year. Thus, the daily demand is calculated taking the vehicle type, the HVAC system and the daily average ambient temperature into account. It is assumed that heating modus is activated for ambient temperature lower than 15°C and providing a required cabin temperature of 17°C. The cooling modus operates from temperatures above 22°C and attains a cabin temperature 3 K less than the respective ambient temperature. For instance, the energy demand for the fuel-fired heater is calculated by determining the daily required fuel consumption for each bus line based on the daily average ambient temperature, the daily operating time and the technical characteristics of the fuel-fired heater such as the efficiency. For the climatic boundary conditions, test reference years (TRY) for Berlin were considered. The TRY consists of actual measured weather sections, so that the monthly and yearly mean values represent the long-term mean from 1988 to 2007. The data contains hourly meteorological data of each day of a year [11].

[1] X is the abbreviated form of express lines. These lines characteristically feature higher velocity and route length above the average.

[2] M is the abbreviated form of metro lines. These lines characteristically hold dense frequencies and daily operating hours of up to 24 h.

Table 2: Relevant cost and technological input data for a procurement in 2020

Input data / Bus technology	D	OC	ON
Vehicle			
SB Bus w/o battery (€)	270,000	325,000	315,000
AB Bus w/o battery (€)	365,000	430,000	420,00
Battery (€/kWh)	-	800	360
Effective battery capacity (%)	-	85	65
Battery longevity (yrs.)	-	10	10
Infrastructure			
Gas station	(300,000)[3]	-	-
Depot charging infrastructure[4] (€)	-	5,000,000	10,000,000
Depot plug-in charging point 75 kW (€)		25,000	25,000
Fast-charging station 150 kW (€)	-	160,000	-
Fast-charging station 300 kW (€)	-	280,000	-
Fast-charging station 450 kW (€)	-	360,000	-
Power transformer fast-charging (€)	-	50,000	-
Charging efficiency (%)	-	95	97
Operation			
Labour (€/h)		33.00	
Diesel (€/l)	1.16		
AdBlue (€/l)	0.58		
Electricity (€/kWh)		0.17	0.17
Maintenance vehicle SB (€/km)	0.35	0.32	0.31
Maintenance vehicle AB (€/km)	0.46	0.43	0.41
Maintenance factor infrastructure (%)	1	2	2
Emissions [CO_2/NO_x/PM] (€/kg)	0.035/4.4/87	0.035/4.4/87	0.035/4.4/87
Financing			
Depreciation period vehicle (yrs.)		10	
Depreciation period infrastructure (yrs.)		20	
WACC[5] (%)		4	

Furthermore, it is assumed that the acquisition cost and maintenance of the electric heater and the fuel-fired heater are equal as well as cooling of both systems is delivered from the same rooftop unit. However, the two different heating systems affect the operating range of the vehicle and hence might require differing bus system designs for line electrification which is finally monetarily determined in scope of the TCO assessment. Differences regarding the system design concerns the vehicles (number and battery capacity) as well as the charging infrastructure (charging power and number of fast-charging stations). Therefore, the number of vehicle operating on a bus line, the vehicle battery capacity and the required charging power can vary. The possible battery capacity is ranging from 300 to 400 kWh for the SB and from 400 to 535 kWh for the AB.[6] However, this specification applies only to ON buses since OC bus systems characteristically are equipped with significant smaller battery capacities (between 60 kW and 150 kW). Whereas, the charging power of the OC system is ranging from 150 to 450 kW as stated in Table 2.

The TCO approach is further based on general assumptions and certain procedures. The basic assumptions of the applied model are summarized as follows:

[3] The investment costs for gas stations is only relevant to derive the maintenance expenditures and are not taken into account as initial installation costs since gas stations are already in place at depots.
[4] These expenditures include regular grid expansion in order to charge the entire fleet at the depot. It is assumed that for ON buses higher peak demand is required compared to OC buses since the buses return to the depot with lower states of charge.
[5] WACC is the abbreviated form of Weighted Average Cost of Capital.
[6] This restriction ensures a minimum of vehicle flexibility and complies with weight limitations without passenger capacity reduction.

(1) The cost assessment of different technologies are carried out individually for each bus line. Possible network effects resulting from a simultaneous evaluation of several bus lines (such as synergies for infrastructure) are not considered.

(2) The considered operational data for determining the total cost are assumed to be constant for each line over the daily operating time. This concerns the velocity, dwell times and intervals. In order to assure that bus operation is sustaining critical conditions, the TCO assessment is conducted for extreme operational conditions such as on climate conditions or vehicle occupancy rate.

(3) It is assumed that the vehicles are assigned to fixed bus lines, which means that the buses mainly serve one line per day.

3 TCO results

The TCO model enables the assessment of bus line electrification. The cost comparison is conducted for OC and ON systems, respectively for a zero emission operation deploying a battery-powered HVAC system and a non-zero emission operation using a fuel-fired HVAC system in heating modus. In order to benchmark cost efficiency the assessment includes an operation by conventional diesel buses. Moreover, 17 bus lines featuring individual operation schedules and two different bus types are examined.

Figure 2 shows the TCO values for different bus operations. For reasons of comparability, the regular personnel cost for drivers are excluded. Only additional required driver costs are considered in case that the number of vehicles of electric bus operation exceeds the number of conventional deployed diesel buses.

The TCO values are highly dependent on the operational and technological parameters. Under the conditions examined, 11 of 17 bus lines shows cost parity or a cost decrease through electrification compared to the diesel bus operation. In particular, bus lines with high daily mileage per vehicle and high annual fleet mileage (metro and express lines) feature superior total cost reductions. For this type of service the OC concept appears the most cost efficient electrification technology benefitting from lower battery capacity and no range limitation compared to the ON buses. The range limitation of ON buses leads to additional vehicle needs which can cause a fleet increase of up to 60 % (L1) for the zero emission operation and around 40 % using a fuel-fired heater (L1).

Employing a fuel-fired heater generally lead to cost savings compared to zero emission operation. Substantial cost reductions are realized if lower electrification requirements regarding charging power and battery capacity are accompanied. The ON bus system greatly benefits from enlarging the operating range. With a fuel-fired heater ranges (even under extreme conditions) of 300 km become possible so that additional vehicle needs can be omitted. Hence, bus lines featuring low daily mileage per vehicle and fleet (such as L3 and L12) are most cost efficiently electrified by ON bus systems using a fuel-fired heater.

The cost difference of zero and non-zero emission OC bus operation is significant less than observed for ON buses. Therefore, fuel-fired heater causes slightly lower operating cost but the impact on the system design is limited compared to the ON buses and affects primarily the charging power.

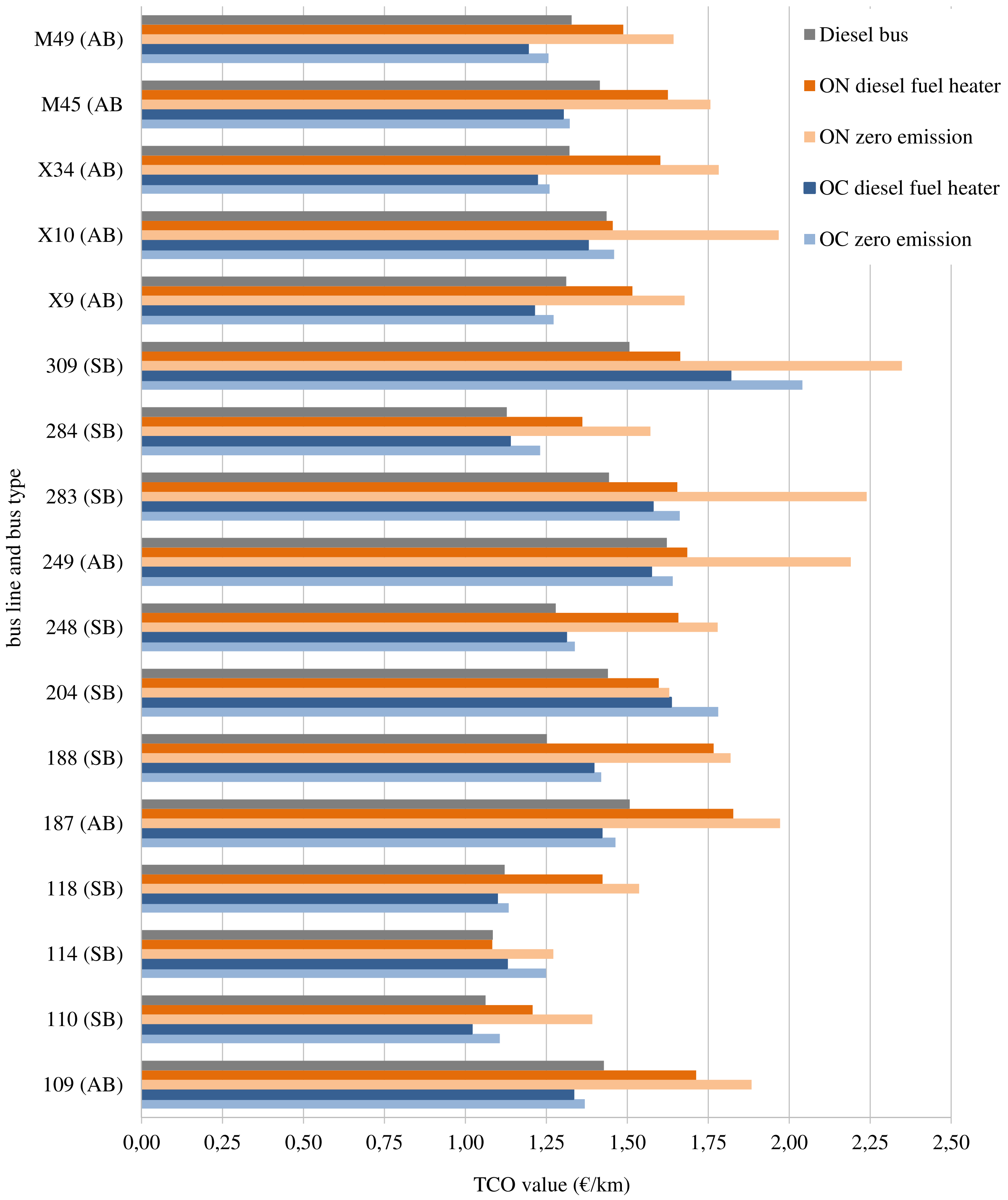

Figure 2: TCO assessment of 17 bus lines for a zero and non-zero emission operation in 2020 (without regular personnel cost)

However, the TCO assessment shows that zero emission bus service in near-term is associated with a cost premium. The cost disadvantage is particularly notable for ON bus system and impede the economic competiveness of the concept compared to the OC. Thus, reducing the energy demand supplied by the battery storage through a fuel-fired heating system opens up a wider range for an economically deployment of ON systems. Apart from economic figures, the ON bus system with fuel-fired heater features advantages with regard to the initial implementation: Since no installation of charging infrastructure outside the depot is necessary and charging events do not need to be scheduled within the regular service hours, the deployment of ON systems, in particular at the early stages of the fleet transition, minimizes the impact of operational processes.

4 Conclusion

In this study, a comprehensive TCO model for the assessment of innovative electric bus systems is introduced. The developed model incorporates operational and technology-related aspects in order to monetarily quantify the electrification cost. In scope of this article the energy demand for the vehicle's heating system and its impact of the bus system design is addressed. The TCO assessment is conducted for the opportunity and overnight charging bus systems considering respectively a zero emission operation using an electric battery-powered heating systems and a bus operation deploying a fuel-fired heater. Finally, the model application is carried out for a bus network consisting of 17 lines.

Under the conditions examined, the deployment of electric bus systems can realize cost advantages compared to diesel buses. The economic feasibility is highly dependent on the electrification requirements taking technological restrictions and operational parameters into account. The presented results reveal that the OC concept is a promising option to electrify high-capacity bus routes, whereas the ON concept can achieve favorable results on bus lines which comply with the vehicle range limitations. In this context, the deployment of fuel-fired heaters aiming to decrease the peak and total energy demand supplied by the battery is an appropriate measure to gain cost efficiency, in particular for the ON system application. Hence, the usage facilitates the implementation of electric bus systems at early stage of market diffusion and should be individually considered and evaluated by the operator. Therefore, an appropriate assessment model is necessary which finally supports the procurement decision process. In addition, an electrification strategy by prioritizing cost-efficient operation profiles can be defined based on the TCO results and enables a cost-based gradual fleet transition.

However, some limitations are worth noting: Apart from the mentioned financial figures additional procurement criteria should be taken into account for the implementation of electric bus systems. In particular, the influence on established operating procedures and the implementation process itself need to be analyzed. For instance, the OC concept usually requires charging stations in public areas which might be linked to special requirements and hence extending the implementation process. Furthermore, charging en route (in case of OC systems) interference existing operating processes and add complexity regarding operational availability of the charging infrastructure. Therefore, further research should include the availability of infrastructure and evaluate the need of additional control centers in order to monitor bus operation.

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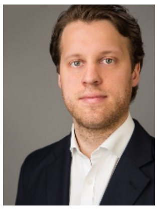

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