ENABLING BATTERY-POWERED TRAIN OPERATION: POWER FORECAST MODEL FOR OVERHEAD CATENARY ISLANDS IN REGIONAL PASSENGER RAILWAY

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1. Introduction

The amendment of the German Federal Climate Protection Act of 2022 defines targets to reduce greenhouse gas emissions by 65% by 2030 and 88% by 2040 compared to 1990 levels. In Germany, the transport sector accounts for 19.8% of 2022`s CO_2-equivalent emissions (UBA 2024). While most of these emissions stem from road-bound traffic, there are still common tailpipe greenhouse gas emissions from diesel vehicles in rail-transport. For instance, a significant share of commuter transport services is currently achieved with diesel multiple units (DMU). To reduce tailpipe emissions, these vehicles are ought to be replaced with electric multiple units (EMU). As the installation of overhead catenary along the entire track is often cost-intensive and not economically viable, battery electric multiple units (BEMU) are going to be utilized in various railway networks, some of them already in operation (Herwartz-Polster et al 2024a).

A major challenge of BEMU is the limited autonomy. Common market-ready vehicles cover autonomy ranges between 80 and 200 km, while circulation plans require often considerably larger ranges of not-electrified kilometres over an operational day. The limited range of BEMU can be accounted for by installing additional recharging infrastructure at selected stations or track sections, typically designed as overhead catenary islands (OCI), as they are not connected to a wider rail catenary network. The vehicles can recharge the traction battery at these OCI the same way they do under conventional overhead catenary – with a pantograph mounted at the vehicle roof. This way, the vehicles can also recharge under already electrified sections. Vehicles often run under existing electrification when regional lines meet long-distance connections – i.e. at the centres of larger cities.

OCI are usually installed alongside selected stations and are connected to the public electricity grid instead of the rail electricity grid. These rural electricity distribution grids might often not be designed for the high-power loads occurring in the recharging of rail vehicles. Therefore, it is crucial to gain insight on future power loads and peaks potentially stressing weak rural electricity grids.

There has been wide research on BEMU operation regarding the necessary recharging infrastructure. Royston et al (2019) built a model to evaluate the power demand of a proposed OCI for a single railway line in UK. They assumed 20 min dwell time under OCI and tested an energy storage connected to the electric grid to validate their c-rate assumptions at discharging and recharging. Another common research approach is to find the best set of electrification in regards to the cost of operation. Streuling et al (2021) considered cost reduction potentials through efficient recharging infrastructure positioning. For various placement strategies of overhead catenary islands or the extension of existing electrification they calculated train and OCI life cycle costs, where they considered the direct use of local renewable energies in comparison to grid connection. While both studies considered single train lines, Juston et al (2023) analysed circulation data from two years of operation of a railway line in France and derived necessary infrastructure length and costs. They applied a statistical approach to determine the optimal sizing of partial electrification. Pugi (2024) made a study on existing lines in Italy to derive optimal locations for trip intermediate recharging locations on train lines with very steep sections, i.e. with a high recuperation potential. They optimized recharging positions in respect to the lowest depth of discharge (DoD) of the traction battery, costs of construction and maintenance of infrastructure, high power flow sections and the mean train speed at sections. The named studies asses optimal electrification patterns for single train lines or a small sample of lines. In contrast, this study attempts to analyse the loads on German OCI currently in implementation (in planning or construction phase). Instead of analysing single train lines, for the first time the operation of an entire regional BEMU rail network is considered, meaning the entire vehicle fleet and all electrification infrastructure in the network. The results of this study will give insight on the actual power demands occurring in a full BEMU-network operation and therefore provide valuable data for transport planning authorities, vehicle manufacturers and especially electric grid operators.

2. METHODOLOGY

The study uses a data driven approach to assess power demands at overhead catenary islands. The data model is based on a real-world circulation plan in a regional railway network in Germany. As the model facilitates the entire circulation it is able to show the demands of all vehicles. The vehicles onboard-energies are interdependent of all proposed OCI and therefore the OCI power demands are interdependent on each other, making this a network-study.

1.1 Modelling Approach

Our model (Figure 1) first links timetable data with vehicle circulation plans and adds infrastructure data such as station locations, line speed limits, track electrification and inclination. These inputs are run through a longitudinal simulation to calculate power at wheel level. Vehicle energy flows are then modelled to calculate the power at the battery and the resulting state-of-charge of the on-board traction batteries. A geospatial sub-model is incorporated, to match the vehicle trajectories to the OCI. On-board battery rechargings are aggregated with regard to the location of the corresponding OCI and the specific time of day. The aggregated curves serve as 24-hour demand profile forecasts of the OCI. A sub-model is set up to understand the implications of additionally installed stationary energy storage system (SESS) to reduce peak loads on electricity grids. The model utilizes the projected real-world circulation plan, provided by the Public Transport Authority.

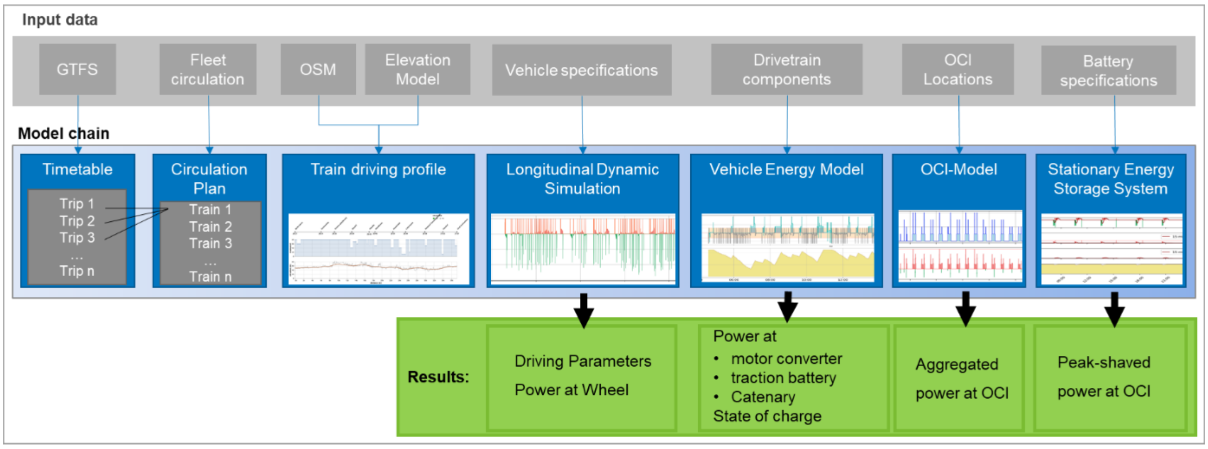

Figure 1: Schematic Modelling Approach

The model is applied on “Pfalznetz”, a German regional passenger railway network where BEMU operation is to start operation stepwise in the years 2025 and 2026 (Figure 2). Five OCI are planned to support the upcoming BEMU operation, three at positions within the network where several train lines intersect and two at terminal stations.

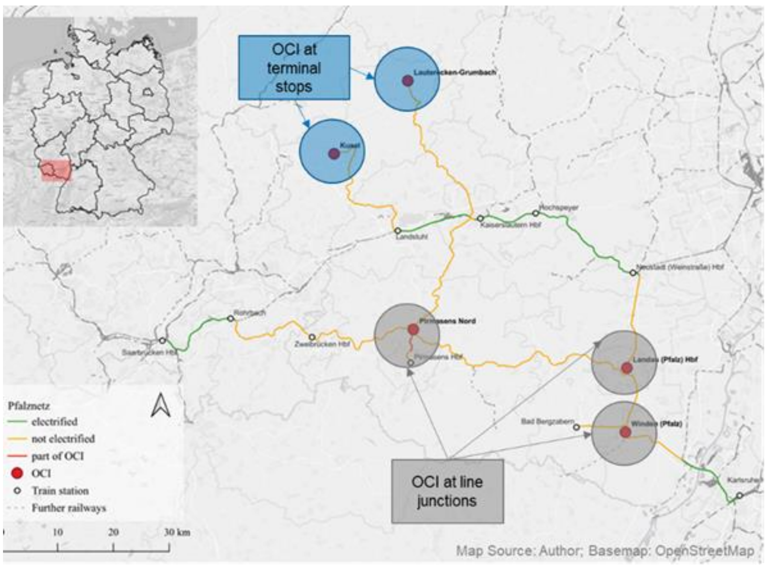

Figure 2: Study area: Regional BEMU network Pfalznetz.

1.2 Vehicle Power Demand

The vehicle power demand is the foundation for the power demand at OCI. The majority of the model chain serves the purpose to adequately assess vehicle power demand. A circulation day in the model represents the operating day of a vehicle. The vehicles are not bound to lines or routes but move across the entire rail network under consideration. On average, a vehicle runs 398 kilometres per day and is in operation for 13.1 hours. With 30 vehicles being in the circulation, a data-driven approach is required to simulate such a comprehensive operation. Trips from the digital GTFS-timetable are linked to the circulation plan of the regional rail network. This is used to create vehicle driving profiles (Streuling et al 2023) using OpenStreetMap data and a digital elevation model (JAXA 2016), which are fed into a longitudinal dynamic simulation tool that outputs the power at wheel level in second increments (Schenker et al. 2020). A vehicle energy model is applied in order to determine the power at the motor converter, the traction battery and the pantograph and to derive the state of energy (SOE) of the traction battery.

This model chain is applied to all vehicles in the circulation. This provides the power requirement of all vehicles operating in the network at all times. As the OCI are already considered in the driving profiles, the power requirements at the OCI are determined dependently of each other, making this a systemic approach. For this study we assumed a 2-car generic BEMU with a Jacobs type boogie, maximum traction power of 1000 kW, max acceleration of 1 m/s² and a mass (seated) of 97.5 tons. A thorough description of the vehicle energy model together with an energy trajectory analysis as well as the vehicle used for simulation is found in (Herwartz-Polster et al 2024b).

1.3 Overhead Catenary Island Modelling

The power demand at OCI is calculated in respect to the location and the time of the power demand of the vehicles. OCI are represented as polygons in a geospatial model. The polygons are constructed to reproduce the projected electrified track length of the planned OCI. As each second in every vehicle's trajectory has a location and a time, the power demand for each vehicle is aggregated for each polygon (i.e. OCI) and mapped onto a 24-hour time series which is the power demand curve of the OCI.

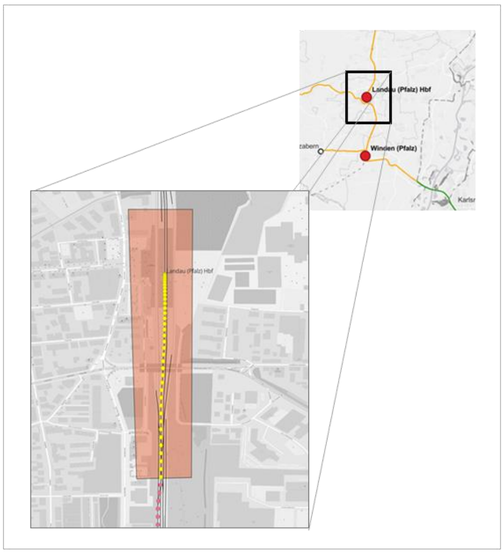

Figure 3: Representation of OCI in the geospatial data model. Points represent seconds in a vehicle's trajectory.

The vehicles' behaviour during recharging is set as a parameter in the OCI module. In the reference case (no SESS and driving under catenary) vehicles lift the pantograph as soon as they drive under OCI and thus draw the traction power from the overhead catenary. This is particularly relevant for acceleration processes. In the second case, which we refer to operational peak shaving, vehicles can only lift the pantograph when they have come to a standstill. The vehicles behaviour under overhead lines are also defined for existing line electrification. Here, the pantograph may always be connected to the overhead catenary during driving. The load with which the driving trains draw power from the overhead line is defined as a vehicle parameter (vehicles can each draw a maximum of 1976 kW). This is done in order to not predetermine the power required at OCI at demanding points in the network and not to keep power demands low by the outset of the model´s specifications.

1.4 Stationary Energy Storage System

A stationary energy storage system module was added to the model to analyze the technical peak-shaving potential. Similar to the vehicle energy model, the sub-model works according to the energy flows between the SESS and the OCI. The model calculates two target values $pbatt_{sess}$ - which is the momentary power at battery - and p_{grid} which is the momentary power drawn at the public electric grid. The functions for derivation of these target values are computed for each timestep and then applied on the time-series. $Pbatt_{sess}$ is computed for two cases, namely for discharging i.e. buffering power peaks and for recharging after buffering. The power consumption at the overhead line $p_{catenary}$ is calculated in advance in the OCI aggregation module and is an input variable for calculating the SESS. If the momentary power drawn at catenary $p_{catenary}$ is higher than the sum of auxiliary power demands of all trains under the OCI, the momentarily SOE of the SESS is queried. If the battery`s SOE is above the lower SOE limit, $pbatt_{sess}$ is calculated as

$$pbatt_{sess} = \min(p_{catenary}, p\_discharge_{max}) * \mu_{battery\_sess}$$

Here, $\mu_{battery}$ represents the battery system efficiency. If $p_{catenary}$ is lower than the current auxiliary power drawn, the current SOE of the battery is queried. If the sess is not fully charged, $pbatt_{sess}$ is calculated as

$$pbatt_{sess} = \frac{p_{charge\ max}}{\mu_{battery\_sess}}$$

The p_{charge} functions are calculated respectively with

$$p_{discharge_{max}} = \mathrm{e_{battery}} * \mathrm{c\ rate_{discharging}}$$
$$p_{charge_{max}} = \mathrm{e_{battery}} * \mathrm{c\ rate_{recharging}}$$

where $e_{battery}$ is the usable energy of the battery, in this case assumed to be the range between 30 % and 70 % of the installed energy. Finally, p_{grid} is calculated as the sum of $p_{catenary}$ and $pbatt_{sess}$ with regards to the efficiency of the SESS`s converter:

$$p_{grid} = p_{catenary} + p\frac{\_batt_{sess}}{\mu_{converter}}$$

Two different SESS were assumed with usable battery capacities of 500 kWh and 1000 kWh. We assumed a 1-hour storage (i.e. a discharge rate of 1 c). For recharging, a c-rate of 0.25 c and 0.5 c was chosen to assume a low-stress operation.

3. RESULTS

The results are calculated for all OCI in the network, however the reference case power load curves for all OCI are shown and discussed in Herwartz-Polster et al. (2024b). This section focuses on the operational and technical peak shaving measures described above and shows result at OCI Kusel (a modest load OCI at a terminal station with long turn-around times) and OCI Landau (with frequent train calling and a high demand load).

3.1 OCI Power Curve

Figure 4 shows power demand curves for OCI Kusel. The upper row displays the number of trains under OCI, the second row shows the power demand of the trains together with the 15-minute rolling average power which represents the time corridor relevant for electric energy billing in Germany. The third row represents the power demand curve if the operational peak-shaving measures described in the methodology section are in place. It can be observed that peak power at this peripheral station reaches 2.64 MW. High peaks typically occur during train accelerations, especially in cases of multiple-unit traction, and are very short in duration. In the case that trains

can recharge only at standstill, the highest peak power is at 1.65 MW, which aligns with the expected operational limits.
Looking at the train's dwell times and corresponding charging curves it is possible to further smooth these power demands by limiting the C-rate during charging of the traction batteries. However, a robust circulation opposes lowering the C-rate: if a train is delayed, it would require charging at higher power levels within a smaller time window, which could push delays throughout the daily schedule. Additionally, in regular operations, it is desirable to recharge the train as quickly as possible to be prepared for unexpected events in railway operations, such as OCI failure, power outages, track changes or unexpected trips. Planned idle times enhance the robustness of the daily schedule, and these intervals might be kept as a reserve for operational reliability. The proper size of this reserve, however, can only be determined through operational experience at the specific site.

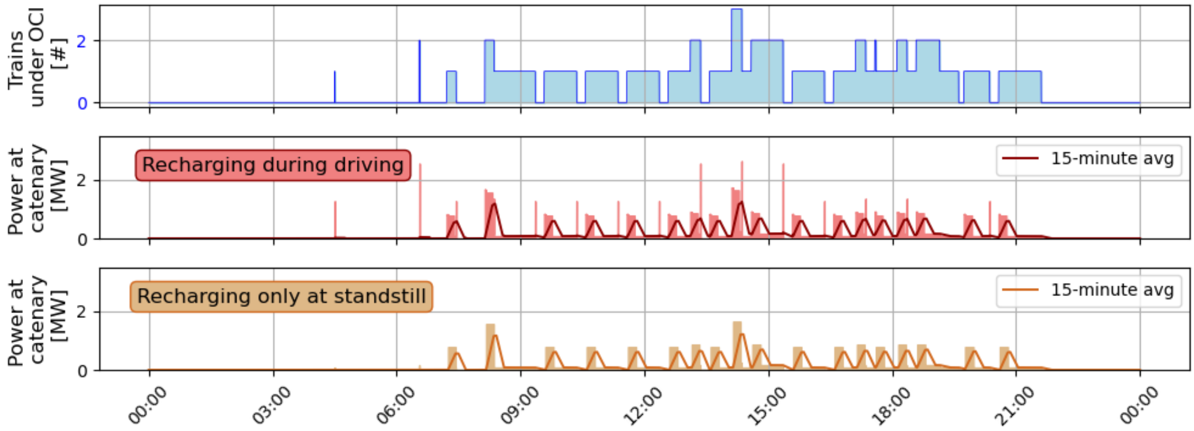

Figure 4: OCI Kusel - power demand curve

3.2 Technical Peak Shaving – Stationary Energy Storage System

The SESS module is applied on the OCI aggregation model to understand implications and potentials on technical peak shaving measures. Here, we calculate the daily operational curves of a stationary battery storage system for various storage configurations. Figure 5 is a comparison of two OCI (Kusel, Landau). Four different variants of SESS (500 kW, 1000 kW, each with a charging c-rate of 0.25 and 0.5) are shown here for the reference case (i.e. with high start-up load peaks). The power consumption characteristics of the two considered OCI are fundamentally different. Kusel has a modest load profile with peaks of up to 2.64 MW on the overhead line. Landau has a frequent and high demand profile with peaks of up to 5.5 MW.

With an installed SESS capacity of 500 kW, load peaks are reduced in different magnitudes in comparison. In Kusel, the application of a 500 kW storage system can reduce power peaks by 19 %. In Landau the same system has a smaller proportional effect with a reduction of 9% (compare figure 5).

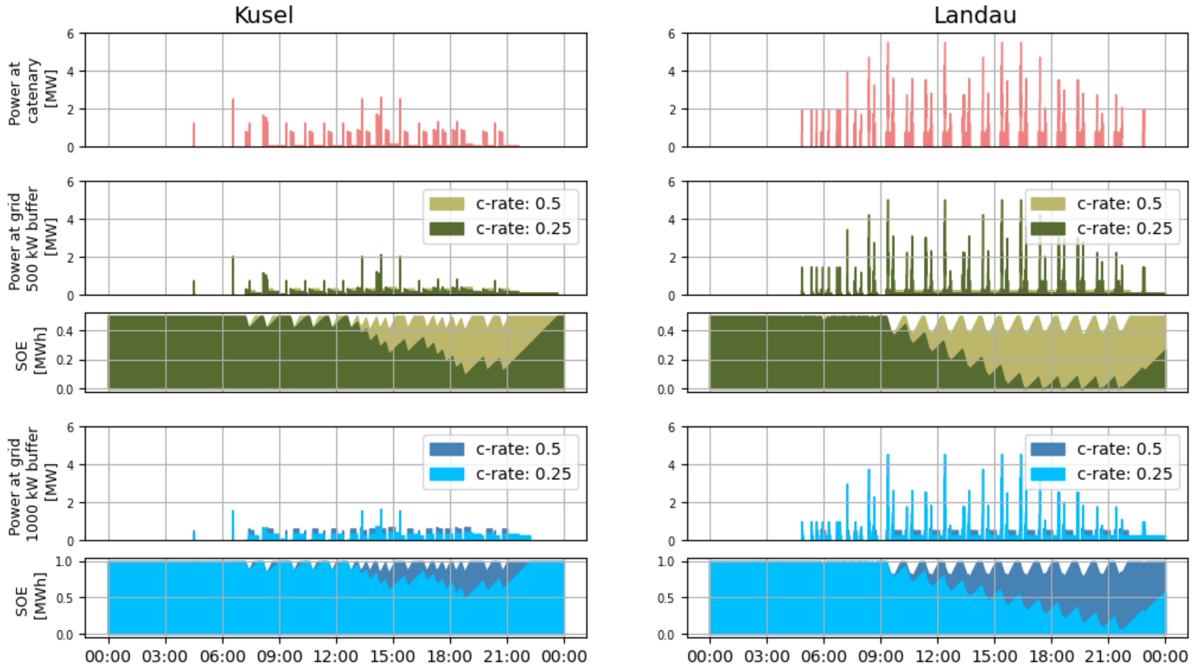

Figure 5: Comparison of various SESS dimensioning's at OCI Kusel and OCI Landau

Facilitating a 1000 kW storage system, the smoothing of the power is much more visible in Landau. Even if the start-up load peaks in Landau are still exceeding the rest of the profile, the remaining power consumption is stabilized.
In almost all cases, a c-rate of approximately 0.5 is necessary for the SESS in order to not discharge the battery over the course of the day. In this application, a cell chemistry able to cope with high charge and discharge currents is more practical than a high energy cell.

4. DISCUSSION: EFFECTS OF PEAK SHAVING MEASURES

This chapter contextualizes and discusses the performance values and the peak-shaving potential described above. Figure 6 shows the load profiles of the OCI Landau and Kusel as sorted power curves. The reduction of power peaks and the distribution of power consumption can be seen particularly well from this. The curves show the reference case, operational peak shaving and the use of technical peak shaving as described above. The last curve of a series shows the sorted power load curve when both peak-shaving measures (operational and technical) are in place.

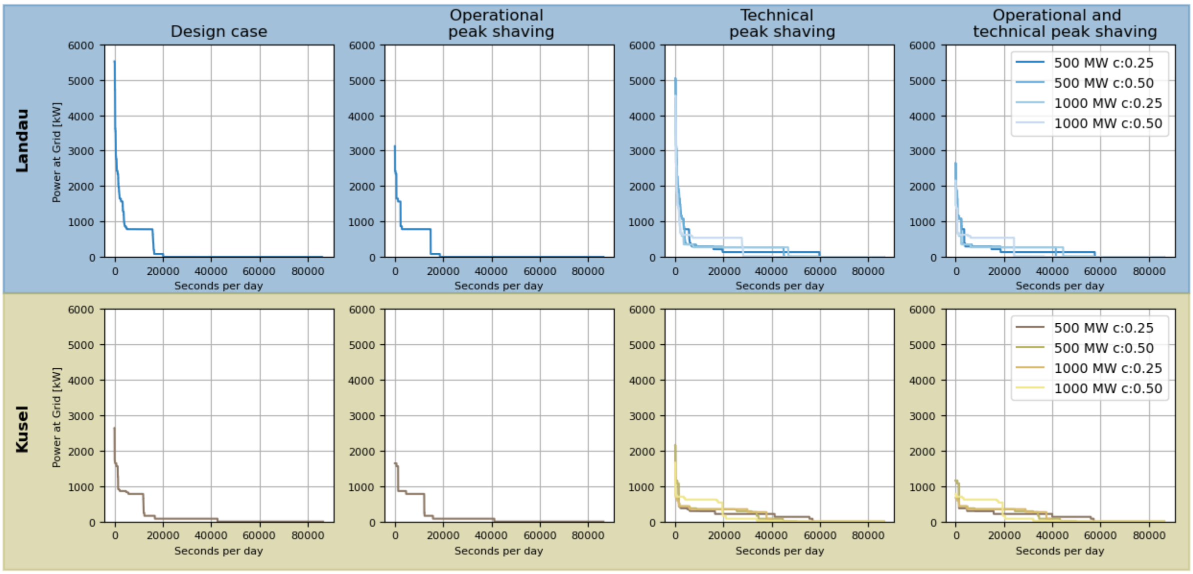

Figure 6: Sorted power-day-curves for various peek-shaving cases at OCI Landau and OCI Kusel

The peak load without peak shaving in Landau is 5.5 MW with a total OCI operating time of 5.7 hours. The operational peak shaving measure reduces the peak load to 3.1 MW, whereby the operating time is only slightly reduced. Utilizing a SESS effectively distributes the load duration over the day. The extension of the OCI operational time grows with the storage capacity and declining c-rates. With a 500 kWh storage and a c-rate of 0.5, the OCI operation time (recharging of traction batteries and dis-/charging of the SESS) is more than doubled to 12.6 hours. This translates to a utilization of 69.7 % assuming the operating hours of the OCI between 04:48 to 22:57. Without SESS, the temporal utilization rate is 31.3 %. The percentual reduction of highest power peaks however is only 9 %, meaning that the SESS is very effective in distributing and harmonizing the overall power load but less effective in reducing short high peaks.

Considering short and high peaks, the difference between technical peak shaving and operational peak-shaving is much smaller in Kusel, where trains spend much more dwell time under OCI. Here, the SESS is more effective in comparison. In both OCI, an energy plateau with a sharp drop in power (after 3.3 and 4.4 operating hours) cannot be reduced by operational measures. This power plateau corresponds to the power required to operate the BEMU. Accordingly, this can only be distributed over time by using a SESS.

Which design and which measures are favorable or necessary for an OCI depends largely on the location in the network and the frequency of calling trains. Next to the peak-shaving possibilities considered in this study, there are numerous additional opportunities to further reduce or distribute the load through operational and/or technical solutions. From an operational perspective, one potential possibility is the optimization of timetables (and accordingly circulation plans) to prevent multiple vehicles with high charging demands charging under the same OCI simultaneously. For instance, simulations by Ritzer et al. (2023) have demonstrated that interconnected driver assistance systems which prevent simultaneous peak loads from acceleration in EMU regional trains can reduce load peaks. Their results showed, that by altering departure times by up to 90 seconds, load peak reductions of between 5.4% and 8.9% compared to regular timetable operations could be achieved. A different approach was modeled by (Meng et al., 2014). Their study on the Tokyo metro system has suggested utilizing the regenerative braking energy of incoming trains to power departing trains to effectively level out acceleration peaks. There are numerous other possibilities, like reducing the battery charging power or lowering the power consumption during acceleration. Which operational measures to manage load distribution are feasible and appropriate for which situation is yet to be determined.

On the technical side, several approaches exist to reduce or temporally distribute loads. Increasing the capacity of traction batteries, for instance, could limit the frequency or intensity of charging events. However, the on-board capacity is limited by various vehicle specifications and is a sensible parameter in the design of BEMU. In infrastructure, load and volume of peak-reducing measures are more flexible. The short but intense power demands during acceleration or deceleration into and out of stations, might be an excellent application for supercapacitors. These could be charged using braking energy and then smooth acceleration peaks using this breaking energy. For example, Jenni & Antoniewicz (2022) calculated and tested a use case for supercapacitors in an electrified DC network for the London Metro. In their study, they showed that a supercapacitor with a usable energy content of 12.2 kWh could effectively reduce grid stress as the energy storage could provide a peak current of 1,000 A. As this kind of storage can sustain over 1,000,000 charge/discharge cycles this could be a promising usage and could be considered for multiple units in AC networks as well.

A key limitation of this study is the lack of validation using real-world data, as such data is not available. By the time of writing, there is only one OCI worldwide in operation. Additionally, the implementation of SESS involves significant costs, which were not considered as a factor in this work. The role of electricity, infrastructure and vehicle component costs will influence how infrastructure is build and how trains will be operated. Furthermore, we did not use actual vehicle specifications of Pfalznetz to maintain manufacturer neutrality. Considering the current BEMU market, it is likely that more heavy vehicles might be deployed, leading to higher power demands. In this model, a lighter short two-car unit was used to represent the existing diesel vehicle market in Germany.

5. CONCLUSION

While many technical and operational parameters play an important role in the power demand, it is crucial to consider the electricity grid itself. Depending on the location of the OCI within the electric grid and it`s distance to substations/transformer stations, grids will cope better or worse with short-term, high-power start-up peaks or with continuous loads. The variety of electric grids, grid owner and operators and the more or less non-existence of data on the grids could not be considered in our model. If power grids are able to cope with the here described load patterns is yet to be determined.

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