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# CHARGING POWER OPTIMISATION FOR ELECTRIC BUSES AT TERMINALS

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## Abstract

Charging infrastructure has a key role in the operation of electric buses in public transportation. In this paper, mixed-integer linear programming was used to model the bus service and capture the relationship among the network characteristics, vehicles, and charging unit attributes. The model supports the charging power optimisation at terminals to reduce the total operating costs of electric buses and charging units. The model was applied for the bus network of Kőbánya, Budapest. It was found that despite using more expensive high-power chargers, the total cost is lower because of the lower number of electric buses. It was also found that higher charging power does not affect the total cost significantly if it is higher than 350 kW.

*Keywords: electric bus, static charger, charging power, optimisation*

## 1 Introduction

Despite the technological improvements in vehicle drivetrains, the emission of road transport increased in recent years. The operation of pure electric vehicles is an efficient tool to decrease the local carbon dioxide ($CO_2$) emission (e.g., [1-3]). In the case of city buses, the $CO_2$ reduction is especially significant because of the high mileage. Accordingly, public bus service providers are making an effort to reduce the carbon footprint by operating electric buses. Between 2014 and 2019, the number of electric buses in Europe has increased from around 200 to 2200 [4]. The overarching objective of this paper is to elaborate an electric bus charging infrastructure optimization tool for public transport operators that aids in reducing the cost of electrification. Electric buses are mainly charged in a stationary position. This paper focuses on stationary charging; however, electric buses may be charged in movement using dynamic chargers (e.g., catenary). On the base of the location, the following stationary (static) charging strategies are distinguished:
- charging at the depot,
- daytime charging at terminals,
- daytime charging at terminals and stops.

The buses are usually charged at the depot overnight. Thus, the long charging time does not have an adverse effect on the operation, and there is no need for high-power charging units. On the other hand, the high battery capacity increases the purchase cost of electric buses, and additional charging significantly during the daytime may increase dead mileage. Fur-

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thermore, 1 charging unit can serve only 1 bus overnight. Therefore, charging at the depot is proposed in the case of low electric bus numbers, and daytime charging strategies are more favourable in the case of high electric bus numbers. In general, conductive charging units are used at terminals because of the higher dwelling time, and wireless chargers are used at the stop because the bus may be charged immediately as soon it is in a stationary position. Furthermore, wireless chargers have a higher purchase price and lower energy efficiency. According to the experiences, conductive charging is considered mature, and the maximum charging power of conductive chargers is significantly higher than inductive chargers [5].
The charging power of static chargers varies on a wide scale. High charging power may reduce the charging cost significantly but increase the deployment cost. On the other hand, low charging power decreases the deployment cost and decreases the utilisation rate of buses. Therefore, the optimal charging power should be derived from the characteristics of the bus service. Accordingly, a mathematical model was elaborated to optimise the charging power at the terminals. The structure of this paper is the following: after a brief literature review in Section 2, the model of charging infrastructure deployment is elaborated in Section 3. In Section 4, the application of the model is presented, and the result is discussed. Finally, the conclusion has been drawn, and directions for future research are given.

## 2 Literature review

Several papers focus on technology, environmental effects, energy management, and cost-benefit analysis (e.g., [6-10]). The number of studies dealing with the charging infrastructure of electric buses increased significantly recently. It was noted that most of the papers either focus on a static (e.g., [11-12]) or dynamic (e.g., [13-14]) charging infrastructure. Furthermore, the optimal charging infrastructure was determined for specific bus lines instead of the bus network in several papers (e.g., [15]). Albeit charging infrastructure deployment based on the network characteristics may significantly decrease electrification cost [11]. In general, charging infrastructure deployment is based on the modelling of the electric bus service. A mixed-integer linear program was elaborated to determine the optimal fleet composition considering battery electric buses and other fuel alternatives, such as biodiesel and biogas [12]. Major public transport hubs and terminals were considered as candidate sites. The relationship between charging power and the number of buses was not investigated. The deterministic and robust planning of dynamic wireless charging infrastructure was elaborated, considering the uncertainty of energy consumption and travel time in [14]. It was found that the deterministic model may effectively determine the allocation of charging infrastructure. Separated models were elaborated for static, dynamic charging, and battery swapping strategies in [16]. It was found that static charging is less cost-effective. However, the comparison was performed assuming low power at static chargers (90kW). The results also suggested that the service frequency, circulation length, and operating speed of a transit system may significantly impact various charging strategies' cost competitiveness. Mixed-integer second-order cone programming was used to formulate static charging stations' deployment at candidate sites into an optimization problem in [17]. Joint optimization of the bus service characteristics and the power grid was conducted. The effect of various charging power on fleet size was not analysed. A stochastic program was developed to optimize the fleet size and charging stations' locations for electric buses in [18]. The charging demand was aggregated at bus terminals. Electric load-dependent tariff and the uncertainty of weather and traffic conditions were considered. A mixed-integer linear program was elaborated to optimize the charging infrastructure at depots and determine the optimal fleet size and composition considering various electric bus types in [19]. However, the charging power of buses was different; the relationship between charging power and fleet size was not investigated in detail. Papers dealing with electrification on a higher level can also be found. The fleet electrifica-

tion problem was formulated into an integer linear program based optimization problem in [20]. Besides purchase and operational costs, various charging technologies, such as slow and fast plug-in stations, catenary, and wireless chargers, are considered. However, the model does not support decisions regarding where to locate the charging infrastructure.
According to state of the art, the relationship between the charging power at static chargers and the fleet size was not investigated. On the one hand, the infrastructure cost of a high-power charger is significantly higher [21]. On the other hand, a high-power charger may decrease the total time spent with charging significantly. Thus, the less electric bus may be enough. This study hypothesises that the lower fleet cost of electric buses exceeds the higher infrastructure cost of high-power chargers.

# 3 Model

The model of public bus service was elaborated to optimize the charging power. The aim was to define the cost of electrification as a function of charging power. In other words, the optimal charging power is where the cost of electrification is the lowest. In the physical model, the assumptions and limitations of the operation were defined. In the mathematical model, the electric buses' charging was modelled in consideration of the energy consumption and capacity limitations.

## 3.1 Physical model

The focus was put on the bus lines. One turn along the entire route was analysed for each bus line. The following assumptions were made:
- Each bus line is served with a homogeneous bus fleet.
- Buses operating on various lines may differ.

The dwelling times at terminals are given by the schedule. The specific arrival and departure times were not considered. The aggregated energy consumption of one turn was considered. The following limitations were applied for the charging units:
- The charging power at a terminal is constant.
- The aggregated cost of a charging unit may contain both the deployment and operational costs.
- The total cost of charging units at a terminal is the aggregated cost multiplied by the number of units.
- The capacity limitation of the power network was not considered. In other words, the cost of power network development was not considered.

## 3.2 Mathematical model

Since the operation of buses is controlled by the schedule, a deterministic modelling approach was applied. The model of public bus service was formulated into a mixed-integer linear program based optimisation problem. The parameters of the bus service are summarised in Table 1.

**Table 1** Model parameters

| Category | Parameter | Description |
|---|---|---|
| Terminal specific | c | Cost of charging unit [€] |
| | cu | Number of charging unit, integer [-] |
| | $\mu$ | Effective charging time [-] |
| | P | Effective charging power [kW] |
| Bus line specific | $e^-$ | Energy consumption of a turn [kWh] |
| | f | Number of departures in peak hour [-] |
| Terminal and bus line specific | $e^+$ | Amount of charged energy |
| | t | Dwelling time at terminal [h] |

The schedule and the technology significantly influence the effective charging time at a charging unit. The arrival and departure times determine the periods when a bus may be charged. The uneven distribution of the charging periods may decrease the effective charging time. Connecting and re-connecting times at conductive charging units also have an adverse effect on the effective charging time. Therefore, the effective charging time parameter ($\mu$) is introduced to consider these phenomena. The charging infrastructure is determined based on the highest energy demand, which occurs during the peak hour. Dwelling time is the available time to recharge a bus at a terminal between arrival and departure.
The parameters are either one- or two-dimensional. The one-dimensional parameters are either terminal or bus line specific. These are row and column vectors, respectively. Two-dimensional parameters are both terminal and bus line specific. These parameters are matrices. The objective of the optimisation is to minimise the total cost of charging units. Accordingly, the objective function is given in Eq. (1).

$$min\left(\sum_{j=1}^{m}\left(c_j \cdot cu_j\right)\right) \tag{1}$$

Where $c_j$ is the cost of a charging unit at terminal j, $cu_j$ is the number of charging units at terminal j, and m is the number of terminals.

## 3.3 Constraints

The solution of the optimisation is valid if the following constraints are satisfied:
- Eq (2): the total charged energy is higher than the energy consumption.
- Eq (3): the total energy demand is lower than the charging capacity.

An additional electric bus should be assigned to the bus line if the following condition is not met:
- Eq. (4): the charging time is lower than the dwelling time.

$$\sum_{j}^{m} e^+_{i,j} = e^-_i \quad \forall i = 1..n \tag{2}$$

$$\sum_{i}^{n}\left(f_i \cdot e^+_{i,j}\right) \le cu_j \cdot P_j \cdot \mu_j \quad \forall j = 1..m \tag{3}$$

$$e^+_{i,j} \big/ P_j \le t_{i,j} \quad \forall i = 1..n \quad and \quad j = 1..m \tag{4}$$

Where i indicates the bus line and n is the number of modelled bus lines.

# 4 Case study

## 4.1 Simulation

The model was applied for the bus network of Kőbánya, Budapest. The peak hour is between 7 and 8 AM. The aim was to minimise the cost of electrification. The cost of electrification consists of the cost of electric buses and the cost of charging infrastructure. 5 terminals were considered as candidate sites for charging units. In sum, 19 bus lines were considered. 15 bus lines may be charged at 1 terminal (strict demand), 4 lines may be charged at 2 terminals (flexible demand). The total strict and flexible demand were 1607 and 340 kWh at the peak hour, respectively. Homogeneous charging infrastructure was assumed. Namely, the charging power is equal for each charging unit. The effect of schedule adjustments on the number of electric buses was not analysed. The number of charging units (cu) and the amount of charged energy ($e^+$) were the variables. The parameters of the optimisation are as follows:

c - $444 per kW [15],
μ - 0.7,
P - several runs were performed with charging power varying between 100 and 450 kW,
$e^-$ - estimated based on the length of the entire route. Solo bus: 1.2kWh/km, articulated bus: 1.5kWh/km,
f - given by the schedule,
t - time spent at the terminal (given by the schedule) minus 2 minutes because of terminal movements.

The utilization of the charging infrastructure (u) was calculated as the rate of total charging demand and the charging capacity (Eq. (5)).

$$\left(1607\ \text{kWh} + 340\ \text{kWh}\right) \Big/ \left( \sum_j cu_j \cdot \mu_j \cdot P_j \right) = u \qquad (5)$$

The built-in intlinprog function was used in MATLAB.

## 4.2 Results and discussion

The total number of charging units, the number of additional electric buses, and the utilisation are summarised in Table 2.

**Table 2** Simulation results

| P [kW] | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 |
|---|---|---|---|---|---|---|---|---|
| Σcu | 29 | 20 | 15 | 12 | 11 | 9 | 8 | 7 |
| Additional electric buses | 15 | 12 | 12 | 8 | 3 | 1 | 1 | 1 |
| u [%] | 96 | 93 | 93 | 93 | 84 | 88 | 87 | 88 |

It is noted that there is a strong relation between charging power and the number of additional electric buses. Namely, the dwelling time at terminals is not enough to recharge an electric bus. In other words, in the case of low charging power, more electric buses are needed to replace a conventional diesel bus. It is also noted that the charging power does not influence the utilization of the charging infrastructure significantly.

The cost of electrification consists of the purchase price of additional electric buses and the cost of charging infrastructure. The cost of an electric bus was 580000 € [22]. The number of additional electric buses significantly influences the cost of electrification. Accordingly, it is advised to increase the charging power if the number of additional buses decreases. In this case, the optimal charging power is 350 kW. The hypothesis of the study has been confirmed. The relation between the cost of electrification and charging power is given in Fig. 1.

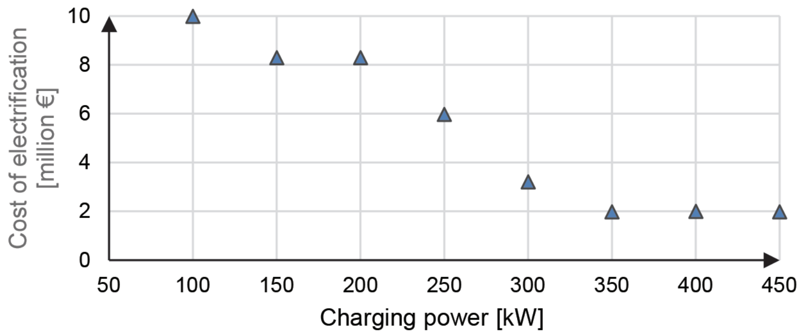


**Figure 1** Cost of electrification according to various charging power

## 5 Conclusion

A mixed-integer linear program was elaborated to support the deployment of charging infrastructure at terminals in consideration of the bus service characteristics. The application of the model indicates that the model supports the minimalization of the cost of electrification. The paper's key finding is that it is advised to increase the charging power if the number of electric buses decreases. Although the trend is to increase the charging power, charging power higher than 350kW did not affect the operation of electric buses, according to the case study. The future direction for the research is to consider other charging technologies, such as wireless and dynamic chargers. Furthermore, other candidate sites, such as bus stops and sections, should be modelled.

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