

Optimization of fast charging infrastructure for electric bus transportation – Electrification of a city bus network

Alexander Kunith¹, Roman Mendelevitch², Anne Kuschmierz³, Dietmar Goehlich⁴

^{1,3,4}*Department Methods for Product Development and Mechatronics Technische Universität Berlin*

Strasse des 17. Juni 135, 10623 Berlin, Germany

alexander.kunith@tu-berlin.de

²*Workgroup for Infrastructure Policy (WIP), Technische Universität Berlin and German Institute for Economic*

Research (DIW Berlin), Germany

Summary

Rising attention for the electrification of public transportation is given to bus systems using fast charging technology. This concept requires a comprehensive infrastructure to charge buses in operation on route. The combination of charging infrastructure and bus batteries needs a reliable energy supply to maintain a stable bus operation even under demanding conditions. Appropriate and efficient layout of the charging infrastructure is crucial to minimize the total cost of ownership and to enable an energetically feasible bus operation. A mixed-integer linear optimization model is developed to determine the minimum number and location of required charging stations for a bus network while respecting operational and technology-related constraints. Based on this simulation different scenarios are examined in order to assess the influence of battery size, charging power, climate and operating conditions. The findings reveal significant differences in terms of required infrastructure. The paper addresses upcoming challenges for transport authorities during the electrification process of the bus fleets and sharpens the focus on infrastructural issues related to the fast charging concept.

Keywords: bus, cost, fast charge, optimization, public transportation

1 Introduction

The implementation of alternative drive technologies such as battery-powered electric bus systems is of major importance to decrease the exhaust gas emissions of public transportation. In order to evaluate the possible substitution of currently deployed conventional diesel buses, transport companies around the globe are intensifying electric bus trials [1-3]. Rising attention has been recently received by bus systems comprising fast charging technology. This application follows the opportunity charging concept which assumes a comprehensive infrastructure of charging points to recharge the buses in operation by using high charging power [4-6]. Importantly, compared to electric trolley bus systems, the fast charging concept does not require continuously connected overhead wires along the entire bus line. Potential charging spots are the bus stops of the served bus line. Through fast charging en route, operational deployment similar to conventional diesel buses is feasible in terms of range and operating time. Opportunity charging bus systems are characterized by smaller dimensioned battery storages compared to overnight slow-charging buses. The smaller

dimensioned battery storages results in lower vehicle weight, higher passenger capacity and lower investment needs for batteries [7]. The fast charging concept allows diesel similar operation and with relatively low bus investment cost compared to overnight charging or fuel cell buses. From a total cost of ownership perspective this approach has a clear advantage under current conditions [8-10].

However, the system imposes high infrastructure planning requirements since bus routes have to be equipped with sufficient charging stations. The number of charging points in turn has significant influence on the initial cost [11]. Therefore, an appropriate layout of the charging infrastructure is crucial to minimize the capital expenditures. Apart from the economic aspects, the charging infrastructure in combination with the bus battery needs to ensure a reliable energy supply to maintain a stable bus operation even under demanding circumstances. The central issue of optimizing the infrastructure is described by a positioning problem of the charging points within a network and aims to determine the minimum number of required charging stations, while respecting operational and technical constraints.

The efficient application of the opportunity charging concept requires a cost-optimized distribution of charging stations. Thereby, a trade-off between the battery capacity (battery cost and weight) and the number of installed charging points has to be made while ensuring that sufficient energy is replenished to comply with the operation schedule. Based on existing work and the approach introduced in [12-13], this paper presents an advanced mixed-integer linear optimization model. The model solves a capacitated set covering problem to determine the minimum required number and the respective location of charging stations for a bus network while complying with the original operational schedule of the diesel bus. The network perspective allows identifying cost synergies when planning the charging infrastructure for several bus lines at once. Hence, the simulation model considerably supports the optimal infrastructure layout of fast charging bus systems.

1.1 Key constraints influencing fast charging infrastructure planning

In planning a charging infrastructure for electric fast charging bus systems, several technology-related and operational constraints have to be respected that can be classified in five different categories: infrastructure constraints, technology-related, operational planning, bus network and energy consumption. Infrastructure issues encompasses building constraints which do not allow the installation of a charging station due to, e.g., landmarked areas and lacking energy grid capability. Bus stops affected by this should be excluded from further investigations. Furthermore, the planning model needs to recognize bus routes, and in particular shared used stops, to account for cost synergies when installing fast charging stations. In addition, the bus fleet consisting of different bus types has to be taken into account.

The energy which can be recharged at charging stations mainly depends on the operational planning, in particular dwell times and daily operation hours, and technology characteristics in terms of charging power and battery specifications. The dwell times are determined by the bus route schedule and might vary according to the type of the bus stops. The charging power itself is constrained by the available grid power, the battery type and the battery's state of charge (SoC) which is of particular significance for actual bus operation. The battery's charging behavior in terms of the charging power and the SoC can be described by a non-linear function. In addition, to improve the longevity of a battery the depth of discharge (DoD) is intended to be kept relatively small [14-15].

2 Methodology – optimization model to determine the number and location of fast charging spots

In the following section, a general mixed-integer optimization model is described that is able to capture the main features of an electric bus system as described in the section above. While reflecting network, operational and technical constraints, it determines a cost minimizing set of charging stations and respective charging profiles for each bus in the system.

The objective function (1) minimizes the number of charging stations and the resulting construction cost for charging station (c_{pad}) and transformer stations (c_{trans}) which can be shared with several charging points at one station, while serving the required daily demand. The binary variable z_i indicates whether a charging station is built at stop i , while $z_{ident_{id}}$ identifies whether a transformer station is built at station id .

$$\min_{z_i, z_ident_{id}, level_{i,n,b}, e_{i,n,b}, e_before_{i,n,b}, idle1_{i,n,b}, idle2_{i,n,b}, soc_{i,n,b}, load_{i,n,b}} \sum_i z_i \cdot c_pad + \sum_{id} z_ident_{id} \cdot c_trans \quad (1)$$

Numerous constraints are necessary to represent the network layout and the technical parameters of the charging process. A nodal energy balance constraint (2) ensures that the current energy level $e_before_{j,n,b}$ at each stop j , for each trip n and for each line b , is equal to the energy level at the previous station ($e_{i,n,b}$) minus consumption for traveling from the previous stop $consume_{i,j,b,n}$ ¹ plus energy recharged at the current station (loading power in the high power segment $lp1_b$ times a variable loading time in the high power loading $idle1_{j,n,b}$). A distinction between $e_before_{i,n,b}$ and $e_{i,n,b}$ which generally capture the same value, becomes necessary due to the complex charging process and is described further later in this section. This energy balance applies to all stops that are adjacent on a line ($s_{j,n,b}$) except for the first stop of each tour $first_stop_{n,b}$. For these stops the alternative energy balance (3) applies, where $last_stop_{n,b}$ is the bus stop just before the first stop.

$$e_before_{j,n,b} = e_{i,n,b} - consume_{i,j,b,n} + lp1_b \cdot idle1_{j,n,b} \quad \forall j \neq first_stop_{n,b}, n, b \mid s_{i,j,b} > 0 \quad (2)$$

$$e_before_{j,n,b} = e_{i,n-1,b} + lp1_b \cdot idle1_{j,n,b} \quad \forall j = first_stop_{n,b}, i = last_stop_{n,b}, n, b \quad (3)$$

Additional constraints specify the initial charging level of the battery as well as the boundary constraints for specific cases as “depot to first stop” and “return from final stop”. The absolute lower bound ($Lbound_b$) and upper bound are specified in (4) and (5).

$$e_{i,n,b} - consume_{i,j,b,n} \geq Lbound_b \cdot b_cap_b \quad \forall j, n, b \mid s_{i,j,b} > 0 \quad (4)$$

$$e_{i,n,b} - consume_{i,j,b,n} \leq b_cap_b \quad \forall j, n, b \mid s_{i,j,b} > 0 \quad (5)$$

To approximate the non-linear form of the charging power function of a battery, the function is split into two different segments divided by a threshold ($threshold_b$). The high charging power $lp1_b$ applies for charging below the threshold and reduced charging power $lp2_b$ applies above. Charging time can be split between the two segments with $idle1_{j,n,b}$ for high power charging and $idle2_{j,n,b}$ for the duration of reduced charging power. The sum of both charging times cannot exceed the idle time at a stop, reduced by pre- and post-processing time before and after charging (6). Maximum charging power can only be performed if the binary variable $level_{i,n,b}$ is flagged to one (7). In turn, (8) guarantees that the SoC -after maximum charging power is applied ($e_before_{i,n,b} / b_cap_b$) - cannot exceed the threshold, otherwise $level_{i,n,b}$ would flag to zero and maximum charging power would not have been possible in the first place. Equation (9) calculates the final battery level by adding charging with limited power.

$$idle1_{i,n,b} + idle2_{i,n,b} \leq idle_time_{i,n,b} - pre_processing_b - post_processing_b \quad (6)$$

$$1 / idle_time_{i,n,b} \cdot idle1_{i,n,b} \leq level_{i,n,b} \quad (7)$$

$$e_before_{i,n,b} / b_cap_b \leq threshold_b + (1 - level_{i,n,b}) \cdot (1 - threshold_b) \quad (8)$$

$$e_{p,n,b} = e_before_{p,n,b} + lp2_b \cdot idle2_{p,n,b} \quad (9)$$

However, charging with any power can only be performed if a charging station is built (10). Moreover, the required number of transformer stations is determined using (11). Max_stops is the maximum number of stops at one station, and the right-hand side of the inequality gives the number of installed charging stations at one stop that is not already equipped with a transformer station due to grid access of the metro network.

¹ The parameter $consume_{i,j,b,n}$ also captures the routes of the lines by only allowing to travel between adjacent i and j for a given line b .

$$1/\text{idle_time}_{i,n,b} \cdot (\text{idle1}_{i,n,b} + \text{idle2}_{i,n,b}) \leq z_i \quad (10)$$

$$z_{\text{ident}_{id}} \cdot \text{Max_stops} \geq \sum_{i \in \{\text{ident}_i = \text{ident_id}_{id} \cap \text{no_train}_i\}} z_i \quad (11)$$

3 Energy consumption simulation

The optimal distribution of charging points fundamentally results from the efficient replenishment of the bus energy consumption. Therefore, it is essential that the route specific energy consumption is represented adequately. Similar to internal-combustion vehicles, several factors such as vehicle weight, topography of operation area and energy efficiencies influence the total energy consumption. In contrast, full-electric buses feature specific consumptions characteristics, in particular in relation to climate conditions and air-conditioning and heating due to low engine waste heat. Thus, significantly higher energy consumption for extreme weather conditions has to be taken into account [16].

However, the energy consumption cannot be assumed constant over the entire route service. The consumption rather varies with the current circumstances the bus is exposed to. The simulation of the energy consumption can be conducted based on recorded driving profiles for each bus line covering the daily driving characteristics [17]. Such driving profiles are rarely available for an entire bus network. The presented approach can be applied using different raw data formats depending on the availability of high-resolution driving profiles. The data collection for simulation is straightforward and uses only existing data and parameters known to the bus operator.

The energy consumption is determined for each route section and time interval, individually. A route sectioning is conducted in accordance with the bus stops (distance between bus stops) and the section's characteristics such as vehicle velocity are captured. Since bus routes feature different operating conditions, it is required to collect the relevant route section data for all bus lines considered in order to manually generate driving profiles. Since some bus route parameters like velocity are usually given as an average speed over the entire bus line, an additional correction parameter is introduced to indicate route segments with significant deviation from the average value.

Apart from the geographical segmentation, a time-dependent examination has to be introduced due to varying service conditions. During daily operation schedule, parameters such as dwell times, frequencies and driving times vary in order to cope with changing traffic and passenger volumes in peak hours. In the presented approach, daily time intervals are defined reflecting the time-dependent influence of the operational environment. For each time interval, the average passenger occupancy is assigned and schedule parameters can be adjusted specifically.

The influence of traffic volume is set as a function of both time and location and is merged in the above mentioned correction parameter named Volume of Traffic (VoT). Based on the geographical and time-dependent segmentation, the energy consumption is simulated and values are finally assigned to every defined bus route section. However, the ambient temperature also varies during the daily operation and the effect on the energy consumption caused by the temperature is captured separately in the model as explained below.

Overall, through route sectioning and the application of time intervals, the different stress situations caused by exogenous factors during the daily operation can be reproduced. This approach is favored over applying a worst-case scenario assuming constant extreme conditions over the entire day of operation. For instance, the maximum passenger occupancy is only reached for a very small numbers of service trips while the average occupancy rate is around 20 percent for public bus transport in Germany [18].

The energy consumption is calculated according to DIN 70030 [19]. The simulation model encompasses the total tractive force F_{Total} consisting of air resistance, rolling resistance, climbing resistance and acceleration resistance. Complementary, the consumption of auxiliaries such as air-conditioning and heating is added, modelled by the electrical power over the usage duration as a function of the ambient temperature. Table 1 and Table 2 shows the simulation parameters applied for calculating the energy consumption. Since the deployed vehicle type usually varies with the bus route, three vehicle types are considered in the presented study and assigned to each bus line. The model distinguishes between a standard 12 m bus (SB), 18 m articulated bus (AB) and double decker bus (DD).

Table 1: Vehicle parameters

Parameter	Value		
	SB	AB	DD
Air drag coeff.		0,66	
Air density [$\frac{kg}{m^3}$]		1,29	
Cross-sectional area [m^2]	8,28	8,28	10,35
Gravitational force [$\frac{m}{s^2}$]		9,81	
Gradient angle (α)		varies	
Rolling resistance coeff.		0,008	
Vehicle curb weight [,000 kg]	12,5	17,5	18,5
Vehicle speed [$\frac{m}{s}$]		varies	
Total vehicle efficiency (η_t)		0,733	

The total energy consumption for a route segment as the distance between bus stop i , and j on bus line b at trip n is finally determined by

$$consume_{i,j,b,n} = \left(\frac{(F_{Total,i,j,b,n} * s_{i,j,b})}{\eta_t} + E_{aux,i,j,b,n} \right) * VoT_{i,j,b,n}$$

where $F_{Total,i,j,b,n}$ is the total tractive force for route segment i,j on bus line b at trip n , $s_{i,j,b}$ is the length of the route segment i,j of bus line b , $E_{aux,i,j,b,n}$ is the energy consumption of the auxiliary devices for route segment i,j of bus line b at trip n and $VoT_{i,j,b,n}$ is the correction parameter for segment i,j of bus line b at trip n . The time interval is derived from the number of trips.

The total vehicle efficiency is composed of the efficiency of the electric machine, traction converter, battery converter and further electronics. The efficiency values refer to [20] and [21]. The total vehicle mass is the sum of the curb weight including battery (given in Table 1 for the baseline scenario) and the passenger load for a specific bus line and time interval. The daily average electrical power for the auxiliary devices of each bus type is shown in Table 2. It is assumed that the required energy of heating, ventilation and air-conditioning (HVAC) and other devices is provided by the battery. The values presented in Table 2 are simulated for different ambient temperatures scenarios using an electric positive temperature coefficient (PTC) heating and a roof top air-conditioner with electric compressor according to methodology of [22-23]. Referring to these studies, the set temperature for the passenger cabin is 20°C for heating mode and 25°C for cooling mode. The values for the articulated bus (AB) is estimated based on vehicle dimension and passenger capacity compared to a standard bus (SB). The energy consumption for auxiliaries of a double decker (DD) is assumed equal to the consumption of an AB.

Table 2: Daily average auxiliary power for different ambient temperatures

Ambient Tem.	-15°C	-10°C	-5°	0°C	15°C	30°C
Aux. Power SB [kW]	12,23	10,34	8,47	6,61	2,57	5,03
Aux. Power AB & DD [kW]	17,06	14,42	11,81	9,21	3,58	7,01

For further investigations it is stated that the required average power of a PTC heater by an ambient temperature of 0°C is equal to the power required by a heat pump exposed to a temperature of -15°C. Furthermore, for an ambient temperature of 15°C, the auxiliary power for the HVAC is negligible and thus additionally represents a possible scenario in which the energy for heating is provided by a fossil fuel heater.

4 Application case – assumptions and operation conditions

4.1 Bus network

For the application case a representative sub-network of the Berlin BVG bus system was chosen as shown in Fig. 1. The sub-network includes 16 lines that all operate from the same bus depot with a total network of 335 km. Moreover, the sub-network features two transport nodes where several lines converge and share the same terminal station. Additionally, the different bus lines have various intersections among each other. For each bus line, two service trips are simulated corresponding to the outward and return trip between different

terminal stations. Since the service trips of one bus line can differ in length, for each bus line the route with the maximum length is selected. The dataset is exclusively based on real bus schedules on workday operation in order to cope with the peak demand requirements.

The network holds a high degree of heterogeneity in terms of the bus line profiles. Thus, the route length of the lines as well as the number of bus stops vary significantly between 12-36 km and 14-86 stops, respectively. The selection includes typical bus routes connecting the city centre to the suburbs (e.g. 110), central interconnectors (e.g. 100, M85), hybrid lines (e.g. M48) and rapid bus routes (e.g. X9 airport express). As described in the previous section for each bus route, the segment specific energy consumption is calculated based on the average velocity observed on the line varying from 13-29 km/h, the time of day (i.e. occupancy rate and expected congestion), relative congestion with respect to centrality of the line segment, and bus type (12m, 18m, or double decker buses). Dwelling time at a bus stop depends on the type of stop: For final stops, equivalent to terminal stops, the observed average dwelling times (between 3-21min) are considered. Hence, for each bus line and its terminal stops, the daily average dwell time is taken into account. For bus stops with a known high transfer of passengers such as intersections with metro or suburban trains, the dwelling time of 40 seconds is assumed. For all other stops the dwelling time of 20 seconds is predefined. Individual bus stops en route are assigned to exact geographical position in terms of line direction and bus stop locations at crossroads so that the potential for shared charging stations can be realistically assessed. In addition, for the operation simulation it is presumed that the buses start from both direction of a bus line and the daily operating hours are up to 21 hours (1am-4am). Finally, the required number of buses for a line is calculated by means of the average turnaround times and average service frequency. However, it is assumed that each vehicle only operate on one fixed route. Despite this, the model would be capable to include vehicle rotation when operating on different bus lines during daily operation by defining artificial bus routes.

4.2 Battery and fast charging system

Referring to the earlier section, the battery storage system and the fast charging technology are crucial elements when planning the charging infrastructure. In this study, a lithium-ion based battery is applied. Since very high charging power is applied, certain battery types such as lithium-titanate (LTO) or lithium iron phosphate (LFP) are used preferably in current electric bus projects. The longevity of the battery depends on time and usage. Thus, the battery degradation in terms of capacity fading is divided into cycling and calendar losses. Several studies attribute the capacity fading to the applied charging power, the depth of discharge (DoD) and the initial state of charge (SoC) when the charging process is started [24-25]. In order to limit and decelerate the capacity fading process, the battery is deployed under several constraints. In this case study, it is assumed that in operation the battery SoC stays within a predefined range. The lower boundary is also defined as the security margin under which the battery level does not drop in operation. The upper level marks the SoC until the maximum charging power can be applied. On exceeding the upper level, the charging power is reduced. The constraints described are applied equally for all simulated buses and are given as percentages of the battery capacity. The battery capacity in turn varies according to the three different bus types. The installed battery capacity for AB and DD is equal.

Fast charging can be realized through conductive and inductive energy transfer. Currently available and tested charging technologies enable conductive fast charging of up to 500 kW and inductive charging of up to 200 kW using a battery as internal storages [26-27]. The examined variations of all parameters are listed in detail in the scenario description section.

4.3 Cost calculation parameters

Table 3 presents the parameters for the bus procurement for each bus type as well as the respective battery capacity and the cost of the fast charging station, including the grid connection and construction expenses as well as additional cost for a power transformer. The cost data for SB and AB are available from several sources [28-29]. The cost parameters shown are derived for electric bus systems recently available on the German market [9] [30-33]. The low market penetration of electric bus systems still leads to relatively high procurement cost compared to diesel buses. In particular, electrified double deckers are rarely deployed in current demonstration projects and only one bus manufacturer has electric double deckers in its portfolio for the European market [34]. Thus, the costs for a double decker are estimated as stated in Table 3. It can be expected, that with increasing demand and higher production output numbers, the acquisition costs of electric bus systems will further decrease. The cost for the fast charging station corresponds to a conductive charging system.

Table 3: Cost data of electric bus and fast charging infrastructure

Bus type	SB	AB	DD
Electric bus w/o battery [€]	420,000	500,000	550,000
LTO battery incl. replacement [€/kWh]	2,000		
Fast charging components and civil works [€]	250,000		
Power transformer [€]	45,000		

The charging infrastructure planning is ideally conducted from the network perspective in order to leverage synergies. This implies that the simulation model depicts network specific information such as bus line intersections and grid accessibility, assuming that the potential multiple use of the charging infrastructure leads to cost savings. Cost savings are realised if existing infrastructure such as power transformers for the metro network can be used or several charging stations can be placed at the same bus stop. In order to determine the potential of using existing grid infrastructure, the location of existing power transformers within the bus network is analysed and where available assigned to a bus stop. In such a case the cost for a power transformer is omitted and only the cost for the charging station equipment and construction cost are applied. The multiple installation of charging points at the same bus station also leads to cost savings accounting only for one power transformer instead of several. If bus stops en route are geographically identical, it is assumed that the charging station can service several bus lines [35-36]. Thus, only the cost for one charging station including power transformer is considered.

4.4 Scenario description

A sensitivity analysis is applied to determine the most significant factors for the cost of fast charging infrastructure. The following section provides an overview of investigated parameter variations compared to the baseline scenario. For the base scenario, technical and operational assumptions are presented in Table 4. All assumptions are applied to the entire bus network.

Table 4: Baseline scenario

Baseline scenario	
Maximum charging power	200 kW
Battery usage	Security margin set to 35%, max. charging power until 75 % SoC
Battery capacity	90 kWh for SB and 150 kWh for AB and DD
Daily operating time	21 hours
Ambient temperature	-15°C

For the baseline scenario, the parameters charging power and battery capacity are derived from current demonstration projects. The daily operating time reflects a bus operation in a metropolitan area. Furthermore, the ambient temperature is defined as the most energy demanding scenario of all simulations performed.

The examined parameter variations are shown in Table 5. The sensitivity analysis is conducted by only one parameter variation for each simulation. In total 10 simulations are performed.

Table 5: Scenario overview and parameter variations

Scenario variation	
Scenario Charging [#]	300 kW / 500 kW
Scenario Battery usage	Security margin of 15 % and max. charging to 90 % of SoC
Scenario Temperature [#]	-10 °C / -5 °C / 0 °C / 15 °C / 30 °C
Scenario Dwell times	Extended dwell times by factor 2

5 Results

In this study, an optimization model for the electrification of a bus network with fast charging buses was developed and applied to determine the needed charging infrastructure. Simulations on the basis of a real bus network and different scenarios reflecting changing operation conditions were carried out. Finally, the number and location of required charging stations were obtained. It is apparent that the variation of simulation conditions, described in the previous section, leads to substantial differences in charging infrastructure requirements. However, the quality of the impact also varies with each bus line.

[illegible]

The summary of the results for all scenarios is shown in Figure 2 where the number of charging stations and the shared stations with other bus lines as well as the related cost for charging infrastructure is presented. As can be seen from Fig. 2, the required charging infrastructure greatly differs between the considered scenarios.

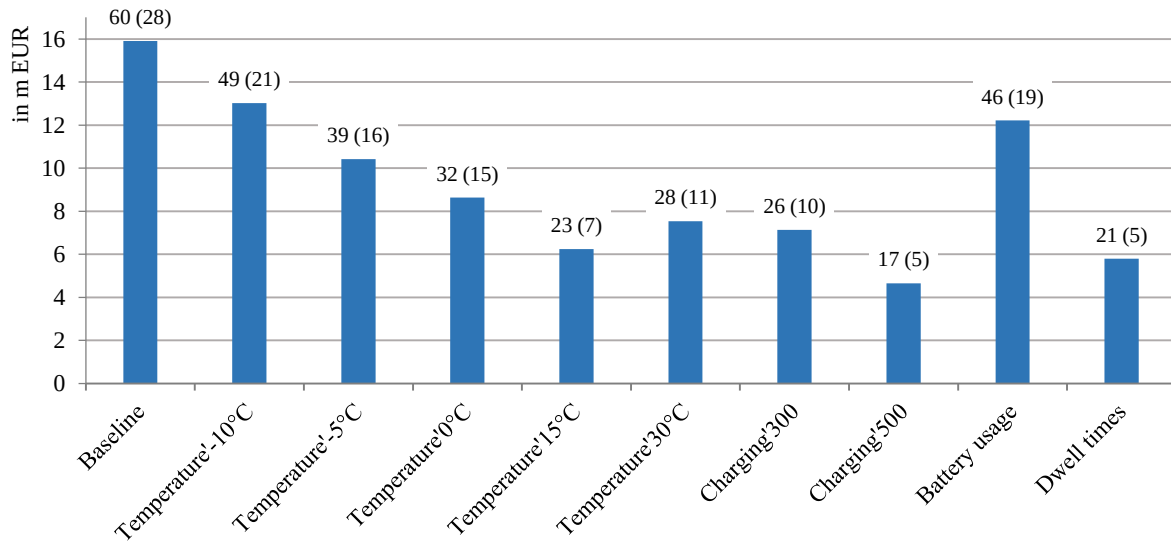


Figure 2: Charging infrastructure cost and number of charging stations (charging stations shared)

In particular, the charging power has significant influence on the number of charging stations, which is consistent with the results obtained in previous studies [37-38]. The extension of dwell times also leads to distinctly lower infrastructure requirements. However, the extension of dwell times in real operation is only possible by adapting the operational schedule or by increasing the number of deployed buses.

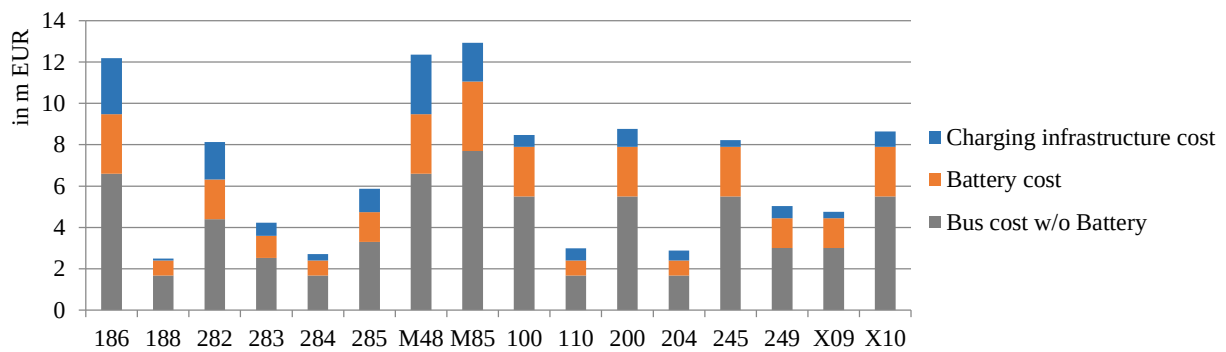


Figure 3: Bus system cost for baseline scenario

As illustrated by Fig. 3 the total cost including the bus without batteries, the battery system and the fast charging infrastructure varies considerably according to the bus line. Bus lines 186 and M48 show the highest infrastructure needs whereas lines 188 and X09 feature low charging infrastructure requirements. The total infrastructure for the simulated bus network of 335 km operated by 126 buses amounts to 15.9 million €, compared to battery cost of 28.92 million € and vehicle cost (without batteries) of 65.84 million €. Therefore, the charging infrastructure for the electrification of the bus network amounts to around 47,000 € per bus route km.

However, as it can be observed from Fig. 3 the battery cost constitutes for a significant proportion of total system expenses. The results of the baseline and the battery usage scenario (see Fig. 2) reveal the importance of investigating a possible trade-off between the charging infrastructure and the (effective) battery capacity. Furthermore, the charging power and the energy consumption for HVAC are relevant parameters affecting the infrastructure complexity. In particular, the reduction of auxiliary power by means of a heat pump (see scenario Temperature 0 °C) facilitates the implementation of fast charging bus systems.

6 Conclusion

In this study we introduced an advanced optimization model for planning the fast charging infrastructure of a bus network. A mixed-integer linear optimization model was developed to minimize the charging infrastructure costs. The applied model determines the minimum required number and the respective location

of charging stations for a real network while ensuring a sufficient energy supply for daily operations. In order to assess the economic impacts of operational and technology-related constraints, several scenarios were examined.

The sensitivity analysis reveals that the complexity of charging infrastructure is highly dependent on the applied assumptions. It is demonstrated that different assumptions lead to infrastructure cost of only one third compared to the baseline scenario. In particular, the charging power indicate remarkable potential to lower the infrastructure cost. Furthermore, the energy consumption of the HVAC system has substantial impact on the infrastructure requirements. The energy efficient supply of heat and cooling is crucial for a cost-effective infrastructure layout. Hence, the deployment of a heat pump might lower significantly the initial cost for charging stations. This study therefore indicates the economic benefits gained from operational and technology-related adjustments. The model is a sophisticated tool for planning and optimizing the infrastructure for fast-charging bus systems and supports transit operators assessing a feasible electrification of bus routes. However, some limitations are worth noting. Although different effective battery capacities for each bus type were simulated, a bus line specific trade-off between battery capacity and charging infrastructure was not investigated. The optimal battery dimensioning for each bus type and bus line from the network perspective should be considered for further research by extending the objective function to include the battery cost.

Acknowledgments

The authors gratefully acknowledge the financial support provided by the German Federal Government. This research was carried out as a part of the German Federal Government's Showcase Regions for Electromobility, the funding is issued by the Federal Ministry of Transportation and Digital Infrastructure.

References

- [1] U.-D. Choi et Al., *Commercial operation of ultra low floor electric bus for Seoul city route*, ISBN 978-1-4673-0953-0, Piscataway, IEEE, 2012.
- [2] K. Erkkilä et Al., *eBUS - Electric bus test platform in Finland*, EVS27 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, Barcelona, 2013.
- [3] J. Laurikko et Al., *Electric city bus and infrastructure demonstration environment in Espoo, Finland*, EVS28 International Electric Vehicle Symposium, Goyang, 2015.
- [4] *Oprid*, <http://www.opbrid.com/~opbridco/images/eevc%20umea%20fast%20charged%20hybrids%20final.pdf>, accessed on 2015-05-06.
- [5] L. Festner et Al., *Foothill Transit Ecoliner Electric Bus Program*, EVS26 International Battery, Hybrid, and Fuel Cell Electric Vehicle Symposium, Los Angeles, 2012.
- [6] J. Miles et Al., *Developing a viable electric bus service: the Milton Keynes demonstration project*, Research in Transportation Economic, DOI 10.1016/j.retrec.2014.09.063, 48(2014), 357-363.
- [7] D. Goehlich et Al., *Stochastic Total Cost of Ownership Forecasting for innovative Urban Transport Systems*, DOI 10.1109/IEEM.2013.6962529, Piscataway, IEEE, 2013.
- [8] *FCH JU - The Fuel Cells and Hydrogen Joint Undertaking*, <http://www.fch.europa.eu/node/790>, accessed on 2013-02-10.
- [9] *IKT-EM*, http://www.ikt-em.de/_media/Gesamtbericht_Wirtschaftlichkeit_von_Elektromobilitaet.pdf, accessed on 2015-05-10.
- [10] O. Vilppo et Al., *Feasibility of electric buses in public transport*, EVS28 International Electric Vehicle Symposium, Goyang, 2015.
- [11] J. Schwürzinger et Al., *Report on Electrified Public Transport Bus System*, Brussels, UITP, 2012.
- [12] K. Berthold et Al., *Planung und Optimierung der Ladeinfrastruktur für E-Stadtbusse*, Der Nahverkehr, ISSN 0179-504X, 7-8(2015), 16–20.
- [13] A. Kunitz et Al., *Planning and optimization of a fast charging infrastructure for electric urban bus systems*, ISBN 978-86-916153-2-1, Belgrade, ICTTE, 2014.

- [14] V. Marano et Al., *Lithium-ion batteries life estimation for plug-in hybrid electric vehicles*, ISBN 978-1-4244-2600-3 Piscataway, IEEE, 2009.
- [15] A. Millner, *Modeling Lithium Ion battery degradation in electric vehicles*, ISBN 978-1-4244-6076-2, Piscataway, IEEE, 2010.
- [16] D. Goehlich et Al., *Technology assessment of an electric urban bus system for Berlin*, ISBN: 978-1-84564-778-0, Southampton, WIT Press, 2014.
- [17] T. Kurczveil, *Energy transfer for electric traffic*, ISBN 978-1-4673-7513-9, Piscataway, IEEE, 2015.
- [18] VDE - Verband der Elektrotechnik Elektronik Informationstechnik e. V., <https://www.vdv.de/statistik-2014.pdf?forced=true>, accessed on 2016-02-02.
- [19] DIN 70030, *Kraftfahrzeuge, Ermittlung des Kraftstoffverbrauchs, Lastkraftwagen und Kraftomnibusse*. Berlin, DIN, 1989.
- [20] R. Schoblick, *Antriebe von Elektroautos in der Praxis*, ISBN 978-3-645-65166-0, Haar bei München, Franzis Verlag, 2013.
- [21] T. Röth et Al., *Entwicklung von elektrofahrzeugspezifischen Systemen*, DOI 10.1007/978-3-642-31986-0_6, Berlin Heidelberg, Springer-Verlag, 2013.
- [22] D. Jefferies et Al., *Energiebedarf verschiedener Klimatisierungssysteme für Elektro-Linienbusse*, DKV Deutsche Kälte- und Klimatechnischer Verein e.V., Deutsche Kälte- und Klimatagung, Dresden, 2015.
- [23] D. Goehlich et Al., *Economic assessment of different air-conditioning and heating systems for electric city buses based on comprehensive energetic simulations*, EVS28 International Electric Vehicle Symposium, Goyang, 2015.
- [24] L. Lam et Al., *Practical Capacity Fading Model for Li-Ion Battery Cells in Electric Vehicles*, IEEE Transactions on Power Electronics, DOI: 10.1109/TPEL.2012.2235083, 12(2013), 5910–5918.
- [25] M. Rogge et Al., *Fast charging of battery buses and its impact on the aging of various Lithium-ion cell types*, ISBN 978-3-937655-30-7, Brunswick, ITS Niedersachsen, 2013.
- [26] B. Propfe et Al., *Cost analysis of Plug-in Hybrid Electric Vehicles including Maintenance & Repair Costs and Resale Values*, EVS26 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, Los Angeles, 2012.
- [27] Bombardier, <http://primove.bombardier.com/projects/europe/germany-berlin-primove-e-bus.html>, accessed on 2015-11-9.
- [28] L. Nurhadi et Al., *A Sensitivity Analysis of Total Cost of Ownership for Electric Public Bus Transport Systems in Swedish Medium Sized Cities*, Transportation Research Procedia, DOI 10.1016/j.trpro.2014.10.058, 3(2014), 818–827.
- [29] M. Pihlatie et. Al., *Fully electric city buses - The viable option*, ISBN 978-1-4799-6076-7, Piscataway, IEEE, 2015.
- [30] ifeu - Institut für Energie- und Umweltforschung - *Electric traction for buses*, http://www.trolley-motion.eu/www/fileadmin/user_upload/EBus_Workshop_Berlin/EBus_Workshop_20.Mai_Berlin_Bergk_ifu_Heidelberg.pdf, accessed on 2015-10-10.
- [31] S. Anemüller, *Bus-Linie 133 der KVB wird elektrisiert*, Verkehr und Technik, ISSN 0340-4536, 2(2015), 50–54.
- [32] A. Uhlenhut, *Erste Elektrobusse neuer Generation: Üstra Hannover erhält drei Fahrzeuge*, Verkehr und Technik, ISSN 0340-4536, 4(2015), 122–125.
- [33] VDV, *VDV-Mitteilungen 2315 - Life Cycle Cost (LCC) bei Linienbussen*, Cologne, beka Verlag, 2010.
- [34] BYD Europe, http://bydeurope.com/vehicles/ebus/types/10_2.php, accessed on 2016-02-23.
- [35] A. Laske, *eBus – Von der Pilotlinie zum Linienbetrieb*, Proceedings of the 7th VDV Conference Electric Buses - Market of the Future, Berlin, VDV, 2016.
- [36] G. de Filippo et Al., *Simulation of an electric transportation system at The Ohio State University*, Journal of Applied Energy, DOI 10.1016/j.apenergy.2013.09.011, 113(2014), 1686-1691.
- [37] M. Rogge et Al., *Fast Charging Battery Buses for the Electrification of Urban Public Transport - A Feasibility Study Focusing on Charging Infrastructure and Energy Storage Requirements*, Energies, DOI 10.3390/en8054587, 5(2015), 4587-4606.

- [38] T. Paul et Al., *Operation and Charging Scheduling of Electric Buses in a City Bus Route Network*, ISBN 978-1-4799-6079-8, Piscataway, IEEE, 2014.

Authors



Alexander Kunith joined the Department of Methods of Product Development and Mechatronics at the Technische Universität Berlin as a research associate in 2013. He is a member of the Research Network Electromobility at the TU Berlin and currently working on the E-Bus Berlin project. His research focus lies on technology assessment in the field of electromobility. In particular, he is dedicated to the electrification process of urban transportation systems.



Roman Mendelevitch joined the Workgroup for Economic and Infrastructure Policy at Technische Universität Berlin, and the Department of Energy, Transport, Environment at the German Institute for Economic Research (DIW Berlin) in 2013. He is a doctoral student in the DIW Graduate Center. He has a broad expertise in applying methods of Operations Research to energy, environmental and transportation-related topics.



Anne Kuschmierz joined the Department of Product Development Methods and Mechatronics at the Technische Universität Berlin as a student assistant in 2014. She is a member of the Research Network Electromobility at the TU Berlin and part of the E-Bus Berlin project. Her research focus is the application of Operation Research methods to the public transportation sector.



Prof. Dr.-Ing. Dietmar Goehlich leads the Department of Methods of Product Development and Mechatronics at the Technische Universität Berlin since 2010. He is also coordinator of the Electromobility Research Network including 26 chairs at the TU Berlin. He became spokesperson for the BMBF research campus Mobility2Grid in Berlin bringing together 36 partners from industry and academia. Previously, he held a senior management position at Daimler AG. His research focus lies on the field of electromobility and innovative methods in the product development process.