Modelling the Electrification of Bus Depots using Real Data: Consequences for the Distribution Grid and Operational Requirements

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***Abstract*—The city of Hamburg will fully electrify the public bus service in the coming years, starting from 2018. The transformation process from diesel to electric mobility will have a significant impact on the electrical infrastructure. Due to this, it is of high interest for both distribution system operators and public transport service companies to quantify the electric power demands and the impacts on the local grid infrastructure. In the following study, bus depots of the Hamburg Hochbahn AG (HOCHBAHN) were investigated. Real data from the field was used to model the bus service trips of a whole week, calculate load profiles, predict yearly energy consumption and identify additional parameters for future bus operation, such as required charging power, battery capacity and effects on the buses' standing time. The results show that the bus depots' peak power demand of up to 15 MW might be critical for a 10 kV medium voltage grid that has a power limitation of about 14 MW. Furthermore it was found that the chosen charging algorithm has a major impact on the peak power demand. Mostly, the charging power of 150 kW per bus is sufficient, however in some cases, articulated buses find it hard to get enough standing and recharging time before starting their next service. The results initially quantify the impacts on the distribution grid when whole conventional bus fleets are transformed into fully electric bus fleets. The broad data basis allows to estimate the actual power demands of future bus depots. Hence, this allows improving long-term development of local distribution grid structures.**

***Index Terms*—electric buses; electric vehicles; grid integration; load profiles; operational requirements**

I. Introduction

The city of Hamburg stipulates that from 2020 onwards, only local emission-free buses for the public transport service must be purchased. This restriction is in line with German goals for the reduction of the emission of climate gases and the air-pollution law. For this reason, electric buses are in the focus of transportation companies. However, the transformation process from diesel towards fully electric bus fleets has impacts on both the transportation companies (TC) and the electric distribution grid system operators (DSO).

The transformation process from conventional to electric mobility will have a significant impact on the electrical infrastructure. The concentration of power demand of bus depots hosting more than one hundred buses might lead to local stress for grid integration. Due to this, it is of high interest for both DSOs and public TCs to quantify the electric power demands and the impacts on the local grid infrastructure. One of the TCs in Hamburg, the HOCHBAHN, operates eight bus depots in the city area. The smallest hosting about 50 buses, the biggest will be hosting about 250 buses from 2019 onwards.

These bus depots must provide the electrical infrastructure to fully charge the buses. This imposes high requirements on the grid connection of each bus depot because today the power limitations are below 1 MW which is far from being sufficient for several hundred buses. Thus, the grid connection must be augmented and the target value for the peak power demand of each bus depot needs to be quantified. This is important information for both the TC and the DSO. Due to the long realisation time windows for new grid connections, it is essential to predict the expected power and energy demand prior to the actual transmission process. Moreover, it needs to be identified whether the bus depot can be connected to the 10 kV medium-voltage grid or if it even needs a connection to the 110 kV high-voltage grid.

The integration of electric vehicles has been widely discussed in literature [1]–[3]. Often stochastic analysis or field measurement data is used to model the behaviour of large electric vehicle fleets [4]–[6]. It is expected that mainly residential areas will face problems due to an increase in electric vehicles [7]. But research on the electrification on bus fleets in metropolitan areas is not that intense. There have been some general investigation on some requirements concerning the battery in buses and the electric consumers in buses [8]. The effects on the power system have for example been investigated in [9] and [6]. In [9], the load profile of a bus charging station with four to six slots was investigated after the buses went on a short tour for several kilometres. Unfortunately the results can not be used to predict the load profile for large bus depots with 50 to 150 buses. Reference [6] used stochastic modelling to forecast the load profile for a battery-swap station and identified some key factors that influence the actual load profile. The investigation is specialized on battery-swapping strategies. Thus, using electric bus fleets without the intention to swap batteries, the charging profiles are less flexible and thus the results can hardly be transferred.

In the following study, all bus depots of the Hamburg HOCHBAHN were investigated: Billbrookdeich (BBB), Harburg I (BBH), Harburg II (BBR), Hummelsbuettel (BBG), Langenfelde (BBL), Gleisdreieck (BBD), Suederelbe (BBT) and Wandsbek (BBW). The bus depots are shown in Fig. 1. The modelling process includes temperature sensitive

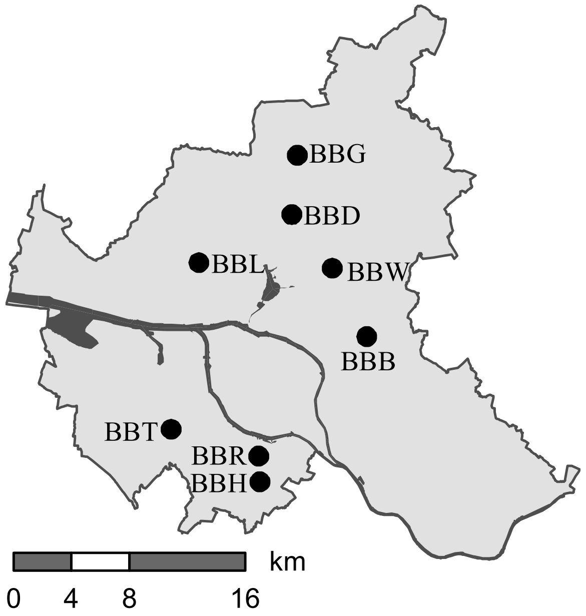

Fig. 1. Map of HOCHBAHN bus depots in Hamburg

models for small-, medium- and large-size electric buses, the allocation of service trips and different bus charging strategies. The assumed electric charging power is 150 kW for each bus. Real data from the field was used to model the bus service trips of a whole week and calculate load profiles. The procedure was executed for eight bus depots from less than 50 buses up to 220 buses. The broad data basis allows generalising the presented methodology in order to estimate the actual power demands of future bus depots. With this, impacts on the distribution grid could be addressed in early planning stages. Hence, this allows improving long-term development of local distribution grid structures.

Section II describes the methodology that was used to obtain models for the electric buses, the bus services and possible charging algorithms. Furthermore it contains the temperature-sensitive calculation of the buses' specific energy consumption and the demand for pre-conditioning. In section III, first results are presented. These include the yearly energy consumption for the whole bus fleet. Furthermore, a comparison between winter and summer times and an evaluation of two different charging strategies is provided. In section IV, the results are used to draw conclusions about the necessary charging power and battery capacities for each bus and the simultaneity of the charging process for the whole fleet. In addition, the effects of reduced standing times of electric buses are illustrated. Finally, the paper provides a short conclusion about the findings and implications for the future.

II. Methodology

A. Modelling of the Buses and the Bus Services

A bus service is defined by start time, end time, type of service/vehicle and the mileage. Every bus depot has to provide services throughout a day. The daily loads vary within a week. From Monday to Thursday, the normal working day load must be provided. On Fridays, the service is extended. During weekends, less service is required. For the calculation of the yearly energy consumption, every weekday must be considered. But for the identification of the maximum power peak, weekend days are not of relevance because the highest level of bus service and thus the highest demand for electrical energy for recharging occurs during the working days. Even if the service is extended on Fridays, the reduced service during the weekend allows the bus operator to prolong the charging process and thus it is very likely to have the highest power demand from Monday to Friday and not during weekends.

There are three types of buses: standard, articulated and double articulated buses. Each bus can only take a service of the respective type of service. For example, only an articulated bus can be used for a service that requires articulated buses. There is no top-down compatibility. When a bus returns from a service, it is available either for charging or the next service. In order to cover delays during the service and on the depot, a general buffer of 15 minutes is scheduled. The bus takes the next service even if the battery has not been fully recharged. In order to simplify the model, it is assumed that a bus is only sent on a service if the battery provides enough energy. Thus, the actual size of the battery is not within the focus of this study (although the results will be used for an outlook of possible requirements on battery capacity). Only the used energy during the service (mileage and consumption) is of relevance for the charging process.

Before a bus leaves the depot, pre-conditioning might be necessary. Pre-conditioning in the context of this paper means the electric heating of the bus prior to its service to ensure a comfortable climate. The energy consumption of pre-conditioning depends on the ambient temperature. For the load profile, a worst-case value of 65 kW heating power for one hour is assumed. This should be enough to heat-up the bus from -15 °C to +20 °C. In case the bus is not fully charged when the pre-conditioning starts, the battery charging power is reduced by 65 kW in favour of the electric heating. In the model, the assumptions for pre-conditioning are the same for standard, articulated and double articulated buses. Although in reality these values will vary because the double articulated buses clearly have a higher mass and volume, 65 kW for one hour is an average assumption over all used bus types. The simulation results also include that a bus might be heated-up twice a day in case the standing time between two services is larger than two hours. In this case, it is assumed that the bus requires a second pre-conditioning before it leaves the depot for the next service.

B. Distribution of Bus Services to the Vehicles

Big transportation companies usually use a management system on their bus depot that distributes buses on the services in an intelligent way in order to optimize bus operation and reduce operational costs. It was not within the scope of this work to integrate the complexity of such a management system. Instead, a first-in-first-out (FIFO) approach was chosen to distribute the bus services to each individual bus. In reality, the bus operator would try to distribute the services in a way that fully charged buses take the long services and almost empty buses take the shorter services. This can have an impact on the results as

TABLE I
ENERGY CONSUMPTION OF THE ELECTRIC BUSES AT DIFFERENT AMBIENT TEMPERATURES. +20 °C REPRESENTS THE SCENARIO WITHOUT ELECTRIC HEATING.

	Symbol	-15 °C	+20 °C	+28 °C	Unit
standard bus	C_S	2.11	1.40	1.60	kWh
articulated bus	C_A	3.25	2.05	2.40	kWh
double art. bus	C_DA	4.50	2.68	3.17	kWh

shown in sections III and IV because some buses might be fully charged earlier and others would take more time to be fully charged. With regard to the calculation of the peak power demand, the FIFO approach provides a relatively robust calculation for the power requirements of the point of common coupling (PCC).

C. Electric Energy Consumption of the Buses

For each bus type, the transportation company has been collecting field data in order to quantify the consumption of electrical power on the road. The values are listed in Table I. The energy consumption on the road strongly depends on the ambient temperature. Further influences like road topography or varying passenger volume are not considered in this model.

For the calculation of the peak power demand in winter, an ambient temperature of -15 °C is assumed.

The yearly electrical energy consumption is temperature sensitive. It uses a model in which the values of Table I are interpolated. Weather data of the German Meteorological Service were used to feed the model with the required ambient temperature curve for one year. The results in section III are based on the weather data of the year 2015 at the measurement point in Hamburg Neuwiedenthal. The values are shown in Fig. 2. It can be seen that there are hardly temperatures below -5 °C and thus the peak power calculation using -15 °C is conservative.

The ambient temperature influences the pre-conditioning and the actual energy consumption during service operation. For the pre-conditioning, the daily lowest temperature was used because buses need to be heated-up in the early morning hours that usually are the coldest hours during the day. For the energy consumption on the road, the temperature value was used that causes the highest consumption. Usually in winter days this is the lowest value and in summer it is the highest value. Fig. 3 shows the yearly change in specific energy consumption of the buses. Fig. 4 shows the daily energy that is needed for the pre-conditioning of the buses.

D. Statistical Projection for Fully Electrified Bus Depots in 2030

The transformation process will start in 2019 and will be completed in 2030. Until 2030, the bus services in Hamburg will increase and the amount of vehicles will change on each bus depot. Furthermore, standard buses will be replaced by articulated buses or vice versa. In addition, a bus depot in Mesterkamp will be replaced with a new one in Gleisdreieck (BBD). In order to cover the changes in vehicles and services on the bus depots, a factor is calculated for every bus depot to predict future energy and power demands in the year 2030.

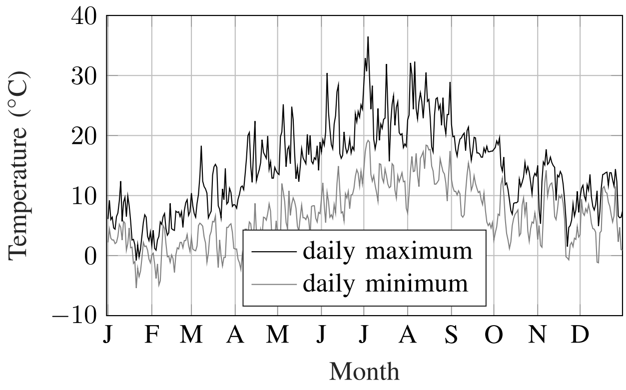

Fig. 2. Temperature trend in Hamburg in 2015, data from the German Meteorological Service measurement point in Hamburg Neuwiedenthal.

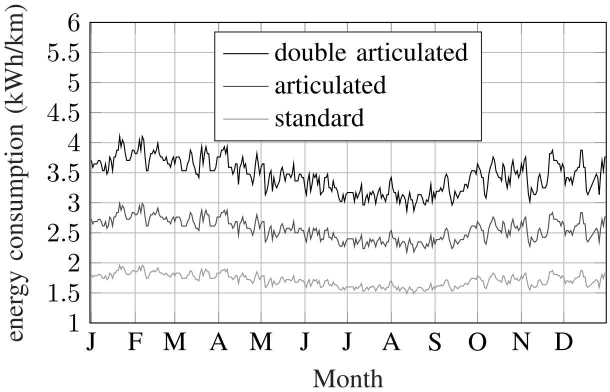

Fig. 3. Specific energy consumption of the electric buses due to the temperature sensitive model for weather data in Hamburg in 2015.

The factor k_{30} is calculated by using today's and future energy consumption. It is assumed that an increase in energy demand results in a linear increase in power demand:

$$k_{30} = \frac{E_{30}}{E_{15}} = \frac{E_{30}^{\mathrm{S}} + E_{30}^{\mathrm{A}} + E_{30}^{\mathrm{DA}}}{E_{15}^{\mathrm{S}} + E_{15}^{\mathrm{A}} + E_{15}^{\mathrm{DA}}} = \frac{M_\mathrm{S} \cdot C_\mathrm{S} \cdot \frac{n_{30}^{\mathrm{S}}}{n_{15}^{\mathrm{S}}} + M_\mathrm{A} \cdot C_\mathrm{A} \cdot \frac{n_{30}^{\mathrm{A}}}{n_{15}^{\mathrm{A}}} + M_\mathrm{DA} \cdot C_\mathrm{DA} \cdot \frac{n_{30}^{\mathrm{DA}}}{n_{15}^{\mathrm{S}}}}{M_\mathrm{S} \cdot C_\mathrm{S} + M_\mathrm{A} \cdot C_\mathrm{A} + M_\mathrm{DA} \cdot C_\mathrm{DA}} \tag{1}$$

M is the total mileage for all buses of the same bus type in 2015 or 2030, C is the specific energy consumption for each bus type (value for -15 °C from Table I), n is the amount of buses on a depot for each bus type in 2015 and 2030.

III. RESULTS

A. Yearly Energy Consumption of the Bus Depots

Fig. 5 shows the yearly energy consumption of each bus depot. It varies from 8 MWh for the small depot Harburg II to more than 28 MWh for the new depot in Gleisdreieck. The total energy consumption of the eight depots is about 132 GWh per year. This is in the order of the yearly energy consumption of all metro lines in Hamburg. The share of energy that is needed for vehicle pre-conditioning is relatively small compared to the energy that is used for traction.

The energy consumption model is temperature sensitive. It was found that when the yearly average in temperature is

TABLE II
PEAK POWER DEMAND INCLUDING ELECTRIC HEATING AND NUMBER OF BUSES IN A BUS DEPOT

Symbol	Quantity	BBL	BBW	BBB	BBD	BBG	BBH	BBT	BBR*
$P_{\max}$	peak power demand	11.0 MW	10.4 MW	9.3 MW	15.1 MW	7.3 MW	5.5 MW	4.4 MW	3.2 MW
n_{bus}	number of buses	153	137	127	220	104	82	47	40
p_{bus}	average power per bus	72 kW	76 kW	73 kW	69 kW	70 kW	67 kW	94 kW	80 kW
g	simultaneity factor	0.48	0.51	0.49	0.46	0.47	0.45	0.63	0.53

* the bus depot Harburg II (BBR) will host about 70 buses in 2030, thus the peak demand increases to about 5.7 MW

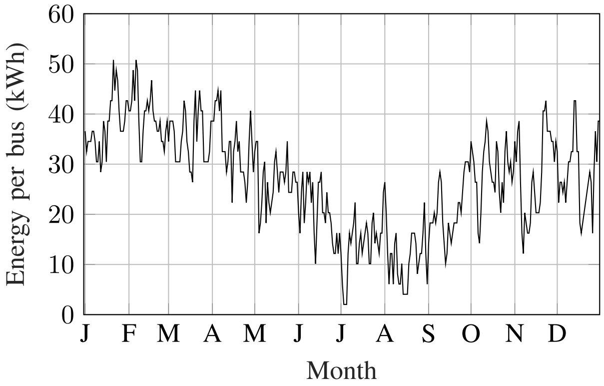

Fig. 4. Temperature sensitive energy consumption for pre-conditioning of a bus for the weather data in Hamburg in 2015.

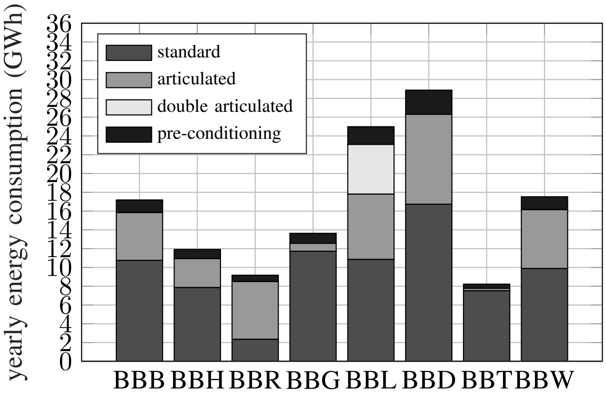

Fig. 5. Yearly energy consumption of the eight HOCHBAHN bus depots after full electrification of the bus fleet in 2030, weather data from 2015 was used.

increased by 5 K, the energy consumption is decreased by 7.5% (about 10 GWh). A decrease of 5 K results in an increase in energy consumption of 8.8% (about 12 GWh). The weather data from 2011 to 2015 has been used to provide an assessment of the variations in total energy consumption. Within the five years, the estimated total energy consumption stays within ± 2.2%. Thus, the calculation based on the weather data of 2015 seems resilient.

B. Peak Power Demand of the HOCHBAHN bus depots

For the calculation of the daily and weekly load profile, worst-case weather conditions (-15 °C) are assumed. In winter, the energy consumption of the bus is largest and the bus requires pre-conditioning. The peak power demand is defined as the maximum power demand in a whole week.

In total, eight bus depots have been investigated. The peak power demand for 100% bus electrification is shown in Table II. It can be seen that except for Gleisdreieck (BBD), all bus depots can be connected to the 10 kV medium-voltage grid which has a power limit of about 14 MW. But the new depot BBD will require more power, thus it must be connected to the 110 kV high-voltage grid. The figures in Table II include electric heating and implement an immediate charging algorithm. Detailed analyses are provided in the following subsections.

C. Load Profiles of the Bus Depots with and without Electric Heating

Fig. 6 shows the time dependent power demand of the bus depot in Langenfelde with (black) and without (grey) electric heating and pre-conditioning of the buses if all diesel buses are replaced with electric buses. The charging algorithm was chosen to fully charge the bus as soon as it arrives in the depot. The following things can be concluded from the results: The grey curve has a much lower peak demand (8 MW vs. 11.5 MW). The pre-conditioning leads to a high peak during the mid-day. Furthermore it leads to an extension of the night-hour peak demand until 6 am, which otherwise would stop at 3 am. The load profile stays almost constant from Monday to Thursday, i.e. equal services lead to nearly equal power demands despite changes in the distribution of services to the individual buses.

In the grey curve, the load profile reaches zero at about 3 am. From this it can be concluded that the charging power for each bus (150 kW) is sufficient to recharge the batteries after the daily service and prior to the next day, because otherwise the load profile would not reduce to zero. But the same cannot be concluded for the curve that includes electric heating and pre-conditioning. Thus, further analysis needs to be done on this issue.

D. Load Profiles for Different Charging Strategies

Fig. 7 shows the expected load profile from Monday to Friday for the bus depot in Langenfelde if all diesel buses are replaced with electric buses. The black curve represents the load for immediate charging. The grey curve represents the load for continuous charging. It can be seen that the highest load demand is during the night, between 8 pm and 6 am with a peak at 4 am. The type of charging strategy has a very high impact on the actual peak. If every bus is charged with maximum power from the moment it arrives at the bus depot, the peak is distributed more equally during the night. If the bus is charged with a constant power throughout its stay in the bus depot, the load demand increases steadily until the early morning hours between 3 am and 5 am. This is when a large share of the buses require pre-conditioning. Thus it can be concluded that an equally distributed charging process for each vehicle does not necessarily lead to a reduced power demand at the point of common coupling.

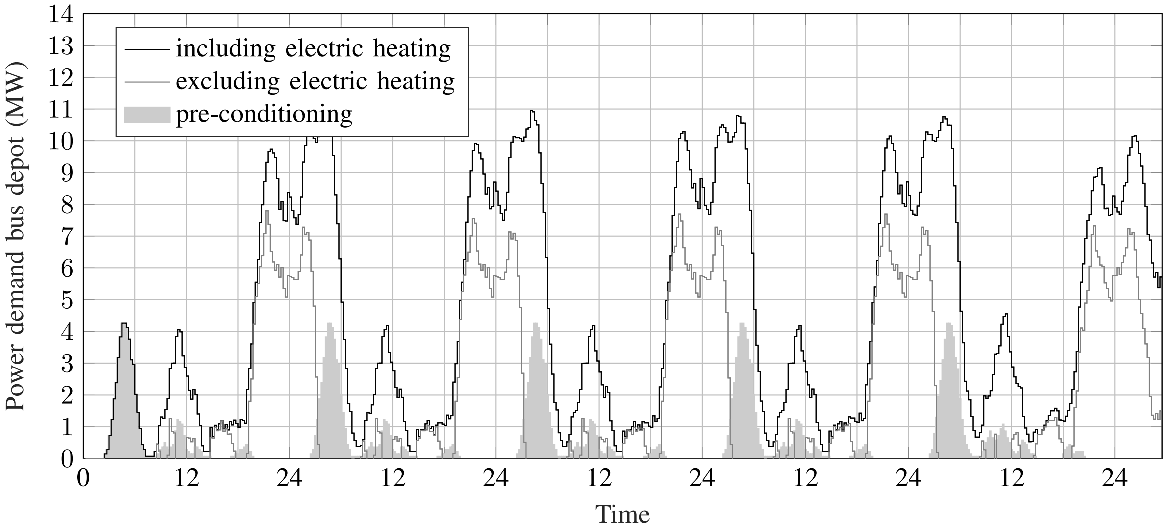

Fig. 6. Load profile of the bus depot in Langenfelde with (black) and without (grey) electric heating for a whole week from Monday to Saturday morning.

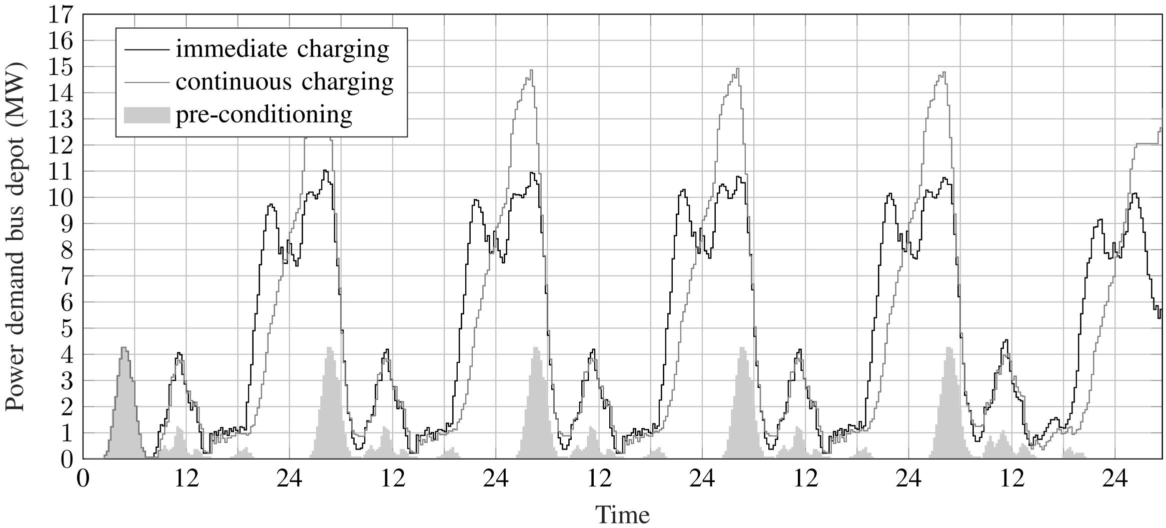

Fig. 7. Load profile of the bus depot in Langenfelde with immediate (black) and continuous (grey) charging of the buses. The black area marks the power demand for pre-conditioning.

In fact it is relatively counterproductive. The buses that return to the depot early in the evening can already be fully charged before more and more buses return and increase the total power demand for charging during late night. An optimum charging strategy might be a mix of the investigated approaches. In this strategy, benefits of low power charging (e.g. lower level of stress for the battery) must be balanced against an increase in dimensioning of the mains connection. Pre-conditioning of the vehicles has a high impact on the peak power demand. More than 4 MW are required and this is one of the reasons for the overall peak at 4 am. The characteristic of the pre-conditioning depends strongly on the actual leaving times of the buses. The shorter the time window in which the first and the last bus have to leave the depot, the higher the peak demand. This offers potential for a reduction by broadening the time windows for the pre-conditioning. For example, buses could be heated with half the power but twice as long in advance to their departure (neglecting thermal losses during heating-up). During the day, buses return to the depot after their first service and start recharging. Some buses can even be fully charged and thus take the load off the peak in the night.

IV. Further Results and Data Interpretation

A. Assessment of the Installed Charging Power per Bus

This work considers a charging power for every bus of 150 kW. This is the maximum charging power that can be used with an air-cooled combined charging system (CCS) in accordance with the IEC 62196 standard. Higher charging powers would require another charging system. It is interesting to see if the maximum IEC 62196 charging power is sufficient to fully recharge the buses' batteries within the standing time on the depot.

Fig. 8 shows the depth of discharge (DOD) of the buses on the bus depot Harburg from Monday to Friday including electric heating and pre-conditioning. The grey area marks the range of all DODs of the buses on the depot. The solid line marks the average DOD of the standard buses

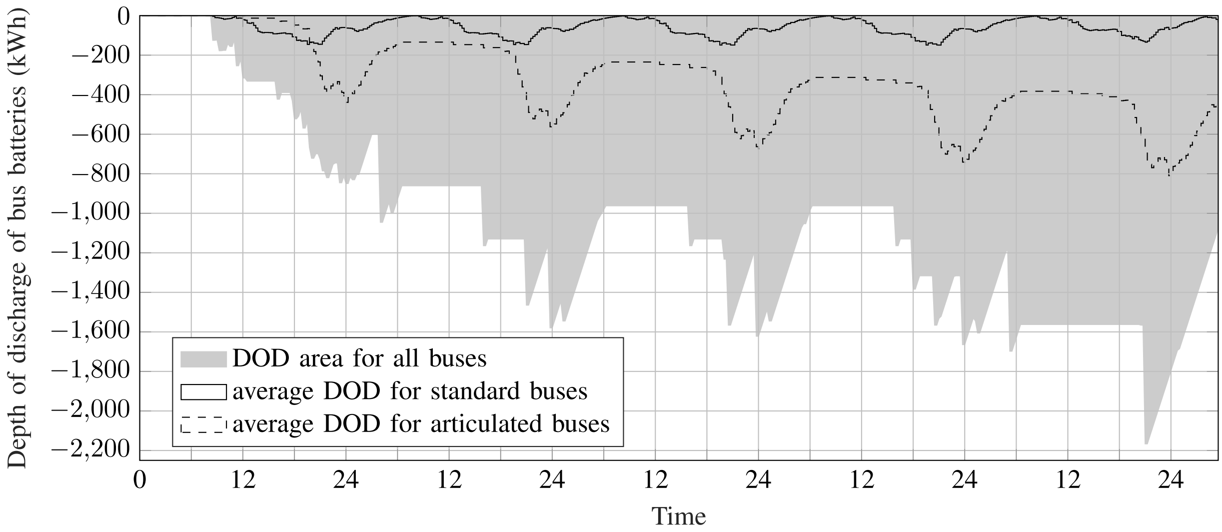

Fig. 8. Depth of discharge (DOD) for the buses of the bus depot Harburg I. Some articulated buses cannot be fully recharged during the night hours.

in Harburg. It can be seen that every morning it returns to almost zero. A DOD value of zero means that the bus is fully charged. Furthermore it stays relatively constant over the week. Thus, the installed charging power of 150 kW is sufficient for the standard buses.

In contrast to that, the dashed line marks the average DOD of the articulated buses in Harburg. This curve does not reach zero during the morning hours. Instead, the average DOD of the articulated buses decreases as the week progresses. Thus it can be concluded that the charging power of 150 kW is not sufficient to fully recharge the energy that is consumed by the articulated buses for the type of operation that is used nowadays. Either the charging power needs to be increased or the standing time of the buses needs to be extended. Increasing the charging power beyond 150 kW could be challenging because with very high charging powers it could become necessary to install water cooled charging plugs and cables. An alternative would be using pantographs which could provide more than 300 kW. Extending the standing time of buses could become expensive because it leads to the fact that the total number of buses in the depot is increased. More vehicles obviously bind more money. In addition, the ground resources might be limited and extending the parking grounds could lead to additional costs for additional bus depots in the long run.

B. Further evaluation of the Peak Power Demand

In total, eight bus depots of the HOCHBAHN have been investigated. Detailed service plans have been used to identify charging time windows and thus the peak power demand.

It was found, that there is a correlation between the number of buses n_{bus} and the peak power demand of each bus depot $P_{\max}$. This correlation is relatively linear. The ratio $p_{\text{bus}} = \frac{P_{\max}}{n_{\text{bus}}}$ is the average share of a single bus from the whole grid power demand. By calculating this value for each bus depot, it is possible to identify the constant of proportionality—which is the simultaneity factor g. Table II shows the results.

It can be seen that for large bus depots with more than 100 buses, the values for p_{bus} are relatively constant. This means that for large bus depots and an installed charging power per bus of 150 kW, the total power demand can be estimated with about 70 to 76 kW per bus. This equals a simultaneity factor g of approximately 0.5. For smaller bus depots (BBT and BBR), the values for p_{bus} are higher, thus every bus has a higher share of the total power demand of the bus depot. The simultaneity of each charging process is higher. With p_{bus}, impacts on the distribution grid could be addressed in early planning stages. Although the actual services of the new bus depot are not known in the beginning, most often a rough number of buses is known in an early planning stage which allows quantification of the grid connection requirements. Hence, this could improve long-term development of local distribution grid structures because the bus operator can inform the distribution grid operator ahead of schedule. Planning and construction of new bus depots usually takes about four years, thus the grid operator could be able to include the bus depot into its mid-term planning.

C. Calculation of Necessary Battery Capacities

All bus services were distributed to the individual buses with the FIFO methodology. With the specific energy consumption for each bus and the distributed bus services for each vehicle, the DOD for each bus can be calculated during the week. The bus model did not include a model for the energy storage system. Instead, the empirical energy consumption values and the bus services are used to calculate the capacity of the battery that would have been required in the field.

Fig. 9 shows the required battery capacities for each standard and articulated bus without electric heating (dark colours) and including electric heating (light colours). Due to the fact that the tours were allocated with the FIFO methodology, there are some buses that require a very large battery and some that require only a very small battery. But the average required battery value is a good indicator. In the shown example of the bus depot Langenfelde the required average battery capacity is about 500 kWh for standard buses

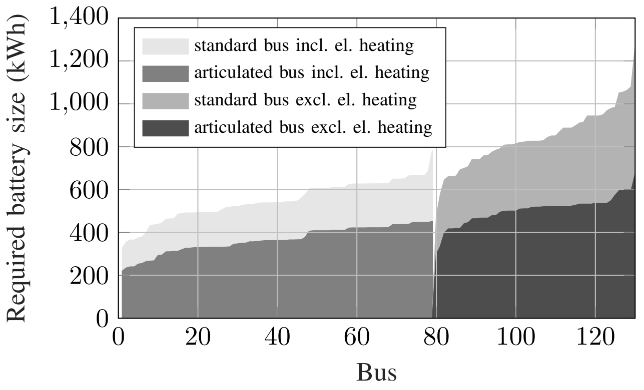

Fig. 9. Required battery capacitance for standard and articulated buses of the bus depot in Langenfelde with and without electric heating.

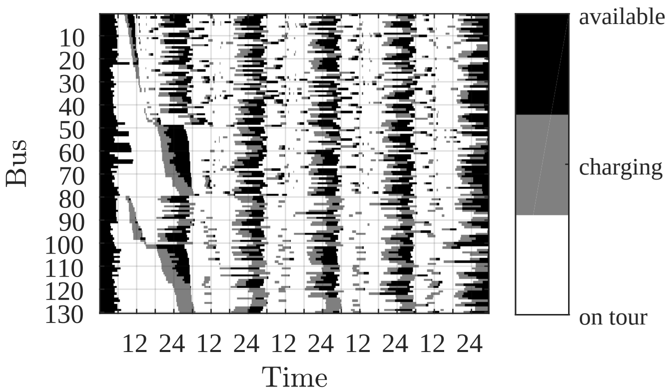

Fig. 10. Illustration of the standing time of each bus of the bus depot in Langenfelde.

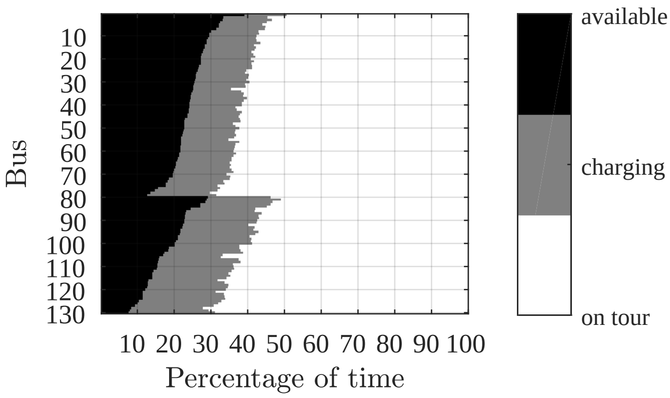

Fig. 11. Sorted standing time of each bus of the bus depot in Langenfelde.

including electric heating. Without the electrical heating, this value reduces to about 350 kWh. Articulated buses have a higher energy consumption and thus require a larger battery: about 800 kWh with, and 500 kWh without electric heating. However, as the FIFO methodology is not very useful in real bus operation, the calculated figures are a relatively conservative guess and are not representative.

D. Impacts on the Availability of Buses

When buses are not in operation, their standing time is used for service, maintenance, cleaning, re-fuelling etc. Spare standing time is costly and is expected to become more and more important for electric buses because standing time is required for the charging process. Furthermore, changes in standing time could be a first indicator for the bus operator to increase its size of the fleet because the buses need a minimum standing time for the above mentioned tasks. This aspect has been under investigation in the study as well.

Fig. 10 shows different states for all buses of the bus depot in Langenfelde. The figure shows the daily operation structure of the buses for a whole week from Monday to Saturday morning. The x-axis describes the time. Each row is a single bus. The buses are grouped into standard (numbers 1 to 80) and articulated (numbers 81 to 127) buses. Black (available) indicates that the bus is standing in the depot without limitations. Dark-grey (charging) indicates that the bus is charged or pre-conditioned. White (on tour) marks the times when the bus is on the road and thus not available on the bus depot. The figure gives an impression of the return and charging process during the night hours.

Fig. 11 shows the re-arrangement of the values in Fig. 10. The buses are sorted by their standing time in the bus depot. It can be seen that 30 to 70% of the standing time is used by the charging process. In average it can be concluded that about 50% of the standing time in the bus depot is used for re-charging the battery. For the articulated buses, this value is even higher. In fact, for some buses there is almost no standing time left that is not used for the charging process. This is a clear indicator that those buses have very long services (sometimes more than 18 or 20 hours) and are not able to fully recharge their batteries before they have to take their next service.

The investigation shows that for the practical use of electric buses, it is essential to define which services (maintenance, cleaning etc.) can be done during the charging process and which cannot. Especially for very long service times, the standing time in the bus depot is very short and must be used even more efficiently. Thus, one finding of this investigation could be that charging infrastructure might not only be necessary at the bus parking but also in the workshop or cleaning facilities in order to give the bus enough time to fully recharge its batteries.

V. Conclusion

In this work, important results for both transportation companies (TC) and distribution grid system operators (DSO) were obtained for the transformation process from diesel to electric bus fleets. The results were obtained for eight bus depots of the Hamburg HOCHBAHN.

A model was derived to calculate time variable, temperature sensitive and charging strategy sensitive power and energy demands for different vehicle types. It was shown that the total yearly energy consumption for all bus depots combined is about 132 GWh—varying from 8 MWh for the smallest and 28 MWh for the largest depot. This is approximately the amount of energy which is needed for the metro in Hamburg. The peak power demand of the bus depots varies from 4.4 MW to 15.1 MW if the buses use electric heating. In the case that the buses use conventional heating (oil), the power demand is significantly lower (several MW). Furthermore, it was shown that the charging algorithm has a strong effect on both the load profile and the peak power demand. Often, immediate charging of the buses results in lower peak power demand than using the whole standing time of the bus for continuous charging.

Further interpretation of the results showed that there is an almost linear correlation between peak power demand and the amount of buses on a depot. The simultaneity factor for the charging process is approximately 0.5 for a charging power of 150 kW. Thus, the peak power demand for future bus depots can be estimated even if the depot has not been built or designed yet. This allows TCs and DSOs to plan in advance.

Finally, the standing time of the buses on the depot was analysed. It was shown that in some cases, not all buses can be fully recharged for the next day because the time in the depot is not sufficient. In average, about 30 to 70% of the standing time is used for recharging, but especially articulated buses find it challenging to get enough recharging time.

How can TCs react to the challenges that were described in this paper? Obviously, the length and structure of bus services has a high impact on the peak power demand and the necessary battery capacity. Services can be shortened or split and they can be moved from one depot to another. Bus depots could be moved or the amount of buses could be increased or decreased. Further options could be hydrogen or range-extender buses. A promising approach could be charging the bus en route during service breaks. There is no general rule for a *best option* because the challenges and constraints are highly individual for every TC.

Future research will cover actual load profiles during the transformation process from 0 to 100% electrification of the bus fleet. Furthermore, the potential of demand side management could be an interesting and promising issue to support the local grid operation. Load management might become even mandatory if the load demand further increases. Due to this, technical and economic optimisation could become more important.

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