Proceedings of the Sixth International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 7, Paper 12.4
Civil-Comp Press, Edinburgh, United Kingdom, 2024
ISSN: 2753-3239, doi: 10.4203/ccc.7.12.4

Power Forecast of Overhead Catenary Islands in Battery Electric Train Operation: Case Study of Pfalznetz

S. Herwartz-Polster, J. Pagenkopf, J. Kaiser and M. Freienhofer

**Institute of Vehicle Concepts, German Aerospace Center
Berlin, Germany**

Abstract

This paper explores the concept of overhead catenary islands (OCI) as a solution to extend the operating range of battery electric multiple units (BEMU) in regional passenger train services. Through strategic placement at terminal stations or along railway routes, OCI facilitate recharging of traction batteries during turnaround times. Using the Pfalznetz rail network in Germany as a case study, the paper employs simulation-based methods in conjunction with a vehicle energy model and an OCI-power aggregator function to forecast power load profiles for OCI. The five OCI in Pfalznetz support a circulation plan of 30 vehicles. Results indicate power peaks during recharging between 2.6 MW and 6.7 MW and daily energy supplies of 3.8 MWh to 9.6 MWh, varying based on OCI locations. The study underscores the potential of OCI to facilitate battery-powered railway networks and the high stress the operation can put on local energy grids and therefore providing valuable insights for stakeholders involved in infrastructure planning and operation.

Keywords: battery electric multiple units, overhead catenary islands, railway electrification, regional passenger trains, infrastructure, charging infrastructure, alternative drivetrains.

1 Introduction

As a viable zero-tailpipe emission solution, battery electric multiple units (BEMU) are increasingly used to replace diesel-propelled multiple units in regional passenger train services. These vehicles are limited in their autonomy range at non-electrified sections. Therefore, a frequently discussed approach is to install overhead catenary in length-limited sections along the route or at terminal stations in railway networks. As they are not connected to the rest of the catenary grid, they are referred to as overhead catenary islands (OCI). In these sections, turnaround times last often long enough to recharge the traction batteries of the vehicles. Installation of OCI could potentially enable BEMU operation in numerous railway networks. Various studies in Germany suggest that this approach is likely to be more cost effective than a full electrification of a network [1–3]. Additionally, full network electrification is a comprehensive infrastructure undertaking requiring a year-long approval process in most EU member states. Therefore, a number of railway networks are ought to be operated with BEMU in the upcoming years.

Beginning in October 2024, the first BEMU have been put into regular service in Germany. These battery railcars, manufactured by Stadler, are currently in use in the state of Schleswig-Holstein. [4] Additional rail networks will be commissioned with BEMU in the near future. In Germany alone, this will result in a BEMU mileage of approximately 60 million train-kilometres per year by 2029, under catenary and in battery mode combined [5]. With the European Union's goal of achieving a zero-emission rail system, battery-powered railway networks will also be implemented in other European countries [6]. In Denmark, Siemens will put seven BEMU into operation in December 2024, while Ireland has ordered 31 BEMU from Alstom, which will begin operating 2025. Another significant order is coming from Austria, where Stadler will deploy sixteen BEMU in 2028, with the possibility of ordering up to 120 trains.

Currently, BEMU that consist of either two or three cars designed for regional travel/commuter services are market-available. These trains can reach a top speed of either 140 km/h or 160 km/h, while utilizing battery power for a typical maximum autonomy of approximately 120 km. Table 1 provides an overview of market-available BEMU [7].

Manufacturer	Siemens		Stadler		Alstom	CAF		Alstom
Type	Mireo Plus B		FLIRT Akku		Coradia Conitnental BEMU	Civity BEMU		Talent 3 BEMU
Number of cars	2	3	2	2	3	2	3	3
Length [m]	47	63	46	56	56	45	55	56
Seats	120	160	105	172	150	120	160	169
Top speed [km/h]	140/160		140/160		160	140		140

Table 1: Market-available BEMU 2024 [7].

The limited autonomy of these vehicles requires frequent recharging throughout a day of operation. The average charging time at an OCI station is likely limited to periods of a few minutes. During these periods, charging systems require high installed capacities, which in turn causes peak loads of several MW in the power grid. In order to ensure reliable BEMU-operation, train batteries often need to be recharged at the end of a trip before turning back. Therefore, OCI are likely to be placed on terminal stations of commuter lines where electricity will be provided from public grids. These public grids however may not be designed for strong peak loads. High demand from railway operation necessitates appropriate configuration of both the OCI station and the local grid to support peak loads, which often result in high costs. Furthermore, network charges tend to rise during peak periods of demand.

As there is little practical experience in the operation of OCI for rail vehicles, we aim to forecast the power load at OCI and the respective energy in a regional rail network, based on a comprehensive circulation plan. We use an automated, data driven and simulation-based approach to predict the power load and energy demand in five OCI supporting a circulation with 30 vehicles in the real-world regional rail network of ‘Pfalznetz’, Germany. In this network the operation of BEMU will start in 2025. The OCI power forecast model generates a power demand profile as it would appear during uninterrupted operation including trips from and to vehicle depots and other additional transfer trips as they are common in many operational plans.

The forecast model results can be useful for tendering authorities, railway operators, vehicle manufacturers, infrastructure managers and grid operators for designing recharging infrastructure and coordinating trade-offs between the amount of installed traction batteries and the layout and positioning of recharging infrastructure in a railway network.

2 Methods

This section describes the study area and the applied methods and data used in this study. It describes the components and parameters of the vehicle which was used for simulation and explains the assumptions and functionality of the vehicle energy model and the OCI power forecast model.

The Pfalznetz rail network is situated in southwest Germany, as shown in Figure 1 and has a total length of 240 km. Starting from December 2025, 44 BEMUs will be operational on the Pfalznetz, with a total of 37 circulation days. Additionally, five OCIs are planned to charge the trains. The OCIs at Lauterecken-Grumbach and Kusel are terminal stops. The OCI at Lauterecken-Grumbach will be built with a length of 700 meters at the train station, while the OCI at Kusel will be built on both platforms with a length of 640 meters. Pirmasens Nord and Landau are junctions where several lines intersect and can use the OCI for charging. In Pirmasens Nord, in addition to the OCI with a length of 2900 meters, a partial electrification is required for a length of 3200 meters. This will be built between Pirmasens North and the Fehrbach tunnel. In Landau, an OCI is planned to be constructed on all five platforms, covering a total length of around 3,700 meters. The fifth OCI is located in Winden. Winden is a terminal station for the line to Bad Bergzabern and a junction station for the lines to Karlsruhe and Wörth am Rhein. As a result, vehicles serving three lines can charge at this location. The OCI will be installed along all three platforms, covering a total length of approximately 2950 meters.

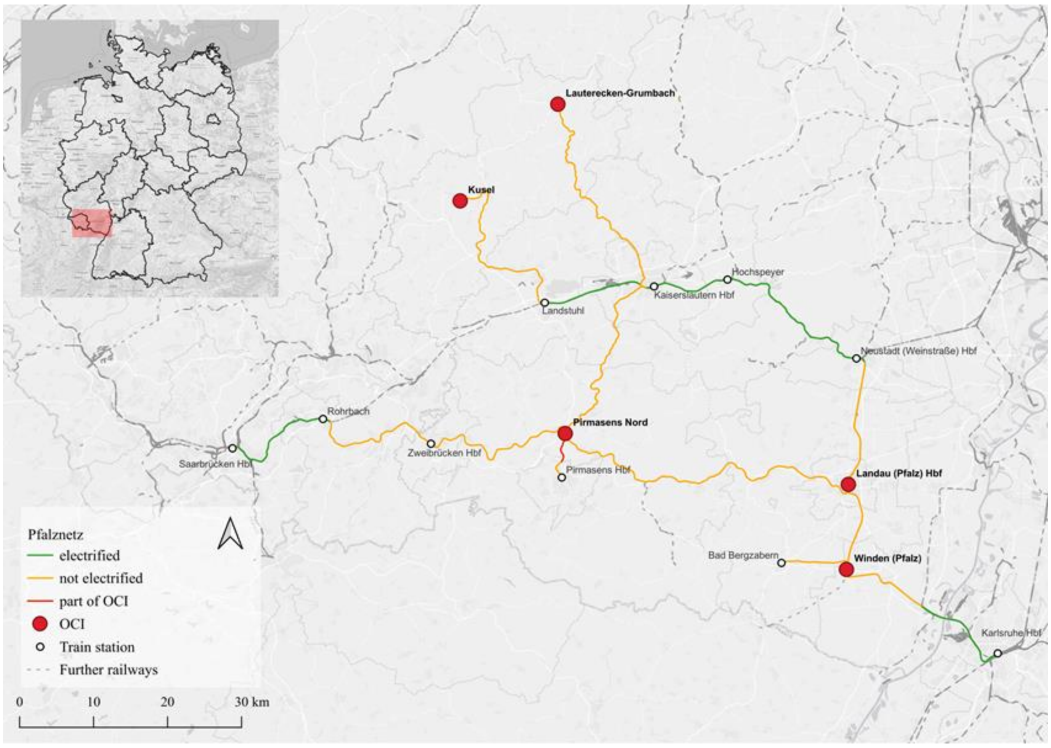


Figure 1: Pfalznetz railway network, Germany.

In order to take the operation of the whole rail network into account, we used the BEMU circulation plan issued by the operating rail company. The circulation plan was linked to the public timetable. The trips from the timetable where enriched with geodata representing the spatial route of the trips, the maximum speed and electrification information along the line (taken from Open Street Map [8]) and the topography to account for inclination in route sections. The topography of the route was derived from a digital elevation model [9]. The derived trip information was put together to a driving profile and fed into a tool for simulating the longitudinal traction power trajectory (power at wheel level) for each trip in the circulation plan. Afterwards the trajectories were put together to describe the operation of a vehicle over the course of a day. A vehicle energy model was used on top of the trajectories to model energy flows within the vehicle's drivetrain incorporating drivetrain efficiencies. Starting from the power at wheel level, the power on DC-link level, at battery, converters and at pantograph level were modelled. The battery state of energy (SoE) was computed. The power requirements of auxiliaries were included in the model, too. Then, OCI locations were defined within a geographic information system. The BEMU trajectories were matched within the same geographic reference system. Finally, the BEMU trajectories with their current SoE and power loads were aggregated under OCI locations, thereby creating a load curve for each catenary island.

The longitudinal simulations were performed with DLR-own trajectory planner tool incorporating a generic 2-car multiple unit as it was used in previous studies [1,10,11]. The output of the simulation is the force at wheel level, generated in the form of longitudinal trajectories. Trajectories are second-resolute time series, consisting of parameters such as acceleration, velocity, driving distance, force at wheel, power at wheel, station locations and electrifications. Each parameter is given for every second in the trajectory. After the simulations are performed, the trajectories are concatenated according to the circulation plan, thereby representing the operation of a BEMU over an operational day. As this is done for each vehicle in the circulation plan, the entire fleet of BEMU is incorporated into the analysis. For each vehicle the vehicle energy model was applied.

The vehicle energy model is based on the drivetrain components and respective static efficiencies as shown in Figure 2. The energy flow within the drivetrain is determined by the power at wheel, the mode of operation, maximum power ratings of components connected to the DC link and their respective efficiencies. If the vehicle uses its brakes, the power at wheel is negative. The recuperable share of the braking power is defined by the maximum force of the electrodynamic brake system at 60 kN. The maximum force in conjunction with the current velocity determines the maximum power to be recuperated. Table 2 gives an overview of various vehicle parameters including characteristic model component thresholds. Power for heating, ventilation and air conditioning (HVAC) and other auxiliaries is assumed to be static with continuous consumption of 76 kW.

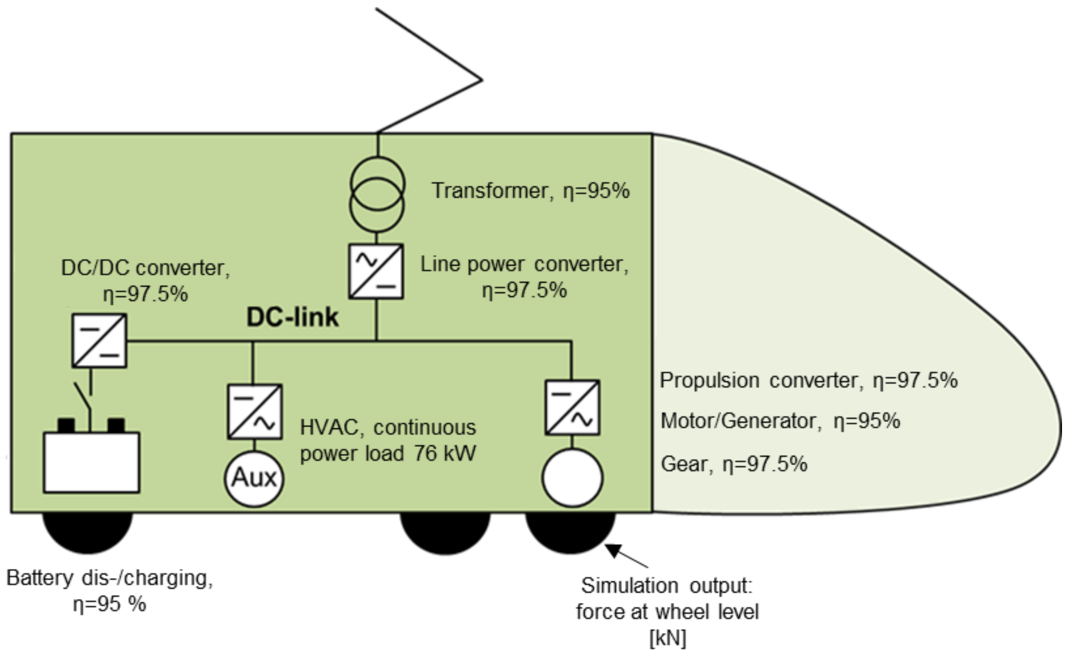


Figure 2: Drivetrain topology of generic 2-car BEMU

Length	42 m
Mass (seated)	97.5 t
Passenger seats	120
Maximum velocity	140 km/h
Max. de-/acceleration	1 m/s²
Max. power at wheels	1000 kW
Davis coefficients A,B,C	1956 N, 17.6 N/ms^{-1}, 2.59 N/ms^{-2}
Maximal power rating of line power AC/DC converter	2000 kW
Maximal power rating of propulsion converter	1400 kW
Maximum force of electro-dynamic brake	60 kN
Battery: installed energy	500 kWh
Maximum c-rate during recharging	1.2

Table 2: Vehicle parameters

The vehicle energy model yields the power at the battery and at catenary at any given time (smallest step is a second) over the course of a circulation day. As a result, it also models the SoE of the traction batteries. Energy flows vary in direction through various components of the drivetrain depending on the current operational mode. Operational modes are defined as functional operational states of the vehicle, namely driving (includes acceleration), braking, and idling at standstill - each mode is possible both under or not under overhead catenary (compare Table 3). For each operational mode, a function defines the power at the motor's DC/AC propulsion converter $p_{motor\_converter}$, the power at the battery $p_{battery}$ and the power at catenary $p_{catenary}$. The term $p_{motor\_converter}$ is determined by the power at wheel p_{wheel} which is yielded by simulation and the efficiencies of engine, gear and propulsion converter. If p_{wheel} is ≥ 0, $p_{motor\_converter}$ is calculated as

$$p_{motor\_converter} = \frac{p_{wheel}}{\eta_{gear}*\eta_{engine}*\eta_{motor\_converter}} \quad (1)$$

If p_{wheel} is negative (i.e. the vehicle is braking), parts of the braking power can be recuperated. Respectively, in this state $p_{motor\_converter}$ is calculated as

$$p_{motor\_converter} = p_{wheel} * \eta_{gear} * \eta_{engine} * \eta_{motor\_converter} \quad (2)$$

The calculation of the power at battery depends on the current operational mode. If the vehicle is operating under catenary, the battery is not fully charged and the train is running or idling at standstill, $p_{battery}$ is calculated as

$$p_{battery} = (P_{\substack{line\_converter \\ max}} - p_{aux} - p_{motor\_converter}) * \eta_{DCDC} * \eta_{battery} \quad (3)$$

During braking, the recuperated energy is prioritized to be used for the HVAC system and for recharging before it is fed into the catenary. Therefore, $p_{battery}$ is calculated as

$$p_{battery} = \left(p_{\underset{max}{line\_converter}} - p_{aux} + p_{motor\_converter}\right) * \eta_{DCDC} * \eta_{battery} \quad (4)$$

$p_{battery}$ is limited at a c-rate of 1.2 to improve battery lifetime durability. This is done for each operational mode by limiting $p_{battery}$ during recharging:

$$p_{battery} = \min\{(p_{battery} \; ; \; energy\ content_{battery} * Crate_{max}\} \quad (5)$$

If the vehicle is operating at catenary-free sections, $p_{battery}$ is calculated in the case of discharging (driving and idling at standstill) with

$$p_{battery} = \frac{p_{motor\_converter} + p_{aux}}{\eta_{dcdc} * \eta_{battery}} \quad (6)$$

During braking (i.e. recuperation) the recharging power at the battery is calculated with

$$p_{battery} = (p_{motor\_converter} - p_{aux}) * \eta_{dcdc} * \eta_{battery} \quad (7)$$

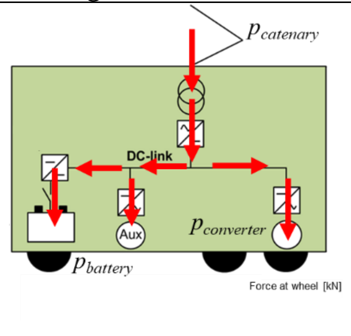
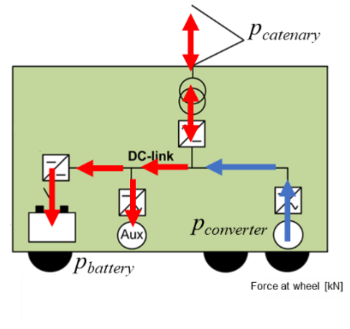
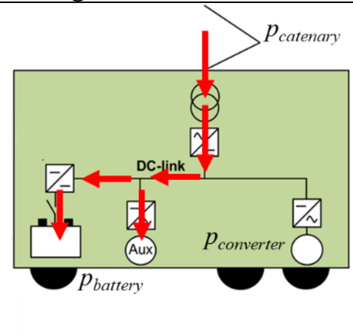
For each second operating under catenary the power at catenary $p_{catenary}$ is calculated. This includes three operational modes, i.e. driving, idling and braking. The power at catenary is determined by the power for HVAC, engine and battery recharging. Driving and idling is calculated as

$$p_{catenary} = \frac{p_{motor\_converter} + p_{battery} + p_{aux}}{\eta_{transf} * \eta_{line\_converter}} \quad (8)$$

If during braking $p_{motor\_converter}$ is larger than the sum of $p_{battery}$ and p_{aux}, $p_{catenary}$ is calculated as

$$p_{catenary} = (p_{motor\_converter} - p_{aux} - p_{battery}) * \eta_{transf} * \eta_{line\_converter} \quad (9)$$

The various power terms are calculated for each second of the trajectory. The SoE of the on-board battery is calculated within an iterative loop applied over the trajectories. This function feedbacks the SoE to the power equations. This way the battery power $p_{battery}$ is limited if the battery is fully recharged.

<table>
<tr><th colspan="3">Under overhead catenary</th></tr>
<tr><td>driving</td><td>braking</td><td>idling</td></tr>
<tr><td>
</td><td>
</td><td>
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<tr><th colspan="3">Catenary-free operation</th></tr>
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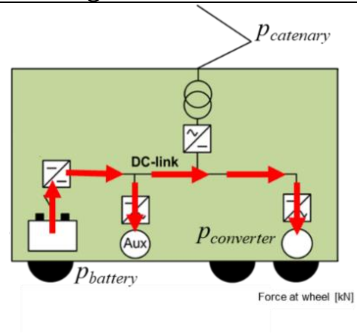
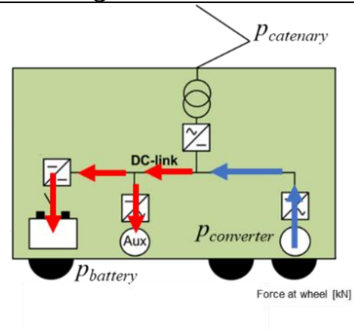
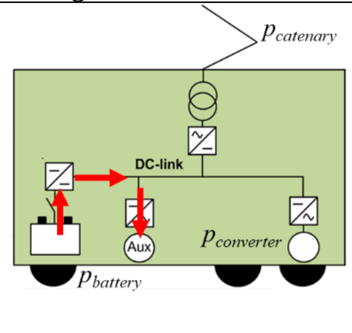
<tr><td>
</td><td>
</td><td>
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Table 3: Operational modes of the vehicle energy model

The vehicle energy model is applied on concatenated trajectories which represent vehicle operational days in the circulation plan. These are then spatially and timely matched and aggregated over OCI. Catenary islands are represented as geospatial polygons covering all tracks ought to be electrified (Figure 3). For each second in the trajectory, the location and geospatial coordinates are known, thereby it can be expressed as a point layer in a geographic information system. With a spatial look-up function, points under catenary islands are identified and assigned to the corresponding catenary island with a respective timestamp and all current operational parameters (velocity, power at wheel, battery, motor converter and pantograph). These are applied on a 24-hour curve to establish a power load diagram for each catenary island.

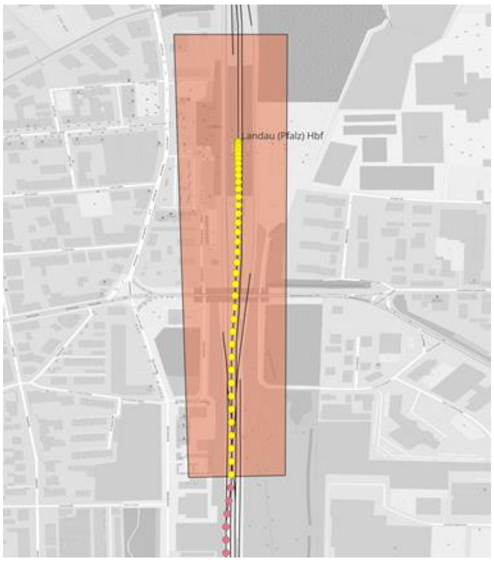

Figure 3: Representation of catenary island 'Landau' (orange polygon) and a part of a vehicle trajectory (points, yellow if under catenary).

3 Results

This section describes and discusses the results of both the vehicle energy model and the OCI power forecast model.

The considered circulation plan consists of 30 circulation days, i.e. 30 rotating vehicles, with some operating in multiple traction at times. These vehicles produce an operating performance of 11930 train-kilometres per day. On average the trains operate 13.1 hours per day, and cover 398 kilometre per day. On each vehicle's operational day, the vehicle energy model is applied.

3.1 Vehicle Energy Model

A graphic representation of the model applied over an operational day is shown in Figure 4. At this day, the vehicle covers 487 kilometres at an average speed of 61.5 km/h (not including stop times) with 127 stops at stations i.e. an average station distance of 3.84 km. The vehicle has a summed downtime at stations of 5.6 hours in an operational corridor between 04:35 and 18:06 (i.e. 13.52 hours). The mean specific energy consumption of this train is 4.9 kWh/km, which is the cumulated energy provided at overhead catenary plus the energy deficit in the battery at the end of the operational day divided by the kilometres covered that day. The train has an overall energy consumption of 2.39 MWh on that operational day.

The highest power loads taken from the catenary to the vehicle peaks at 1976 kW, while the average power at catenary is 604 kW (considering solely sections under catenary). Battery power peaks at 1277 kW which equals a maximum C-rate of 2.6. The battery makes 3.83 equivalent full cycles of the battery during operational hours with the lowest depth of discharge (DoD) of 25.3% and an average DoD of 70.3 %.

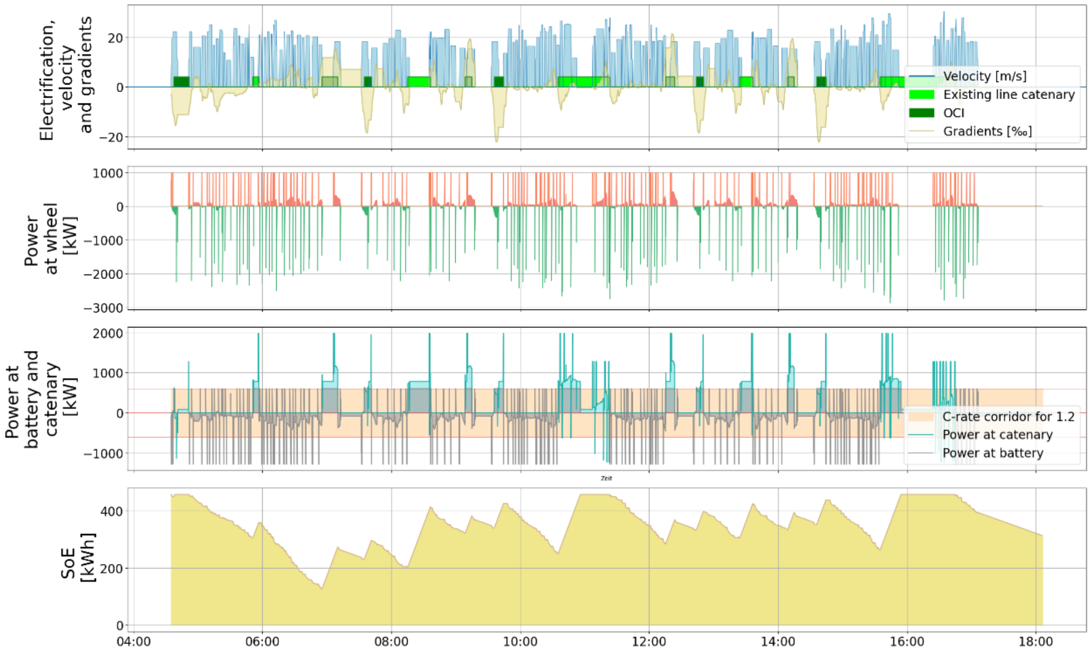

Figure 4: Representation of the vehicle energy model over a day for a specific vehicle circulation.

3.2 Overhead catenary islands

30 vehicle-day trips are mapped onto five OCI resulting in the power load profile of each OCI. An exemplary power load curve of OCI Kusel is shown in Figure 5. The upper part shows the number of vehicles, frequenting the OCI, the lower part shows the power demand at the catenary. The highest power peaks occur when several trains are recharging under an OCI at the same time (compare upper part). In Kusel the power load peaks at 2.6 MW. Each of the four high peaks shown in Figure 5 continue over a period of 14 seconds or lower. If averaged over a 15-minute moving window the peak power demand is reduced to 1.24 MW (dark red line). This 15-minute corridor represents the time period relevant for electric energy billing in Germany.

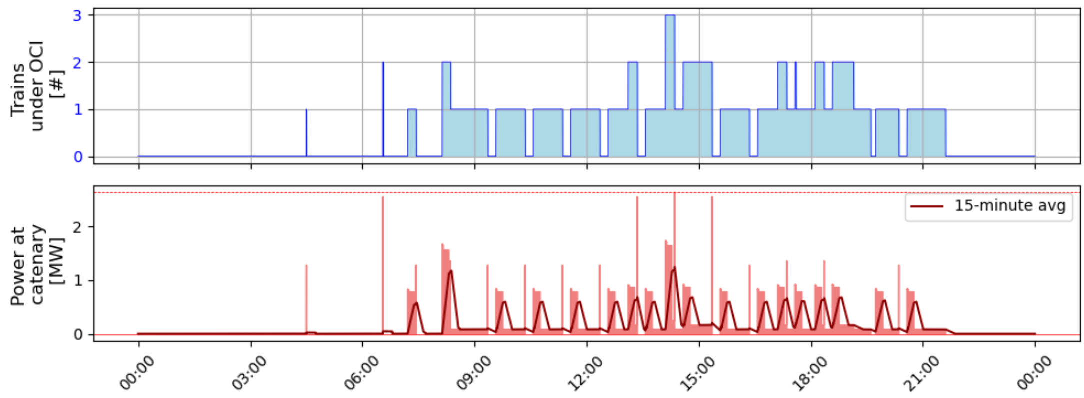

Figure 5: Power load curve of overhead catenary island Kusel

Figure 6 shows the power load curves for all OCI in the railway network. In conjunction Table 4 shows characterizing parameters of the corresponding OCI. The location of an OCI in the network determines the shape of the power load curve. While the OCI of Kusel and Lauterecken-Grumbach are placed at terminal stations, OCI Pirmasens Nord, OCI Landau and OCI Winden are located at stations within the railway network. The location has a relevant impact on the power load. Kusel and Lauterecken-Grumbach are frequented by trains mostly serving a single train line and they stay under catenary at the end for a longer period. i.e. they recharge their batteries i) constantly and ii) almost solely at these stations. This results in homogenic and even load patterns with modest power peaks. OCI Pirmasens Nord, Landau and Winden are frequented by trains mostly passing through, resulting in short recharging periods and more occurrences of peaks.
In order to meet good transfer options for passengers from one train to another, vehicles often meet under OCI, meaning that it is common for several BEMU to recharge under the same OCI simultaneously. At the terminal stations this is usually true for two vehicles (or sometimes three in case of multiple traction). Cross station OCI have up to five multiple units recharging at the same time in Pfalznetz.

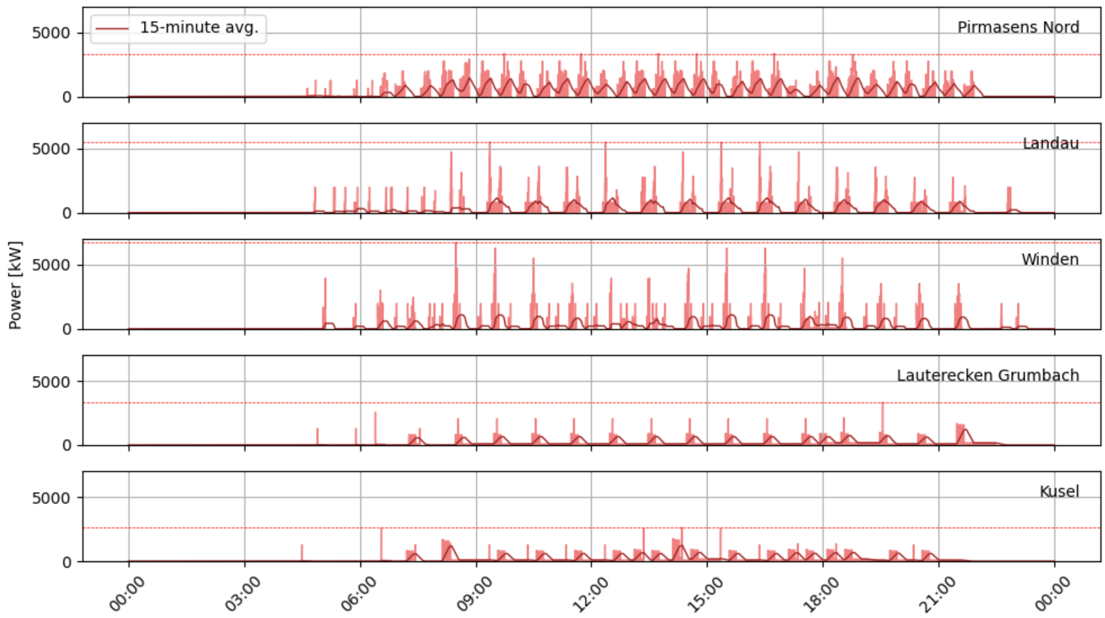

Figure 6: Power demand curves of planned Pfalznetz OCI.

	Pirmasens Nord	Landau	Winden	Lauterecken Grumbach	Kusel
Daily recharges [#]	36	29	39	5	13
Operating hours [h]	9	5.6	4.8	14.3	11.9
Downtime hours [h]	14.7	18.3	19.1	9.7	12.1
Power day peak [MW]	3.4	5.5	6.7	3.3	2.6
15-minutes rolling peak [MW]	1.5	1.1	1.1	1.2	1.2
Average power [kW]*	1063	906	1041	261	322
Daily energy [MWh]	9.6	5.1	4.9	3.7	3.8

* Averaged over OCI operating hours.

Table 4: OCI parameters

OCI are often in idle mode during the day and thus the upstream public grid is intermittently loaded. This can be illustrated if the power occurring at OCI over the day is sorted by descending power charges in kW. (Figure 7). Power at catenary at Lauterecken-Grumbach and Kusel drop quickly from high loads, while low power charges occur over longer periods. These low power charges result from fully recharged trains using energy for HVAC support during long turnaround times. Distinct from this, power peaks in Landau and Winden drop later but do not provide the auxiliarie power of waiting trains over longer periods. Pirmasens Nord delivers higher loads over longer times as i) its location in the railway network is more central with more trains passing through and ii) it provides energy to the line catenary over the route section towards Pirmasens Hbf, which is a very steep section, with high traction energy demand. During idle times there is no relevant load for the upstream public supply grid apart from the losses for the operating equipment. The peak loads are only required for short time frames.

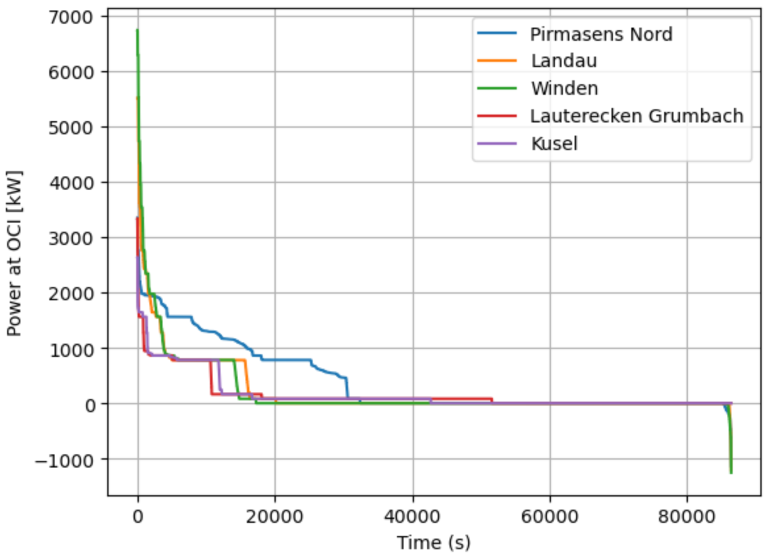

Figure 7: Descending sorted power charges of Pfalznetz OCI.

It should be noted, that the HVAC power demand is assumed to be very high, to model high-demand times (such as cold winter days or hot summer days). Therefore, waiting trains under OCI represent relatively high consumers over long periods. Depending on the actual weather conditions and the operational strategy, these - rather permanent – loads may be reduced strongly.

4 Conclusions and Contributions

In this paper we developed and executed a data-driven approach to forecast power demand of overhead catenary islands. We conducted this study on the railway network of Pfalznetz with real-world circulation and timetables. The location, time and severity of power charges from battery multiple unit operation is forecasted in detail. While the energy demand needed for traction and comfort systems are strongly determined by the circulation plan, there are many options to influence the severity of power peaks on the public electricity grid. For instance, timetables could be altered to give vehicles more time for acceleration under OCI as lower acceleration rates could reduce power peaks from the vehicles. The on-board energy management could be optimized, e.g. in a way that batteries are not recharged under acceleration or with stronger reducing c-rates during recharging. This is especially true as the average DoD of 70.3 % indicates, that with the proposed vehicle and its installed battery energy of 500 kWh, there is a large operational energy reserve. If that reserve would not suffice, timetables could be altered to allow for longer charging times with reduced power, especially at OCI`s where more than one train's battery is recharged at the same time. Finally, the use of stationary battery buffer stations can reduce peaks loads. As high-power peaks usually occur over periods of less than 30 seconds, even lean dimensioned buffers could cut peaks quite efficiently.

In general, it is to be expected that the use of BEMU will increase significantly in the future. Therefore, many technical solutions will also be available on the market in the future to charge these vehicles. Whether and which solutions will be found to operate these recharging facilities depends largely on the electric distribution networks and their operators. Our framework offers the opportunity to help making informed decisions for vehicle designers, railway operators and electricity grid operating companies to find viable solutions for this new emerging technology.

Acknowledgements

The authors would like to express their gratitude to ZÖPNV-Süd for generously providing circulation plans, which were instrumental in conducting this research.

References

[1] C. Streuling, J. Pagenkopf, M. Schenker, K. Lakeit, Techno-Economic Assessment of Battery Electric Trains and Recharging Infrastructure Alternatives Integrating Adjacent Renewable Energy Sources. Sustainability 13, 15,2021, 10.3390/su13158234

[2] Stephan A, Thomas Wittemann N, Bregulla T, Wissenschaftliche Bewertung von alternativen, emissionsarmen Antriebskonzepten für den bayerischen SPNV: Arbeitspaket 1: Analyse der Antriebsarten, Dresden, 2020

[3] Klebsch W, Guckes N, Heininger P, Bewertung klimaneutraler Alternativen zu Dieseltriebzügen: Wirtschaftlichkeitsbetrachtungen am Praxis-Beispiel >Netz Düren< Frankfurt am Main, 2020

[4] NAH.SH, Die Ausschreibung der Akkunetze in Schleswig-Holstein, 2024 https://akkuzug.nah.sh/. Accessed 16 February 2024.

[5] Bundesverband SchienenNahverkehr, Wettbewerbsfahrplan, 2023: Langfristplanungen der Aufgabenträger des Schienenpersonennahverkehrs, 2023 Accessed 7 March 2024.

[6] European Commision, Europe`s Rail Joint Undertaking Master Plan (Draft): Annex to the commission decision on the submission of the Europe`s Rail Joint Undertaking master plan for adoption by Europe`s Rail Governing Board, Brussels, 2022

[7] Herwartz-Polster S, Böhm M, Stickel S, Streuling C, Hertel B, Pagenkopf J, Rail vehiucles: Fuel cells and batteries, Encyclopedia of Electrochemical Power Sources, Elsevier, in press, 2024

[8] Open Street Map Contributors, Open Street Map 2020

[9] JAXA, ALOS Global Digital Surface Model (AW3D30) 2016 https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm. Accessed 23 July 2021

[10] M. Schenker, T. Schirmer, H. Dittus, Application and improvement of a direct method optimization approach for battery electric railway vehicle operation, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 2020

[11] C. Streuling, S. Herwartz-Polster, J. Pagenkopf, M. Schenker, M. Böhm, J. Polster, S. Arens, R. Völker, B. Hanke, A. Windt, T. Röpcke, Berichte des Deutschen Zentrums für Schienenverkehrsforschung: Versorgungskonzept und Integration von Erneuerbaren Energien in neuartige Tank- und Ladeinfrastrukturen: Schlussbericht, In press, Dresden, 2023