Evaluation of Modular Infrastructure Concepts for Large-Scaled Electric Bus Depots

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***Abstract*—The city of Hamburg, Germany committed to buy exclusively emission free buses by 2020. Thus, public transportation companies as Hamburger Hochbahn AG (HOCHBAHN) must build a charging infrastructure for large electric bus fleets. Currently HOCHBAHN is planning an urban charging depot for 240 electric buses (EBs). This pilot project is the first large-scale infrastructure project for EB fleets in Germany. New electrical infrastructures for bus depots must comply with local grid capabilities. Furthermore, they have to fulfill highly individual boundary conditions and operational requirements. In the close future, most public transportation companies will face the challenge of developing electric infrastructures for EB fleets. This paper identifies the key components of electric infrastructures for bus depots based on the introduced concept. It outlines decision objectives, that describe the characteristics of a concept, and confronts them among themselves. The authors apply a sensitivity analysis to evaluate how dimensioning of components affects bus charging times and operation. The developed algorithm in this work uses real data and demonstrates that components can be downsized by 8%. Furthermore, the method is extended to evaluate needed capacity for varying module sizes of concepts.**

***Index Terms*—electric buses, electrical infrastructure, decision objectives, charging profiles, power demand, modularity**

I. Introduction

To reduce the emission of greenhouse gases in the city of Hamburg, politics adopted a resolution that local transportation companies must buy exclusively emission free buses from 2020 onwards. Hamburger Hochbahn AG (HOCHBAHN) and Verkehrsbetriebe Hamburg-Holstein GmbH (VHH) are the main public transportation companies in Hamburg. Currently, they operate about 1100 diesel buses in the city area. By 2030, they will operate approximately 1500 electric buses (EBs) in Hamburg. It is in their high interest to go smoothly from diesel to electric bus fleets in the upcoming years. One of the main challenges for this transformation process is to build a large-scaled charging infrastructure for EBs.

In the close future, most public transportation companies in Europe will face the challenge of developing electric infrastructures for EB fleets. A lack of experience in building and operating them may lead to wrong decision-making and bad investments. Thus, public transportation companies in Hamburg are developing a flexible strategy in order to react on market developments and to avoid bad investments as far as possible. Strategies need to take into account different technology developments for the drive train (such as hydrogen and battery electric buses) and the available range of future buses. The key concept for the next years is to use electric buses with large batteries which will be operated as depot chargers. Thus, invests in charging infrastructure on the bus depots is required. Additional infrastructure – for example opportunity charging using pantographs – is an option that is currently under development in order to be ready if future battery developments are not meeting the requirements.

A major requirement for electrical infrastructures on bus depots is to comply with local grid capabilities. Large EB charging depots cause high local load demands on the distribution gird, which may overload the grid. A previous study estimated the electric power demands caused by bus depots in Hamburg [1]. The authors derived a model to calculate the power demand profiles for EB fleets based on real data sets. Currently, HOCHBAHN is operating eight bus depots in Hamburg. If buses use electric heating instead of oil heating the peak power demands of those depots are predicted to vary from 4.4 MW for the smallest depot hosting 40 EBs to 16.6 MW for the largest depot hosting 240 EBs. Due to its outstanding size this paper focuses especially on the latter depot named Gleisdreieck (BBD).

Starting in 2018, public transportation companies in Hamburg are electrifying their bus depots successively. First, HOCHBAHN is equipping BBD with the required amount of electric charging infrastructure for 40 electric buses. In the future, more charging points will be installed, following the procurement of electric buses. With the step-by-step rollout, infrastructure owner intend to gain experience with each extension, to use technological progress in power electronics and to benefit from improvements in the standardization of communication protocols.

Several publications study the impact of electric vehicles (EVs) on power systems. In [2], [3], [4] and [5] EVs are utilized for peak shaving and ancillary services. [6] optimizes location of EV charging infrastructure regarding consumer and power system concerns by particle swarm optimization. However, few researchers address issues concerning electrification of bus fleets in urban areas ([7],[8]). Infrastructure planning has mostly be considered from an opportunity charging perspective as in [9] and [10]. [11] presents an economic evaluation model for EB depots. The authors conclude than life circle costs for bus fleets with battery swapping stations need more subsidies that depots with fast DC charging stations. However, the authors do not consider operational boundary or technical conditions. A lack in research concerning the planning objectives for electrical infrastructure projects on bus depots is noticeable. This paper presents one of the first large-scaled infrastructure projects and defines project specific decision objectives. It takes up on the load profiles modeled in [12] and analysis impact on bus operations by infrastructure dimensioning. From there it highlights how the size of a bus depot and its modules affects the size of electrical components.

Section II introduces the main features of the new planned bus depot BBD. Section III proposes objectives to evaluate EB depot concepts. It introduces a method to evaluate electrical infrastructure in detail. First, an algorithm is developed to evaluate the impact of dimensioning of components on bus charging times. Second, the authors extend the method to analyzes needed capacity of each module depending on the size of a module and bus allocation. Section IV presents results of both analysis. Finally, Section V draws a brief conclusion on the outcomes of this study.

II. Electrical Infrastructure for Bus Depot Gleisdreieck (BBD)

Bus depot BBD is a newly planned bus depot in the City of Hamburg. This brings several advantages. Other than most bus depots infrastructure has not to be reconstructed in running bus operation. Furthermore, location and size of BBD could be chosen according to functional requirements. In future mostly already existing bus depots will be electrified, which are constraint by depot specific boundary conditions.

The electrical infrastructure of BBD is based on AC grids with DC charging units. The main elements of the concept are six identical carports, which are later on as referred to as modules. Earlier investigations estimated a peak power demand of BBD of 16.56 MW [1]. If a distribution grid consumer has a peak demand higher than 50% of the maximum transmission capacity of a medium voltage ring, it is categorized as a large consumer and has to be connected to the HV distribution grid [13]. The local distribution system operator in Hamburg estimated the maximal power to $P_{\max} = 14\,\mathrm{MW}$. Therefore BBD is directly connected to the 110 kV high voltage grid. Figure 1 outlines the concept for bus depot BBD. A substation with two redundant HV transformers converts voltage to 20 kV. The grid layout consists of four open rings. The first ring includes self consumption of the depot and an emergency power supply provided by a local metro station. The three remaining rings contain two carports each. In normal operation the networks operate as a radial network. If a fault occurs on one of two stups, the ring closes. Each carport is equipped with four MV transformers, that are located on top of the carport. Each MV transformer is connected to ten fast charging DC-charging stations.

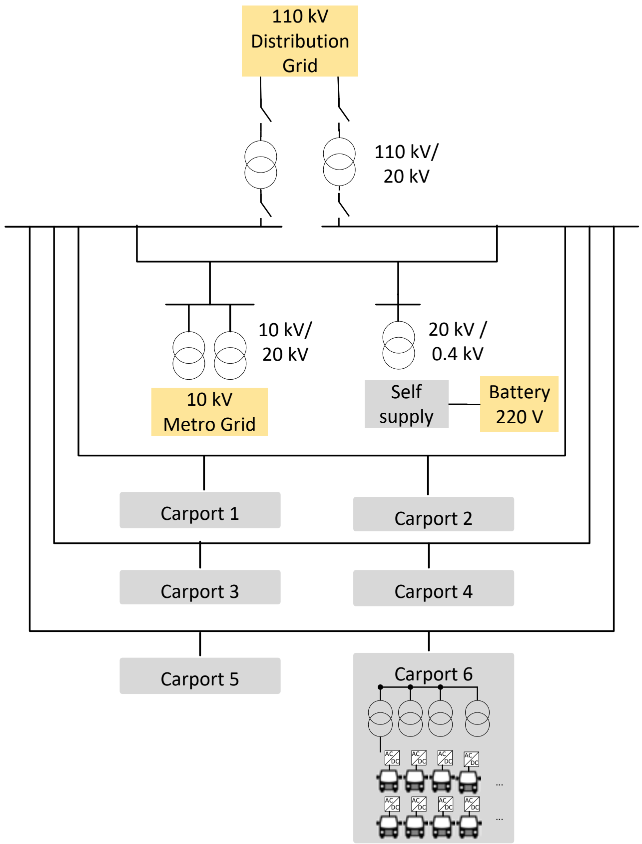

Figure 1. Charging infrastructure concept for bus depot BBD

Table I
Objectives to plan electrical infrastructure concepts on bus depots

Objectives	
1	High supply reliability (n-1)
2	High voltage quality
3	Power demand coverage
4	Low investment costs
5	Uncomplicated system management
6	Secured bus operation
7	Modularity of the system
8	Transferability to other depots
9	Extensibility (renewable energy sources, storage,)
10	Reliable and sufficient emergency supply

III. Methodology

A. *Objectives*

Table I lists ten objectives to evaluate infrastructure concepts for bus depots. Objective 1-5 are general planning criteria for electrical power distribution plants, as suggested in [13]. Objective 6-10 are specific planning criteria, that are in special interest to transportation companies. A common concern in public transportation industry is that EBs are not as reliable in running scheduled bus tours as diesel buses. Objective 6 indicates that charging infrastructure must ensure that buses are sufficiently charged to carry out all tours, they are assigned to. Transportation companies are aware of the potential of renewable energy sources combined with storage systems on bus depots. Hence, Objective 9 implies if a concept is expendable for those possible future add ons. Table II compares Objective 1 to 10 among each other. It

Table II
COMPARISON OF OBJECTIVES.

Objectives	1	2	3	4	5	6	7	8	9	10
1		+	+	-	-	+	+-	o	o	+
2	+		o	-	+-	+	o	o	+	o
3	+	o		-	+	+	o	-	+	o
4	-	-	-		o	-	o	o	-	-
5	-	+-	+	o		+	o	+	-	o
6	+	+	+	-	+		o	o	+	+
7	+-	o		-	o	o		+	+	o
8	o	o	o	o	+	o	+		+	o
9	o	+	+	-	-	+	-	o	+	o
10	+	o	o	-	o	+	o	o	o	

identifies mutually beneficial (+), unrelated or not rateable (o) and controversial (-) objectives. The table shows that Objective 3 "power demand coverage" correlates with Objective 6 "secured bus operation". The former is limited by dimensioning of components as transformers or grid connection capacity. The latter, a secured bus operation, may be disrupted by bus delays, system faults or curtailed charging processes. Downsizing of components decreases investment costs but may effect charging schedules or bus operations. In the following a sensitivity analysis is used to show how downsizing of components affects bus operation.

B. Capacity Curtailment

This subsection describes a sensitivity analysis to determine the effects of capacity curtailment on bus operation. An algorithm is developed that defines the available power capacity and shifts loads to other time slots, if needed and possible. It generates adjusted load profiles that are compliant with available capacity. By varying the power limitation, additional charging times and the lack of charged energy can be quantified.
The power capacity P_{capacity} depending on a variable curtailment factor c is defined as

$$P_{\text{capacity}}(c) = (1 - c) N_{\text{b}} P_{\text{charge,max}} \tag{1}$$

with N_{b} as the number of buses at the depot and $P_{\text{charge,max}}$ as the maximal power per charging unit.

$$P_{\text{charge,max}} = 150\, kW \tag{2}$$

If the grid connection is not curtailed ($c = 0$) all buses can be charged simultaneously. If $c = 1$, buses can not charge at any time. Figure 2 gives an overview on the load shifting algorithm depending on c.

The original power demand P_{original} states power consumption for every bus charging unit b at time interval t. It represents charging power over a period of one week. Every interval is 15 minutes long.

$$i_{\text{length}} = 15\,\text{min} \tag{3}$$

The original power demand profiles are based on the assumption that buses are charged with $P_{\text{charge,max}}$ immediately after they return to the depot. Furthermore, the electrical heating system is pre-conditioned one hour before a bus departs. ΔP defines the difference in total power between available power P_{capacity} and the original total load.

$$\Delta P(t) = P_{\text{capacity}} - \sum_{b=1}^{N_b} P_{\text{original}}(t, b) \tag{4}$$

Equation 5 calculates curtailed load profiles for every bus at every time interval. If ΔP is negative, charging power $P_{\text{curtail}}(b,t)$ reduce equally among all active charging units. If ΔP is positive, charging power $P_{\text{curtail}}(b,t)$ increases up to $P_{\text{charge,max}}$, if required. Increased charging power is needed if charging power of a bus has been curtailed before ($P_{\text{reduced}}(b,t) > 0$).

$$P_{\text{curtailed}}(b,t) = \begin{cases} P_{\text{original}}(b,t)\left(1 + \frac{\Delta P(t)}{\sum_{b=1}^{N_b} P_{\text{original}}(b,t)}\right), & \text{if } \Delta P \leq 0 \\ \\ P_{\text{original}}(b,t) + \frac{\Delta P(t) P_{\text{reduced}}(b,t)}{\sum_{b=1}^{N_b} P_{\text{reduced}}(b,t)}, & \text{if } \Delta P > 0 \end{cases} \tag{5}$$

However, $P_{\text{curtailed}}(b,t)$ is limited to $P_{\text{charge,max}}$.

$$P_{\text{curtailed}}(b,t) = P_{\text{charge,max}}, \text{ if } P_{\text{curtailed}}(b,t) > P_{\text{charge,max}} \tag{6}$$

$P_{\text{reduced}}(b,t)$ defines the accumulated charging power reduction for every bus from the time it returned to the depot until t as

$$P_{\text{reduced}}(b,t) = P_{\text{reduced}}(b,t{-}1) + (P_{\text{original}}(b,t) - P_{\text{curtailed}}(b,t)). \tag{7}$$

Since charging power for every bus is limited, it may occur that power capacity is still available and buses that are not fully charged are not charging with maximal power. An internal loop ensures that power is allocated iteratively as long as possible, see Figure 2. After generating charging profiles for varying curtailment factors $c = [0;1]$, charging times and missing energy can be calculated. If capacity is curtailed, charging power for every bus may decrease. This leads to longer charging times. The average additional charging time due to capacity curtailment yields

$$\Delta t_{\text{charge}}(c) = \sum_{b=1}^{N_b} \sum_{t=1}^{t_{\text{end}}} s_{\text{charge}}(b,t) \frac{i_{\text{length}}}{N_b} \tag{8}$$

with

$$s_{\text{charge}}(b,t) = \begin{cases} 1, & \text{if } P_{\text{original}}(b,t) = 0 \wedge P_{\text{curtailed}}(b,t) > 0 \\ \\ 0, & \text{otherwise} \end{cases}. \tag{9}$$

If power capacity is decreased further, charging process can not be conducted fully and less energy is charged to a bus before it goes on its next tour. The average reduction in charged energy leads to

$$\Delta E_{\text{charge}}(c) = \sum_{b=1}^{N_b} \sum_{t=\vec{t}_{out}(b)} P_{\text{reduced}}(b,t) \frac{i_{\text{length}}}{60 \frac{\text{min}}{\text{h}} N_b}. \tag{10}$$

with $\vec{t}_{out}(b)$ as a vector of times when bus b goes on a tour.

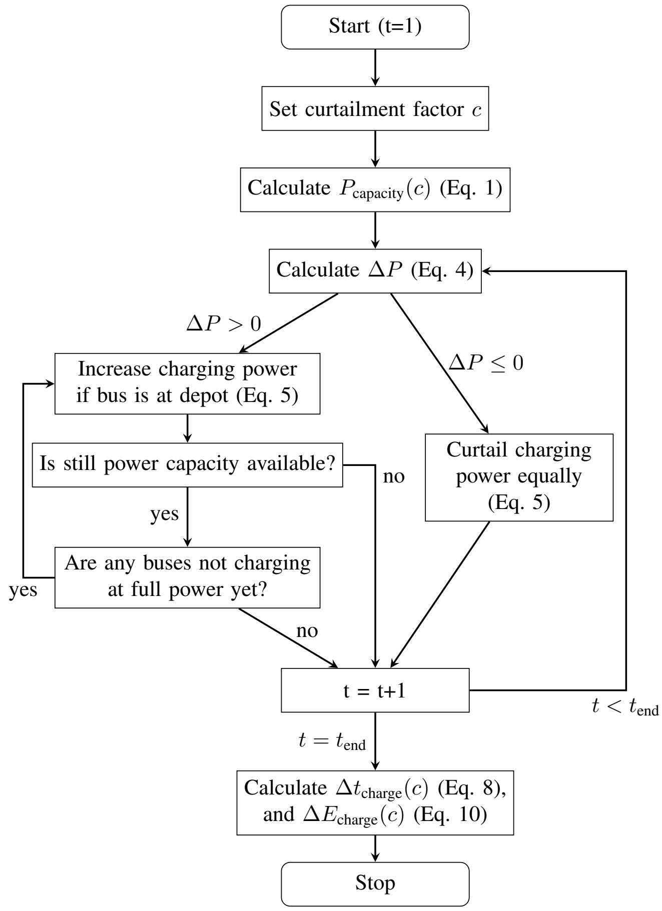

Figure 2. Flow chart for the capacity curtailment algorithm

C. Modularity Criterion

Charging concept for BBD is based on six identical carports. Each Carport is referred to as a module hosting 40 EBs. The modularity criterion shows which power capacity each module must provide to operate buses without any delay. The algorithm is an extension of the capacity curtailment in Subsection III-B. Figure 3 demonstrates the process of this method. Two additional input parameters are added to analyze the impact of module sizes on their needed capacity. First, number of modules at depot N_{m} must be defined. Second, a typ of allocation of buses A over modules must be chosen. Two types of bus allocation, A1 and A2, are determined as:

A1 - Equal allocation: Busses are equally distributed among modules. The first bus that arrives at the depot is assigned to Module 1, second bus is assigned to Module 2, and so on. After one bus is allocated to every module, it starts from the beginning until all buses are allocated.

A2 - Block allocation: Buses are distributed in blocks. If $N_{\text{b,m}}$ defines the number of buses every module has to host, first $N_{\text{b,m}}$ buses are assigned to module 1, next $N_{\text{b,m}}$ buses are assigned to Module 2 and so on.

Next, the capacity curtailment algorithm from Figure 2 is applied for a range of curtailment factors c=[0,0.01,0.02,...,1]. $\Delta t_{\text{charge}}(c)$ and $\Delta E_{\text{charge}}(c)$ are calculated for every c. Two characteristic curtailment factors, c_1 and c_2, are identified depending on N_m ans A.

c_1 - Smallest curtailment factor that causes additional charging times, $\Delta t_{\text{charge}}(c) > 0$. Charging is delayed. For smaller curtailments original charging schedule is unaffected.

c_2 - Curtailment factor that causes maximal additional charging times. From c_2 on $\Delta t_{\text{charge}}(c)$ decreases and $\Delta E_{\text{charge}}(c)$ increases. A lack of capacity causes that EBs can not be fully charged before they go on their next tour.

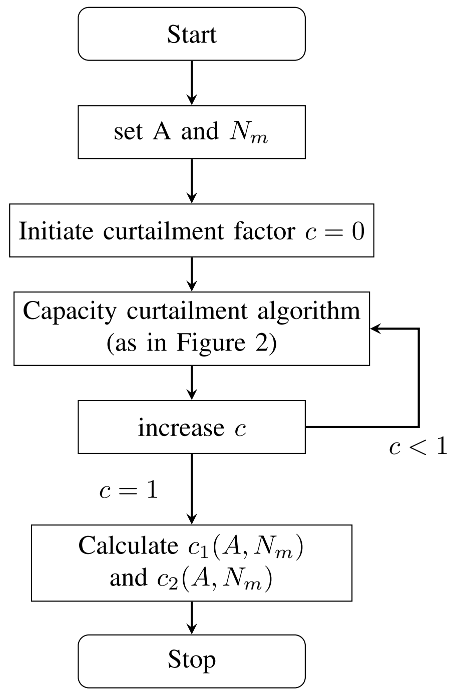

Figure 3. Flow chart for the modularity criterion algorithm

IV. RESULTS

A. Impact of Grid Connection Capacity on Bus Operation

The original load profiles for BBD are utilized to analyze the impact of capacity curtailment on bus operation. However, given data is based on a depot with 127 buses, which will prospectively be located at BBD. Since BBD will host 240 EBs in the future, it is important to mention that results presented in this section consider only half the bus fleet hosted at BBD.

The upper parts of Figure 4 and 5 show the original and curtailed power consumption of bus depot BBD for two exemplary chosen curtailment factor values ($c = 0.61$ and $c = 0.85$). The lower part in both figures demonstrates the charging profile for one single bus. In Figure 4 te power profile is only curtailed a little. Hence, power cut offs can be shifted to other time slots. In Figure 5 power is curtailed severely. Due to the high curtailment factor, EBs are not able to shift missing charging energy to other time intervals.

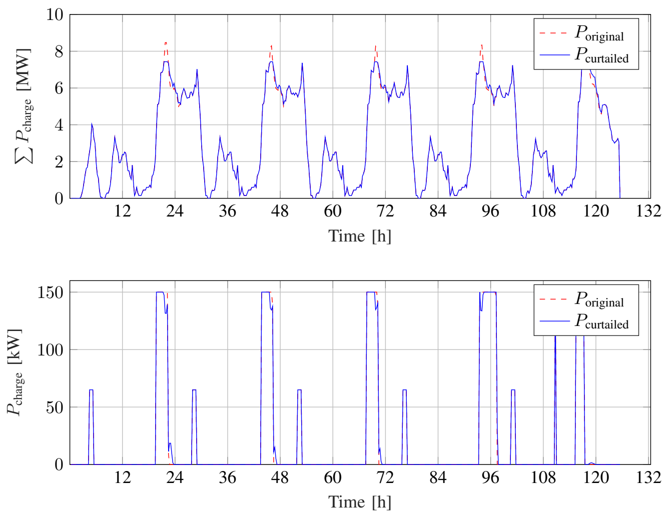

Figure 4. Bus depot BBD: Power demand at grid connection (upper part) and for a single solo bus (lower part) at c = 0.61

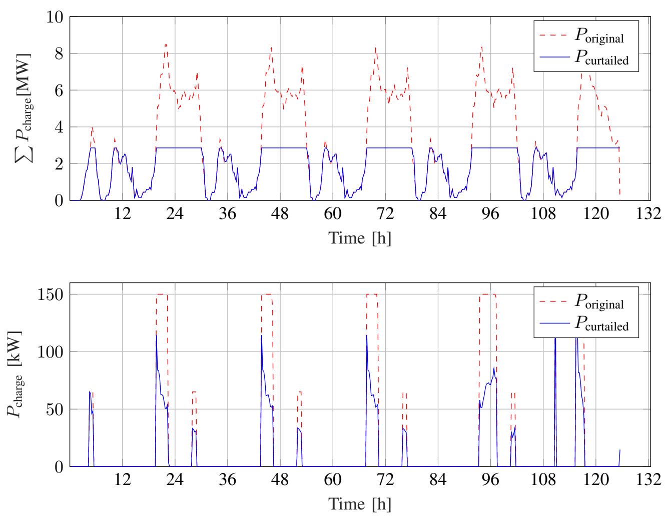

Figure 5. Bus depot BBD: Power demand at grid connection (upper part) and for a single solo bus (lower part) at c = 0.85

Figure 6 depicts additional charging time Δt_{charge} and missing charged energy ΔE_{charge} over c. The plot is divided into three sections.

Original charging: For $0 \leq c < c_1$ original charging profiles can be maintained. The capacity curtailment has no impact on either charging power nor charging times.

Delayed charging: For $c_1 \leq c < c_2$ charging delays. Charging times increase, buses are charging for a longer time before they go on their next tour. Hence, buses are less flexible to leave the depot earlier. Furthermore, it is less time available to maintain or repair buses at the depot without influencing bus schedules. However, if everything goes according to plan, bus operation are steady.

Reduced charging: For $c_2 \leq c < 1$ capacity is curtailed severely. Therefore charging power for single buses are reduced most of the time. If a bus had to reduce its charging power before, it can only make up for it if capacity is available and no other bus has to decrease its charging power, see Equation 5. Due to capacity limitation, this opportunity is given less frequent. Thus, charging times decrease and lacking charged energy increases. EBs are not charged fully before they leave the depot. This may disturb bus operation, if buses state of charge (SoC) is below needed battery capacity to run a specific tour.

For the grid connection capacity curtailment of BBD c_1 and c_2 yield

$$c_1 = 0.54 \text{ and } c_2 = 0.68. \tag{11}$$

Table III shows the needed capacity of BBD, calculated according to Equation 1 for three curtailment factors. If all chargers operate simultaneously, power demand of BBD would be 36 MW. By taking into account load profiles needed capacity reduces to 16.56 MW as predicted in [1]. However, this work reveals that power demand can be reduced up to 11.52 MW by increasing charging times.

B. Impact of Module Size on Curtailment Factors

Figure 7 depicts characteristic curtailment factors c_1 for a favorable (A1) and unfavorable (A2) allocation of buses over varying module sizes. Markers identify curtailment factors for BBD calculated by the modularity criterion in Section III-C. Single points are fitted with a two-term exponential increasing function.

The model is based on 127 buses, which will be prospectively located at BBD. Thus, results of Equation 11, that state c_1 and c_2 for possible grid connection curtailment at BBD, correspond to the curtailment factors for 127 buses per module ($N_m = 1$). Figure 7 highlights that curtailment factors increase with number of buses per module. For one to circa 100 buses per module curtailment factors increase steeply. From there on the fitted curves flatten. The number of modules at a depot has a high impact on minimal needed capacity for each module, if each module hosts less than 100 buses.

If buses are allocated unfavorable (A2), load peaks are higher and maximal curtailment factors are smaller than for equally distributed loads (A1).

If single modules or depots host a large number of buses, depot owner can downsize electrical components to a higher degree. Therefore, the authors assume that grid connection for the future depot BBD with 240 buses can be dimensioned smaller as pre-studies expected. Figure 7 expects $c_1(240) = 0.62$, which reduces the needed capacity to $P_{\text{capacity}} = 13.68$ MW (Table III).

Table III
NEEDED POWER CAPACITY AT BBD FOR VARYING CURTAILMENT FACTOR ACCORDING TO EQUATION 1

c	$P_{\text{capacity}}(c)$	Description
0	36.0 MW	all chargers operate simultaneously
0.54	16.56 MW	original charging profiles, pre-study
(0.68	11.52 MW	no lack of charged energy but curtailed charging)
0.62	13.68 MW	original charging profiles, modified

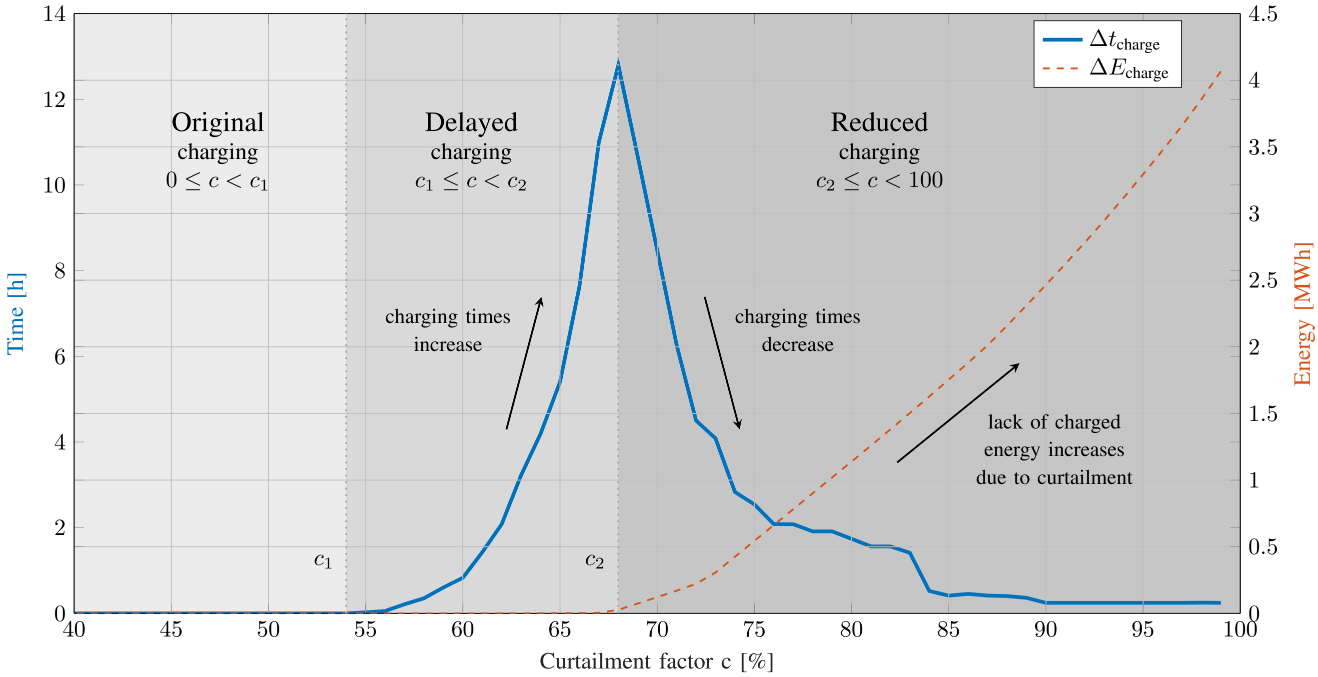

Figure 6. Bus depot BBD: Additional charging time and not charged energy for every bus in average over curtailment factor c. Original, delayed and reduced charging sections are identified.

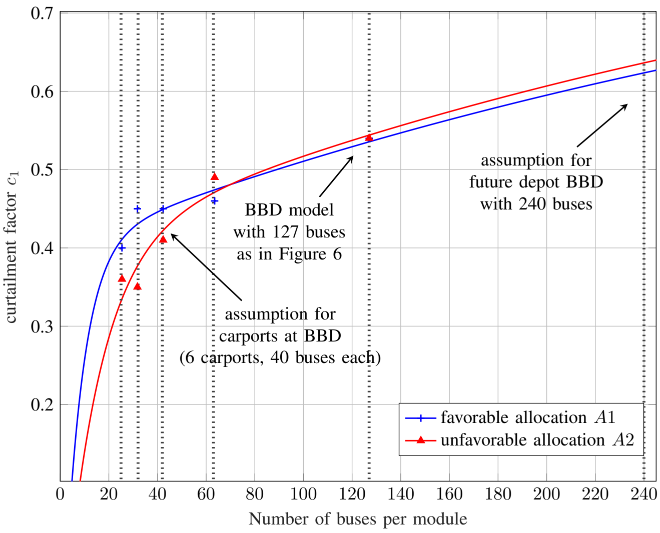

Figure 7. Characteristic curtailment factors c_1 with favorable (A1) and unfavorable allocation of buses (A2) over changing module sizes at BBD. Vertical dotted lines identify expected curtailment factors if BBD is split into 10, 8, 6, 4, 2, 1 modules (from left to right).

V. Conclusion

This paper illustrates an electrical infrastructure concept for one of the first planned large-scaled electric bus depots in the city of Hamburg: Furthermore, it identifies evaluation parameter for planning infrastructure on bus depots. Based on this, the paper introduces a detailed model to evaluate the impact of available power capacity on bus charging times and operation. The authors developed an algorithm that helps depot owners on dimensioning grid connection and module capacity for bus depots.

A sensitivity analysis shows that charging times at the depot start to increase if power capacity is reduced by 54 %. If capacity is reduced further by up to 68 %, charging power decreases and charging times increase. EBs can still be charged in time before they go on their next tour. For a curtailment higher than 68 % charging can not be competed in time. EBs must leave the depot with less charged batteries, which may cause that they are not able to run tours they are scheduled for. This analysis shows that power demand peaks can be decreased by maximal 14 %, if charging power and times are flexible.

Furthermore, the paper reveals impact of depot sizes on needed power capacity. It shows an increasing curtailment possibility with rising number of buses. By hosting 240 EBs, the needed capacity for BBH is expected to be smaller than pre-studies assumed. It can be decreased by 8 %.

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