PLANNING AND OPTIMAZATION OF A FAST-CHARGING INFRASTRUCTURE FOR ELECTRIC URBAN BUS SYSTEMS

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Abstract: The deployment of battery-powered electric bus systems within the public transportation sector plays an important role to increase the energy efficiency and to abate emissions. Raising attention is given to bus systems comprising fast-charging technology. This concept requires a comprehensive infrastructure to equip bus routes with charging points. The number of charging points in turn has significant influence on the financial investment needs. Therefore, an appropriate and efficient layout of the charging infrastructure is crucial to optimize the total cost of ownership of the deployed technology. The central issue of optimizing is described by a capacity set covering problem. A mixed-integer linear optimization model was developed to determine the minimum number and location of required charging stations for a bus line service while respecting operational and technology-related constraints, particularly the battery charging behavior. Within the scope of the study, different energy consumption scenarios are examined in order to reflect external factors affecting the bus energy consumption such as traffic volume and climate conditions. Furthermore, a sensitivity analysis on the battery capacity and required charging infrastructure was conducted. The findings reveal significant differences in terms of needed infrastructure based on the consumption scenarios and the daily operation time. Moreover, a trade-off between battery size and charging infrastructure has to be made. The model is an advanced tool for planning the fast-charging infrastructure of a bus system and hence supports the financial assessment of respective bus systems. 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: electric bus, charging infrastructure, fast-charging, cost optimization

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 the 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 (Choi et al. 2012; Erkkilä et al. 2013; Halmeaho 2014). Raising 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 (Bedell et al. 2011; Festner & Karbowski 2012; Miles & Potter 2013). Potential charging spots are the bus stops of the served bus line. Through fast-charging en route operational deployment in terms of range and operating time similiar to conventional diesel buses is feasible. Opportunity charging bus systems are characterized by smaller dimensioned battery storages compared to overnight slow-charging buses. The smaller dimensioned battery storages benefit lower vehicle weight, higher passenger capacity and lower investment needs for batteries (Goehlich et al. 2013).

The system imposes high infrastructural requirements since bus routes have to be equipped with charging points. The number of charging points in turn has significant influence on the total costs (Schwuerzinger & Puetz 2012). Therefore, an appropriate layout of the charging infrastructure is crucial to optimize the capital expenditures. 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.

The emerging infrastructural challenges related to the deployment of alternative-powered vehicles such as electric vehicles (EV) are attracting widespread interest and have been recently addressed in the pertinent literature. Research has been conducted in the field of distributing charging point locations for passenger electric vehicles. Frade et al. (2010) developed a covering model to determine the optimal locations for a fixed number of public charging stations for an urban area to maximize the demand covered. Sadeghi-Barzani et al. (2014) established a model for the optimal placing and sizing of fast charging stations for electric vehicles. The approach comprises a mixed-interger non-linear (MINLP) optimization in order to minimize the total cost associated with supplying the energy demand of EV based on the number of charging stations. Liu et al. (2013) introduced a two-step screening method to identify the optimal sites of EV charging stations taking into account environmental factors and service radius, followed by the application of a mathematical algorithm to solve charging stations' optimal capacities. By employing an integer programming optimization model adapted from a Vehicle Routing Problem (VRP), Worley et al. (2012), presented an approach to perform the routing of commercial EV and distribution of charging stations simultaneously. Also based on VRP, Kameda and Mukai (2011) set up a model using the Node Insertion Algorithms for solving the location problem in context of an on-demand electrical bus system in Japan. The placement of charging stations is finally determined by means of taxi probe data. An alternative technique is proposed by Boostani et al. (2010) for an analogous location

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problem of compressed natural gas refueling station. The method applies a heuristic algorithm to solve the arc demand coverage problem of determining the optimal location of refueling station such that the flow demands are met and capital expenditure is minimized.

However, public buses within a transport networks in general differ from the behavior of electric vehicles. In contrast to the above mentioned studies -focusing on passenger electric vehicles- the objective of this paper is to apply an optimization model for an urban public bus network. Central for bus network operations are predetermined and fixed scheduled routes. Hence, optimization models allocating a given number of charging points purposing to maximize the covered demand are not an appropriate approach to solve the infrastructural issue for fast-charging bus systems.

The application of the opportunity charging concept requires a cost related trade-off between battery capacity (battery cost and weight) and number of installed charging points. Only very limited research for electric bus operation had been carried out to broach the described issue. Chao et al. (2013) dedicated their investigation to establish a single depot vehicle scheduling model for a battery-switching station. The multi-objective model minimizes the number of vehicles to serve all trips, the number of standby batteries reserved for the continuous operation and determines the energy supply to meet daily demand. Concerning the charging schedule of fast-charging electric buses De Filippo et al. (2014) developed a simulation model to examine how electric bus charging patterns and queuing times are affected by the number of chargers deployed in the system and the charging policy employed.
A cost-optimized distribution of charging stations was not subject of these studies. To the authors' best knowledge, no comprehensive contributions are made in the field of planning a multi-charging station infrastructure for innovative electric bus systems following a cost optimization approach.

In this paper, a mixed-integer linear optimization model is presented. The model solves a capacitated set covering problem to determine the minimum required number and the respective location of charging points for a bus route while maintaining the same operational requirements which are applied for conventional diesel buses. The model simulation supports considerably the optimal infrastructure layout of fast-charging bus systems.

2. Problems planning the charging infrastructure for bus systems

In planning a charging infrastructure for electric fast-charging bus systems, several technology-related and operational constraints have to be respected. The following section aims to specify relevant aspects and requirements for setting up an appropriate optimization model.

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 and efficiently supplied during daily operation. The energy which can be recharged at charging points mainly depends on the dwell times at bus stops and on the available charging power. The dwell times are determined by the schedule and the operational planning of the bus route and might vary according to the characteristics 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 so that in operation the battery is attempted to perform in a predefined SoC range (Marano 2009; Millner 2010; Lam & Bauer 2013).

Several factors similar to internal-combustion vehicle 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 (Goehlich et. al 2014).

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. Therefore, it is crucial to determine the energy consumption for route sections. A route sectioning can be conducted in accordance with the bus stops and the section's characteristics such as traffic volume and passenger occupancy rate have to be captured by an optimization model. Since bus routes feature different driving profiles it is required to collect the relevant route section data for all bus lines considered. Furthermore, each potential bus stop needs to be evaluated individually in context of dwell times and usage but also regarding possible institutional and local structural reservations against the installation of charging points at certain bus stops. Bus stations affected by such reservations should be excluded from further investigations.

Finally, 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 assuming that the potential multiple use of the charging infrastructure leads to cost savings.

3. Methodology – optimization model

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 representing 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) in the original version of the model minimizes the number of charging stations and the resulting cost of construction at the respective stop (ccosts_i) while serving the required daily demand. The variable z_i indicates whether a charging station is built at stop i .

$$\min_{z_i, e_{i,n,b}, load_{i,n,b}, u_{i,n,b,(1,2)}, load\_level_{i,n,b,l}} \quad \sum_i z_i \cdot \text{ccosts}_i \tag{1}$$

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 tour n and for each line b, is equal to the energy level at the previous station minus consumption for traveling from the previous stop $t_{i,j,b}$ [4] plus energy recharged at the current station (dwelling time of a bus at a stop wz_j times a variable kW charging power $load_{j,n,b}$). Distinction between $e\_before_{i,n,b}$ and $e_{i,n,b}$ which generally capture the same value, namely the current energy level, become necessary due to the complex charging process and is further described later in this section. This energy balance applies to all stops except for the first stop of each tour y_b. For these stops the alternative energy balance (3) applies, where w_b is a stop just before the first stop.

$$e\_before_{j,n,b} = e_{i,n,b} - t_{i,j,b} + load_{j,n,b} \cdot wz_j \qquad \forall j \neq y_b, n, b \mid t_{i,j,b} > 0 \tag{2}$$

$$e\_before_{j,n,b} = e_{i,n-1,b} + load_{j,n,b} \cdot wz_j \qquad \forall j = y_b, i = w_b, n, b \tag{3}$$

Additional constraints specify the absolute lower bound and upper bound and initial charging level of the battery as well as the boundary constraints for specific cases as “depot to first stop” and “retour from final stop”.
To approximate the non-linear form of the charging power function of a battery the function is split into three different segments divided by thresholds $tr_{1,2}$, where different charging power levels lp_{ll} represent the average charging power in the respective segment. To pin down the segment of the energy level at stop j before charging which depends on the battery capacity bt_b, logical equations are employed. Here, $load\_level_{j,n,b,l}$ is a binary variable that flags the respective segment (c.f. Table 1).[5]

$$(e_{i,n,b} - t_{i,j,b}) / bt_b \leq 1 - (1 - tr_l) \cdot load\_level_{j,n,b,l} \qquad \forall i, j, n, b, l = 1,2 \mid t_{i,j,b} > 0 \tag{4}$$

$$tr_l \cdot load\_level_{j,n,b,l} \leq (e_{i,n,b} - v \cdot t_{i,j,b}) / bt_b \qquad \forall i, j, n, b, l = 2,3 \mid t_{i,j,b} > 0 \tag{5}$$

$$load\_level_{j,n,b,'1'} + load\_level_{j,n,b,'2'} + load\_level_{j,n,b,'3'} = 1 \qquad \forall j, n, b \tag{6}$$

Table 1
Boolean values of logical conditions for different energy levels [6]

load_level before charging/ load_level after charging	$e \leq tr_1$	$tr_1 \geq e \geq tr_2$	$tr_2 \leq e \leq 1$
l=1/4	0/1	0	0
l=2/5	0	0/1	0
l=3/6	0	0	0/1

Additionally, it is necessary to account for the fact that during the charging, one of the threshold levels might be passed which would result in over- or understating the battery level after charging. To correct for that the hypothetical battery level after charging is identified with the same charging power using equations (7)-(9). For the first stop of each new tour equations (4)-(9) have to be adjusted following the same logic as applied in equation (3).

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

[5] Quotation marks ‘’ refer to the section of specific entry of a set

[6] Equations (6) and (9) force the conditions to flag true whenever it is possible.

$$e\_before_{j,n,b} / bt_b \leq 1-(1-tr_{l-3}) \cdot load\_level_{j,n,b,l} \qquad \forall j,n,b,l=4,5 \tag{7}$$

$$tr_{l-4} \cdot load\_level_{j,n,b,l} \leq e\_bofore_{j,n,b} \cdot bt_b \qquad \forall j,n,b,l=5,6 \tag{8}$$

$$load\_level_{j,n,b,'4'} + load\_level_{j,n,b,'5'} + load\_level_{j,n,b,'6'} = 1 \qquad \forall j,n,b \tag{9}$$

Next, the amount of energy is calculated that was incorrectly accounted for ($u_{i,n,b,(1,2)} \cdot wz_i$) in equations (10) and (11). Additional constraints are required to make sure that $u_{i,n,b,x}$ is only associated with a non-zero value if a threshold is passed during the charging process. Moreover, constraints ensure that $u_{j,n,b,(1,2)}$ only has a value if one of the thresholds was passed and charging has occurred at the station under consideration.

$$e\_before_{j,n,b} / bt_b - tr_l \leq (1\text{-}load\_level_{j,n,b,l}) \cdot BIG + u_{j,n,b,l} \qquad \forall j,n,b,l=1,2 \tag{10}$$

$$e\_before_{i,n,b} / bt_b - u_{p,n,b,l-4} \geq tr_{l-4} \cdot load\_level_{p,n,b,l} + tr_{l-4} \cdot load\_level_{p,n,b,l+1} \qquad \forall j,n,b,l=5,6 \tag{11}$$

The flags from equations (4)-(6) are used to determine the maximum charging power at each stop in equation (12). Charging is only permitted if a charging station was built at stop p which is ensured by equation (13).

$$load_{j,n,b} \leq \sum_{l=1}^{3} lp_{l,b} \cdot load\_level_{p,n,b,l} \qquad \forall j,n,b \tag{12}$$

$$load_{j,n,b} \leq z_p \cdot BIG \qquad \forall j,n,b \tag{13}$$

Due to the potential overcharging the preliminary energy level at each station $e\_before_{i,n,b}$ potentially needs to be corrected to reach the final level $e_{i,n,b}$ if during charging, one of the thresholds was passed. In equation (14) (14)(14) $u_{p,n,b,(1,2)}$ is multiplied with the respective correction factor and added to or subtracted from the preliminary energy level.

$$e_{j,n,b} = e\_before_{j,n,b} - \left(u_{p,n,b,'1'} \cdot bt_b \cdot \left(1 - lp_{'2',b} / lp_{'1',b}\right)\right) - \left(u_{p,n,b,'2'} \cdot bt_b \cdot \left(1 - lp_{'3',b} / lp_{'2',b}\right)\right) \tag{14}$$

4. Application case - model assumptions

The application of the developed optimization model described in section 3 is conducted under certain constraints and assumptions. In the following paragraph the scope of modeled scenarios is defined and the data basis is specified.

The simulation is exemplarily applied for a reference route. Therefore, the siting of the charging points is determined for a single bus route and a 15-hour service. This bus line covers around 28.5 km (total route including return) and 30 bus stops with the turning point at the 15th bus stop. It is assumed that the stops of the forward and return run are different and no cost benefit can be realized when placing a charging point. For each bus stop the dwell time and the distances between stops are provided as input parameters. It is assumed that the bus, when coming from the depot for the first ride, reaches the initial stop with a SoC of 90% and returning from the final stop of the bus route to the depot at the end of service with a battery capacity not below the critical level of 20%. Reflecting the battery charging behavior, it is presumed for simplification that within a range of 30-70% SoC the energy is transferred with a charging power of 200 kW, outside this range the power is reduced to 100 kW.

Furthermore, three energy consumption scenarios are defined: low corresponding to 0.8-2.4 kWh/km, medium stating 1.0-3.0 kWh/km and high 1.2-3.6 kWh/km. The different scenarios represent the factors described in section 2 such as traffic and temperature causing a varying bus energy consumption. The values within the stated ranges for each scenario are assigned to the route sections which are defined as the distance between two subsequent bus stops. Additionally, the simulation is modeled with two different bus batteries providing 90 kWh and 120 kWh.

5. Results

In this study, an optimization model for the layout of fast-charging infrastructure was developed and simulations on the basis of one bus line and different scenarios were carried out. The number and location of needed charging points to operate the bus route described in section 4 were obtained. The final results are presented in Fig. 1 and Fig. 2. The two figures respectively show the results for daily service with 15 round trips per bus for the low, base and high energy consumption scenario as well as for battery energy capacities of 90 kWh and 120 kWh. Since the last trip of the day determines the final number of required charging stations, the figures display the bus SoC chart (in percentage) during the 15th trip serving the 30 bus stops. The curves feature noticeably SoC jumps which indicate that at the corresponding bus stop a charging station is placed and the bus is charged. Additionally, the charged energy in proportion of the battery capacity is given exemplarily for the base scenario.

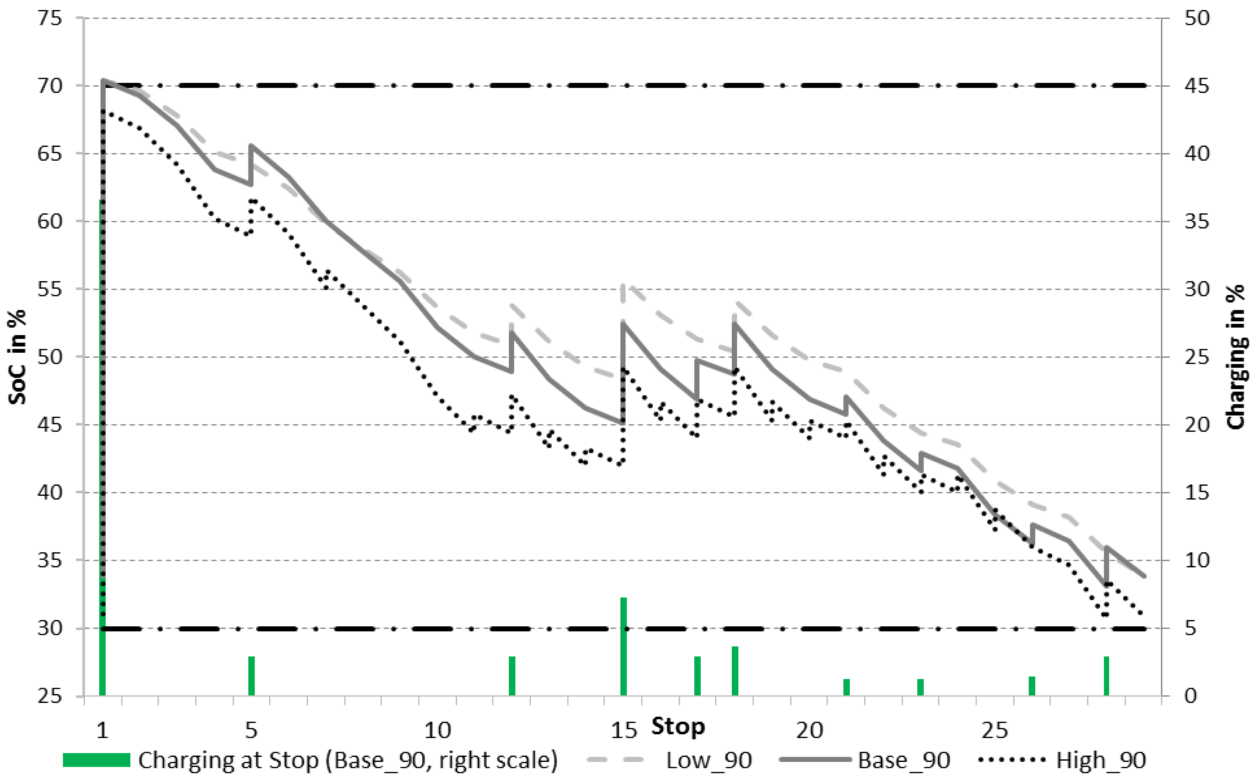

Fig. 1.
Needed charging infrastructure considering three consumption scenarios and a battery energy capacity of 90kWh

As can be seen in Fig. 1, in order to operate the bus line with a 90 kWh battery for the low, base and high scenario, 4, 10 and 19 charging points are required, respectively.

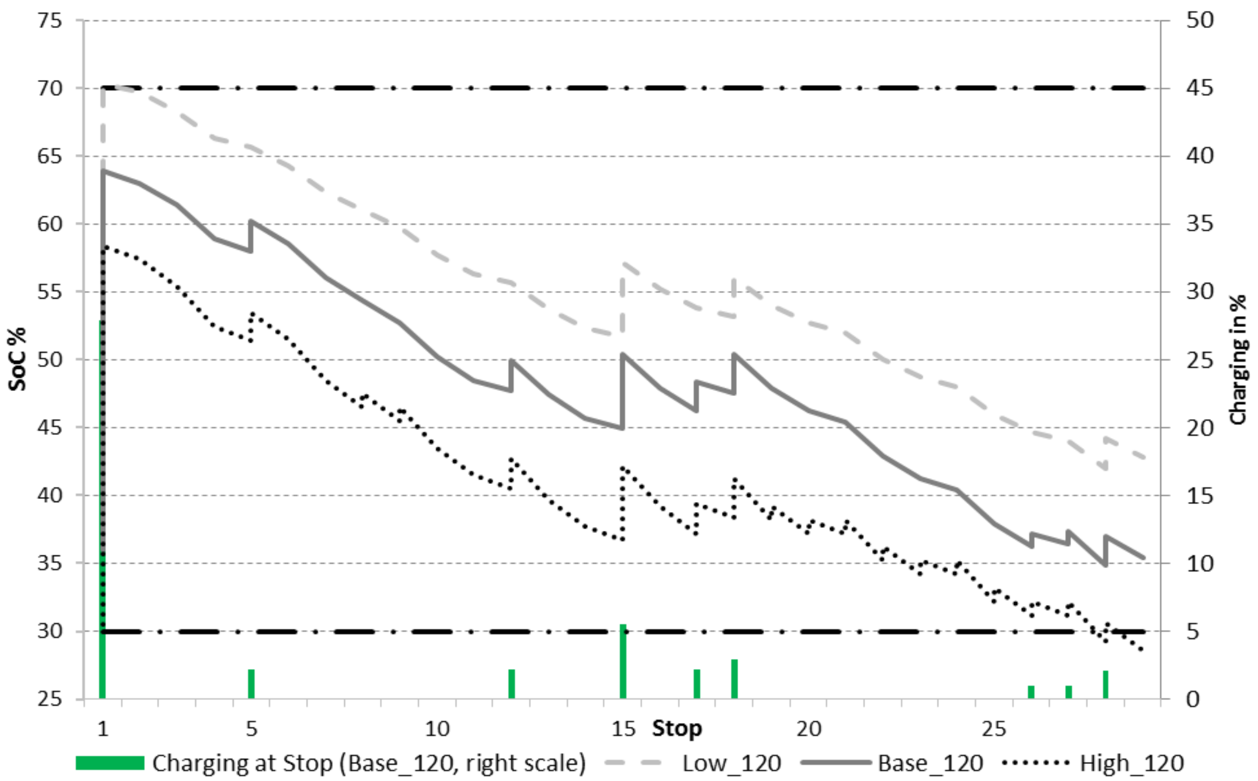

Fig. 2.
Needed charging infrastructure considering three consumption scenarios and a battery energy capacity of 120kWh

The results presented in Fig. 2 reveal that for bus operation with 120 kWh, 4, 9 and 18 charging points are needed depending on the consumption scenario. The number of charging points in Fig. 1 and Fig. 2 are slightly different comparing the equivalent scenarios. A possible significant decrease in charging points due to higher battery capacity could not be observed for the application case. Furthermore, the placement of the charging points comparing 90 kWh and 120 kWh are almost identical resulting from similar SoC curves considering the entire dataset. In addition to the described model variations, the number of round trips was reduced to fewer repetitions (2-4). In case of the 120 kWh and base scenario, for instance, the number of charging point counts 1 when simulating only 2 round trips. Therefore, the daily operation time of a bus affects considerably the infrastructure requirements.

However, these results suggest that the model is capable to provide comprehensive data on central issues of planning a fast-charging infrastructure and thus supports the evaluation of innovative bus systems.

6. Conclusion

The planning and optimization of fast-charging infrastructure for the deployment of electric buses was studied. 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 points for a bus route while taking operational and technology-related constraints, in particular the battery charging behavior, into account. It is demonstrated that different assumptions regarding energy consumption leads to significantly different charging infrastructure requirements. Thus, potential factors causing increased energy consumption need to be carefully analyzed. Contrarily, the battery size does not prove substantial influence on the number of charging points in the application case. Nevertheless, a possible trade-off between battery size and installed charging points has to be attended in order to optimize investment needs. Moreover, the number of scheduled trips, equivalent to the daily operation hours, can cause remarkable discrepancy of the needed infrastructure complexity in terms of installed charging spots.

The model is sophisticated tool for planning and optimizing the infrastructure for fast-charging bus systems. The optimized layout supports transit operators in their financial assessment of respective bus systems. However, some limitations are worth noting. The application case allows the limited simulation of one single bus line. Expected synergy due to the electrification of an extended bus network should be addressed in future work. Furthermore, additional constraints resulting from power grid limitations and availability of the charging spots, in particular for network operation, should be considered for further research.

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