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Application Potential of Long-Range Battery Electric Multiple Units for Challenging Regional Railway Applications in Germany

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Abstract

This work investigates highly demanding regional railway services in Germany, which are partly electrified and currently operated with diesel-powered trains. It explores the operation of upcoming long-range battery electric multiple units (BEMUs), defined here as vehicles with a traction battery capacity of 950 kWh. The analysis is based on twelve exemplary service days in German regional rail networks featuring track electrification gaps of more than 80 km.

Train operations are modelled across entire service days rather than individual routes, thereby extending the perspective from individual route-based assessments to real-world operational conditions in complex regional rail networks. The selected service days cover total daily distances between 704 and 1323 km per train. A longitudinal simulation framework was applied to determine operational feasibility of BEMUs in regards to traction battery state of charge.

The results show that long-range BEMU are capable of serving roughly half of the examined routes, without any additional infrastructural or operational adjustments. Moreover, minor timetable adjustments - particularly increasing turnaround times under catenary for battery recharging - can significantly enhance operational feasibility. The results highlight the potential of long-range BEMU for widespread application in German regional rail systems.

Keywords: BEMU, alternative traction, long-range, requirements, regional railway, Germany

1 Introduction

Due to ongoing efforts to decarbonize the German transport sector, there is a strong trend toward shifting from diesel multiple units (DMU) to the adoption of battery electric multiple units (BEMU) in regional railway operations [1]. The state-of-the-art autonomy range for BEMU is approximately 80–120 km [1]. DMU offer a high autonomy range and they can be operated independently of existing overhead electrification. In contrast, BEMU are far more limited in their autonomy range and rely on sufficient recharging opportunities. Although Germany has a dense railway network with approximately 62 % electrification degree, demanding electrification gaps remain, particularly on rural train lines served by multiple units.

To compensate for the limited vehicle autonomy of BEMU, commonly additional recharging infrastructure is planned and constructed. In Germany, however, adding or altering infrastructure are typically multi-year high-cost procedures involving several groups of actors. Another challenge for BEMU operation in Germany is the occurrence of highly demanding circulations, where vehicles are intensively rotated over the course of a day, resulting in short recharging windows between trips. Consequently, railway networks in which BEMU have recently been deployed have typically required adjustments to circulation plans to ensure sufficient operational robustness.

Increasing vehicle range can reduce the need for such infrastructural and operational adjustments and can contribute to a more robust and therefore more resilient operation. While most manufacturers have entered the market with first-generation BEMU platforms (typically two- to three-car units [1]), new concepts featuring higher battery capacities (here referred to as 'long-range BEMU') are currently under development.
This study aims to highlight the advantages of a long-range BEMU with 950 kWh traction battery capacity, by focusing on regional passenger rail networks with high demanding attributes such as electrification gaps and high daily train kilometres. We assume that a long-range vehicle enables operation on railway lines that were previously considered to be difficult to operate with BEMU. To support the development of such vehicles, we investigate the requirements of demanding regional railway operations in Germany.

To demonstrate the benefits of extended range, we identified demanding service days on regional railway lines throughout Germany. A service day is defined as the sequence of timetable trips and turnaround times that a vehicle must cover over a 24-hour period. We selected service days that include sections with electrification gaps exceeding the autonomy range of state-of-the-art BEMU. These service days do not represent average daily train kilometres, but most demanding operational scenarios. We conducted longitudinal simulations, using both a generic conventional BEMU and a representative long-range BEMU.

2 Methods

We selected twelve train routes with continuous electrification gaps exceeding 80 km and derived the most demanding service day profiles for these routes and prepared them for simulation. On these lines, conventional BEMU operation is often not feasible without additional charging infrastructure. The routes considered in this analysis were selected qualitatively based on in-depth knowledge of the German regional rail system. Lines for which BEMU or HEMU procurement has already been tendered, or where electrification is likely (e.g., due to existing funding agreements, planned electrification projects, or classification as "urgent need" in the Federal Transport Infrastructure Plan [2]), were excluded.

As circulation plans are subject to non-disclosure, train runs were derived from public timetables. Service days were prepared by combining route, trip, and infrastructure information. We simulated the planned operation using a longitudinal dynamic simulation model (see below). The simulated service days were subsequently analyzed with regard to their state-of-charge (SoC) profiles. The analysis was conducted exemplary for both a conventional-range vehicle and a long-range BEMU. Figure 1 shows a map of the considered regional railway lines.

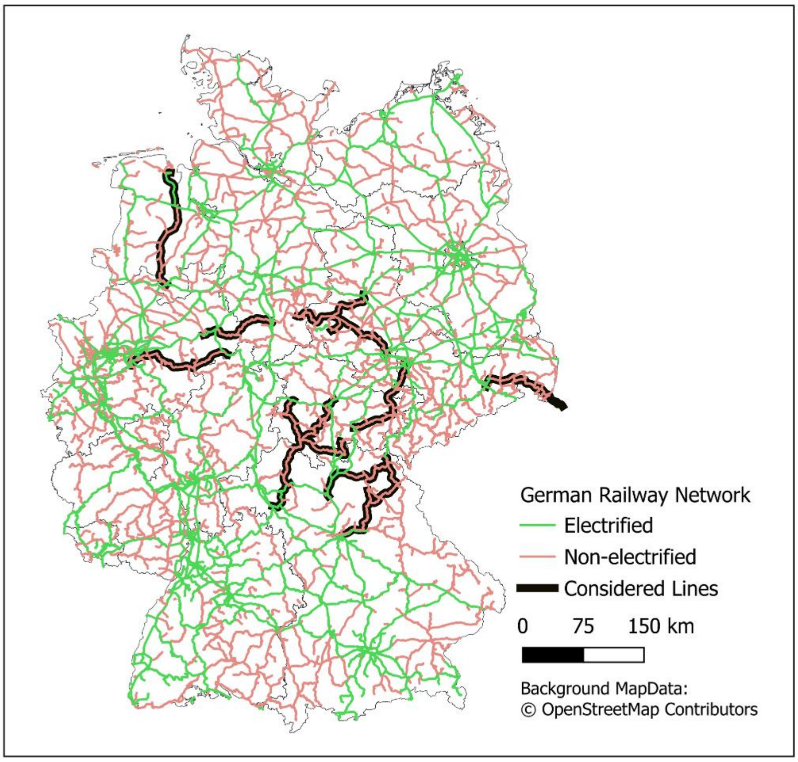

Figure 1: Map of the analyzed regional railway lines.

Deriving service days from timetables

To identify the longest non-electrified railway lines in Germany, a systematic map-based analysis was conducted using OpenRailwayMap [3] as the primary data source. The railway network is examined sequentially from north to south to identify extended sections without overhead line electrification. Once a potential candidate is identified, the corresponding network map of the respective regional transport association is consulted to determine the official line designation as well as its terminal stations. Subsequently, both the total route length and the extent of the non-electrified section were calculated in a GIS analysis. Only railway lines featuring a continuous non-electrified segment of at least 80 km were included in the analysis. For each selected line, research was conducted to determine whether BEMU operation was already planned or in service, and to identify existing or planned recharging infrastructure. Lines with confirmed BEMU implementation were excluded from further consideration. In the following step, official timetables for the remaining lines were collected and systematically evaluated. Based on the published timetables, detailed vehicle circulation plans were developed. Individual timetable entries were consolidated and temporally aligned to reconstruct operationally feasible vehicle rotations. Extended dwell times at intermediate stations were cross-checked against station-specific timetables to verify whether vehicles are assigned to additional services during these intervals. Where applicable, such services were incorporated into the reconstructed circulation plans. Finally, the circulation exhibiting the highest operational demand is selected as the reference case for further analysis.

The line RE4 between Halle (Saale) main station and Goslar is used as an illustrative example (Figure 2). According to the line timetable, services operate only between these two stations. However, when analysing the timetable in detail, extended dwell times between arrival and the next scheduled departure become apparent at Halle (Saale). For example, the train departing from Goslar at 06:06 arrives in Halle (Saale) at 08:11, while the next scheduled departure as RE4 is not until 09:49. By examining the station timetable of Halle (Saale), it becomes evident that line RE24 operates along part of the same route segment, terminating earlier in Halberstadt before returning towards Goslar. The next RE24 departs from Halle (Saale) at 08:49 and arrives in Halberstadt at 09:57. It then departs again at 10:02 and arrives back in Halle (Saale) at 11:11. From there, the train can operate the next scheduled RE4 service departing at 11:49. In this way, the vehicle alternates between RE4 and RE24 services, which significantly reduces dwell times at Halle (Saale) and results in a more realistic representation of the vehicle circulation.

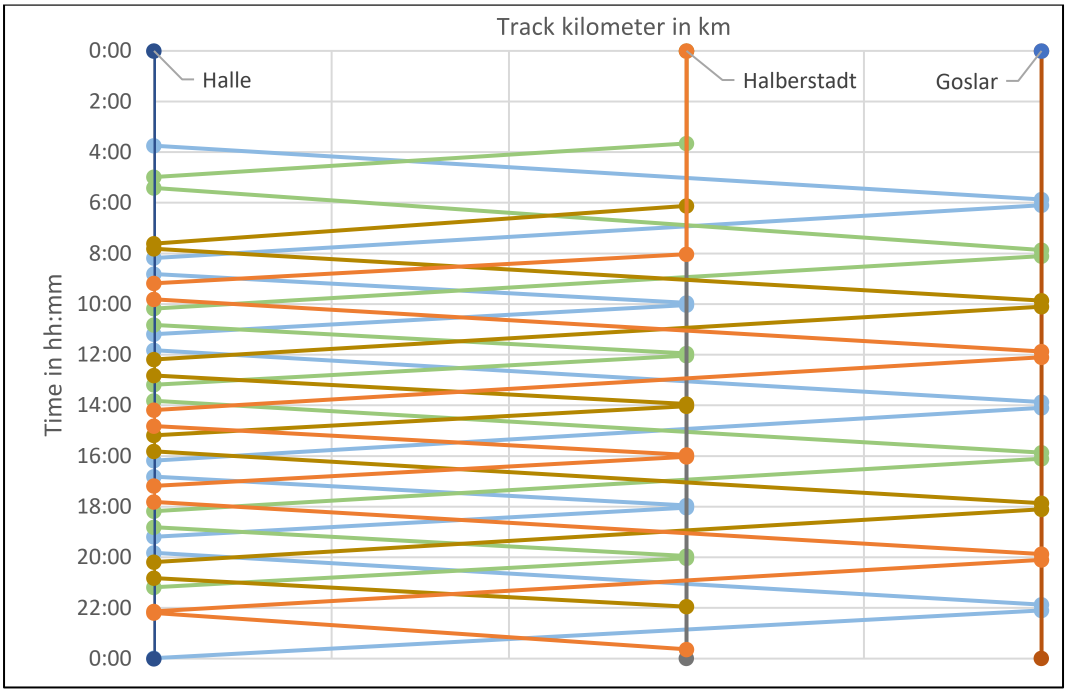

Figure 2: Train run diagram for regional railway lines RE4 Halle (Saale) – Goslar and RE24 Halle (Saale) – Halberstadt.

The so derived service days were fed into a geo data model to generate service profiles consisting of distance, inclination, max-speed limitations, electrification and timetables [4,5]. These service profiles were then fed into the longitudinal simulation software, described below.

Battery Electric Multiple Unit – Conventional and Long-Range Version

For the analysis, two versions of the BEMU were set up, a 'conventional' version with a battery capacity of 330 kWh that is common for existing operation [1,6], though on the lower end of the range, and a 'long-range' with almost three times the capacity, at 950 kWh. The values were taken from the EU-Rail Rail4Earth specifications of a generic battery vehicle and general assumptions [7]. Detailed sub-models of components within the vehicle are not in the scope of this analysis. The vehicle versions only differ in their battery capacity and, thus, in weight and resistance coefficients. For battery weight scaling a specific energy of 90 Wh/kg is assumed. The assumption for the resistance calculation is that the speed-independent Davis coefficient A is fully weight dependent, while the others are not weight dependent. A full overview of parameters and assumptions are given in Table 1.

Table 1: Vehicle parameters and assumptions [7].

	Conventional	Long-Range
Battery capacity in kWh	330	950
Length in m	50	
Power at motor in kW	1,000	
Max force at wheels in kN	151 (motor), 151 (generator), 160 (mech. brake)	
Weight in t (static)	142.4	149.3
Rotating mass in t	7.5	
Resistance (Davis coefficients)	A = 818.8 N B = 9.2 N/(km/h) C = 0.4 N/(km/h)²	A = 859.9 N B = 9.2 N/(km/h) C = 0.4 N/(km/h)²
Auxiliaries (constant) in kW	56.9	
Efficiencies	Wheel ↔ DC-link (traction): 85% Wheel ↔ DC-link (braking): 87% Overhead line ↔ DC-link: 93.1% Battery ↔ DC-link: 93%	

Simulation framework *pySimRail*

The *pySimRail* simulation framework, a multi-level, modular Python model, was used for the holistic simulation of energy flows in the rail vehicle [8]. *pySimRail* allows for comprehensive mapping of the entire energy chain in the vehicle:

- Drive dynamics: longitudinal dynamics of the vehicle with route-specific boundary conditions
- Heating, ventilation and air conditioning: thermal control of the cabin
- Energy management system: power distribution between fuel cell and battery

The modules are functionally separated from each other, but include predefined interfaces that enable integrated simulation of multiple modules. This reduces the susceptibility to errors and allows systematic and rapid analysis of results through automation. In addition to the simulation of existing vehicles, *pySimRail* also allows the data-driven design of the battery. An overview of the interaction of the modules is shown in Figure 3.

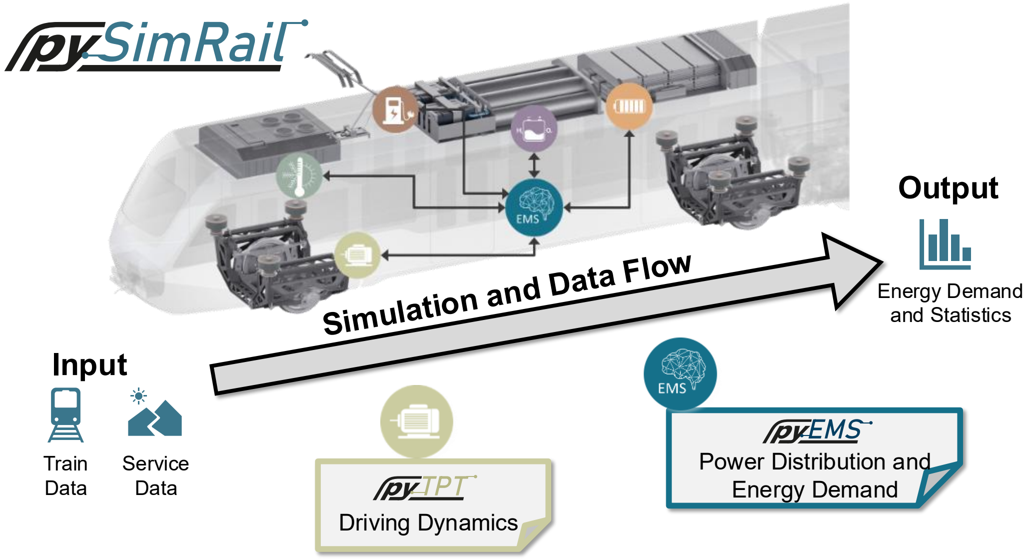

Figure 3: Schematic representation of the vehicle model in the simulation framework *pySimRail*.

In the driving dynamics module, a speed profile and the corresponding mechanical power profile at the wheels are determined on the basis of the route data (e.g. timetable, speed limits, gradients, curve radii and electrification) and vehicle data (e.g. weight, length, resistance coefficients according to Davis formula, traction and braking force characteristics, maximum speed, acceleration and braking acceleration as well as jerk). With this information, the equation of motion is solved over the whole track in order to determine the longitudinal dynamics of the train:

$$\dot{v} = \frac{F_{\text{traction}}(v) - F_{\text{resistance}}(v, s)}{m_{\text{total}}}$$

The maximum force on the wheel F_{traction} is limited by the current speed. The resistance force $F_{\text{resistance}}$ considers of gradient, curve and rolling resistance. A rule-based approach with different phases (acceleration, constant speed, coasting, braking) is selected to determine the necessary speed profile to meet the timetable.

In the energy management module, the speed and power profiles of the previous calculation are used as input to calculate the overall energy demand of the vehicle as well as the load on the battery. There, component specifications (e.g. efficiencies, maximum loads) and an energy management system (EMS) logic are defined. The primary aim is to cover the power requirements, i.e. to balance the following equation:

$$P_{\text{traction}} + P_{\text{aux}} + P_{\text{rheo-brake}} = P_{\text{overhead-line}} + P_{\text{battery}}$$

The power distribution between the overhead line (whenever available) and the battery, as well as the recharging strategy of the battery must be determined by the EMS in such a way that the desired boundary conditions are met, for example energy-efficient and component-friendly operation. Given the parametrization of the specific vehicle, the final output is the dynamic state of charge of the battery and power profiles for both battery and overhead line. This allows for analysis of the battery's behaviour, energy losses of BEMU and the overall demand at overhead line.

3 Results

The considered service days provide insight into the characteristics of highly demanding regional railway operations. Table 2 presents an overview of key attributes of the selected service days. These include daily distances ranging from 725 to 1,323 km. The shortest electrification gap is 87 km, while the longest reaches 291 km. To put this into perspective, the selected train routes represent the upper end of the typical daily train-kilometre range in German regional passenger rail transport.[6] (Figure 4).

Table 2: Train run characterization.

Train service and route	Daily distance	Non-electrified distance	Longest electrification gap	Cumulative climb	Avg. speed	Operating hours	Idle time share
	[km]	[km]	[km]	[m]	[km/h]	[h]	[%]
RE35 Bamberg-Hof	1051	618	87	1669	85.2	17.0	27.5
RB84 Paderborn-Kreiensen	837	620	89	2275	73.7	18.8	39.5
RE12 Leipzig-Saalfeld	1061	829	128	1722	78.6	20.3	33.4
RE17 Warburg-Hagen	896	777	186	1993	85.3	16.0	34.4
RE11 Magdeburg-Thale	809	772	165	862	75.7	18.6	42.4
RE4 Halle-Goslar	1274	1256	291	2887	85.4	20.4	26.9
RE2 Dresden-Liberec	790	726	242	1641	76.1	16.3	36.2
RE18 Wilhelmshaven-Osnabrück	1323	862	108	715	83.3	19.7	19.4
RE30 Hof-Nürnberg	1201	1193	185	2101	101.6	17.9	33.9
RB40 Meiningen-Schweinfurt	725	692	154	1772	75.5	17.3	44.4
RE7 Erfurt-Würzburg	1208	864	144	4079	97.1	17.5	28.7
RB41 Eisenach-Neuhaus	704	700	140	2752	62.8	17.9	37.4

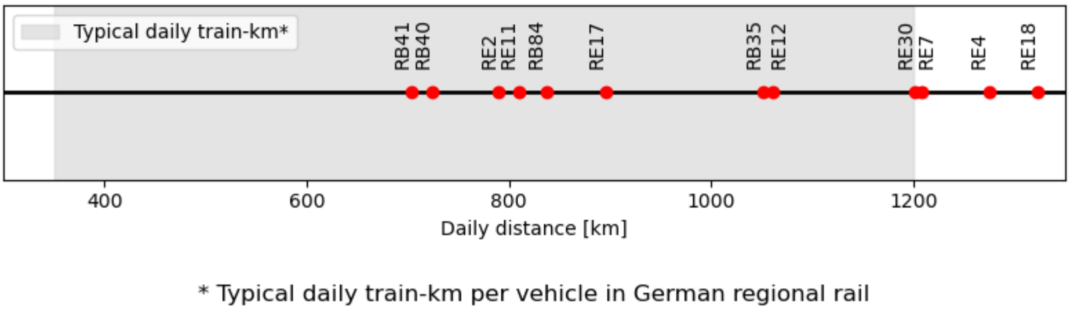

Figure 4: Covered daily distance and typical daily train kilometer in German regional passenger railway [6].

To showcase the advantages of a long-range BEMU, simulation results for one of the abovementioned scenarios are discussed in detail. The service day RB40 between Meiningen and Schweinfurt in central Germany, with a distance of roughly 80 km between the two cities, is only electrified around Schweinfurt. Thus, the trip to and back from Meiningen, including the stop for turnaround, needs to be covered without external power supply.

The top of Figure 5 shows the simulated speed profile over time, also marking out electrified sections and the elevation profile. Over the day, the train moves with an average speed of 76 km/h over 724 km. During the day it covers an elevation gain of around 1772 m and is in idle mode for 7.7 h. The lower diagram of Figure 5 displays the corresponding SoC for both BEMU versions. While the conventional version is barely able to reach the electrified section, when starting with a fully charged battery in Meiningen (only with deep discharging below SoC of 10%) and fails to make the trip back, the long-range BEMU covers the whole service day without going below the absolute minimum safety threshold of 10% SoC. In order to provide the required energy, the deepest discharge of the long-range battery shows a DoD of 72% and over the whole service day requires 4.79 equivalent full cycles of the battery. Due to the high installation capacity of the battery, C-rates can be kept low during operation. For this service day the maximum discharge rate is 1.3 C, charging goes up to 2.6 C, but can be further restricted as the stops are well sufficient for recharging. These relaxed requirements allow the implementation of other battery technologies or result in reduced battery ageing compared to the conventional version of the BEMU.

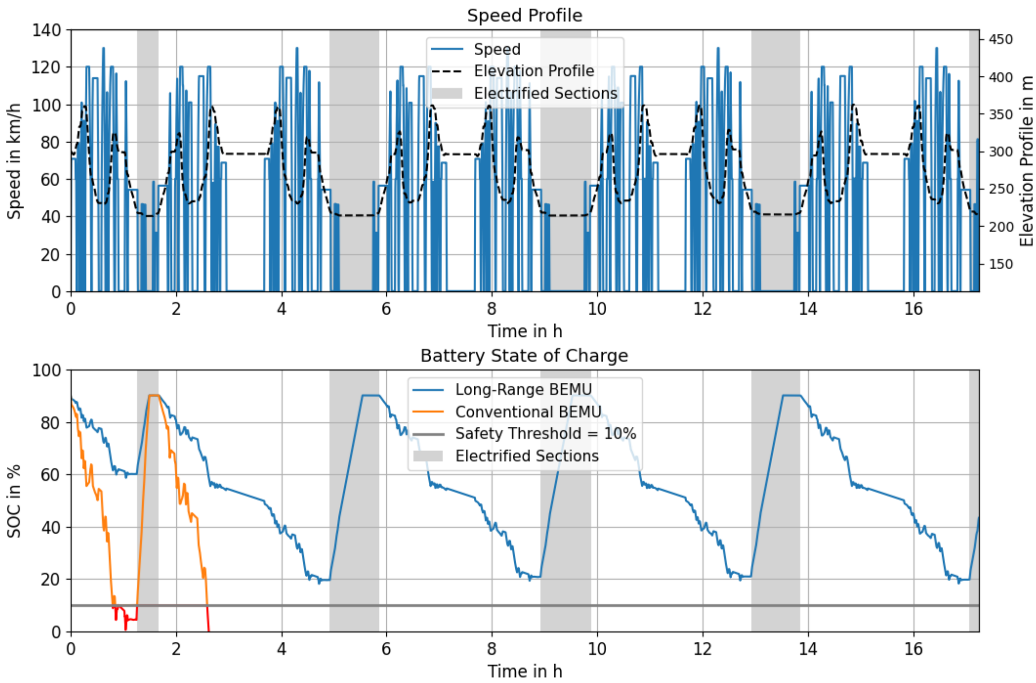

Figure 5: Simulated speed and elevation profiles of the service day Meiningen – Schweinfurt (top), battery state of charge for the conventional and the long-range version of the BEMU (bottom).

Collective analysis of all service days

The simulations were conducted for twelve service days. Figure 6 illustrates the battery SoC together with the lengths of the longest non-electrified section and the operation time under catenary, i.e. the cumulated recharging opportunities over the day. While it is not possible to serve these service profiles with a conventional BEMU at all, the long-range BEMU allows operation on 8 out of the 12 routes, although commonly, a minimum safety threshold of 10% SoC is to be maintained, which would reduce feasibility to 7 out of 12 routes.

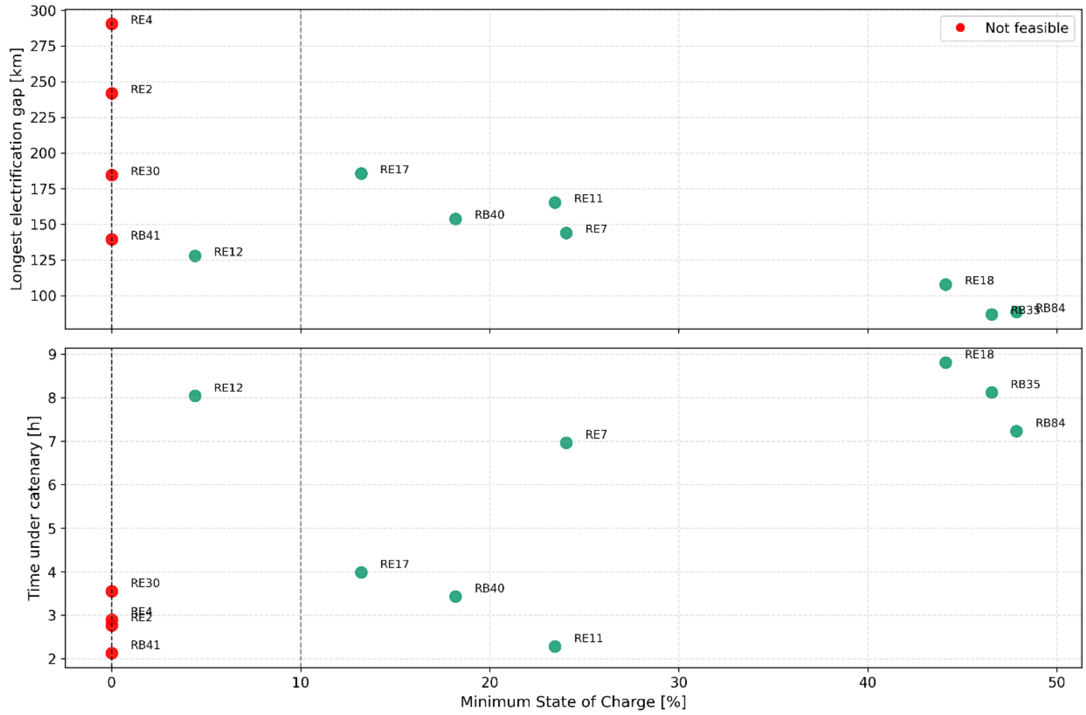

Figure 6: Long-range minimum battery state of charge and electrification share in day-trajectories.

As mentioned, the main restrictions for a feasible operation are the length of longest electrification gap and limited time under catenary. As the data in the upper panel of Figure 6 suggest, RE4 and RE2 (see Table 2) are limited by the length of the electrification gap. These routes could still be operated with relatively minor infrastructural measures at the terminal stations, namely in Halle and Liberec. However, some of the service days in analysis indicate potential operational mitigations for battery operation. As illustrated in Figure 7, short turnaround times or idle times under electrification lead to incomplete recharging. Over the whole days, this leads to starvation of the battery. Slightly longer stopping times under catenary could mitigate this issue and enable battery-electric operation without the need for additional infrastructure. A full recharge from 10 to 90% would take around 45 min in the specified scenario. This is required mostly in the turnaround. Even slightly longer recharging durations often allow sustained operation since the battery is usually not depleted when entering electrification. The lower part of Figure 6 indicates services, which might profit from this mitigation, namely RB41 and RE30. However, even with a high overall time under catenary, there might be an insufficient stop in the middle of the day, as it is the case with RE12.
With these additional operational and infrastructural changes, the use of long-range BEMU variants enables the operation with battery-powered trains on a wider range of regional networks.

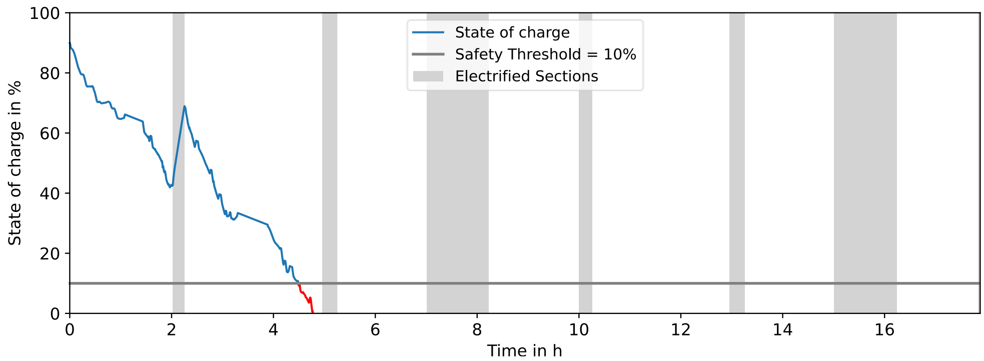

Figure 7: Battery state of charge of long-range BEMU on the RE30 Hof - Nürnberg with longest non-electrified section of 185 km. Longer idle times under catenary and an additional recharging opportunity would make the service day feasible.

4 Conclusions

The ongoing development of BEMU vehicles foreshadows the development of long-range BEMU. These vehicles have the potential to enable a catenary-free zero-tailpipe emission operation on demanding routes, while reducing the need for additional charging infrastructure.

In this evaluation, we modelled train operations across entire service days. With total daily distances between 704 and 1323 km per train and including long non-electrified sections up to 290 km, these services represent challenging regional operation in Germany. Utilizing long-range battery vehicles, 7 of the 12 considered services could be operated with BEMU, without any additional infrastructural or operational adjustments.

While additional infrastructure can help bridging long electrification gaps, even slight adjustments to timetables and circulation plans as well as limited installation of recharging opportunities on end stops can enable operation on lines with a dense circulation. Challenging circulations in regional rail operations in Germany are often a result of long-established operation with diesel multiple units. A more flexible approach to revising these tightly constrained, diesel-based timetables offers improved operational conditions for BEMU.
Our results represent planned uninterrupted operation during common operational conditions. In the event of operational disruptions, long-range BEMU services may approach or exceed their feasibility limits sooner, leading again to higher infrastructure requirements. However, this is highly route- or network-specific and forms part of the detailed project engineering process.

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References

[1] Herwartz-Polster S, Böhm M, Stickel S, Streuling C, Hertel B, Pagenkopf J. Applications – Transportation Applications | Rail Vehicles - Fuel Cells and Batteries. In: Garche J, editor. Encyclopedia of Electrochemical Power Sources (Second Edition). Oxford: Elsevier; 2025, p. 268–279.

[2] BMVI. Bundesverkehrswegeplan 2030. Berlin; 2016.

[3] Reichert M. www.openrailwaymap.org. [April 08, 2026]; Available from: https://www.openrailwaymap.org/.

[4] Herwartz-Polster S, Pagenkopf J, Kaiser J, Freienhofer M. Power Forecast of Overhead Catenary Islands in Battery Electric Train Operation: Case Study of Pfalznetz. In: Pombo J, editor. Proceedings of the Sixth International Conference on Railway Technology: Research, Development and Maintenance: Civil-Comp PressEdinburgh, United Kingdom; 2024, p. 1–14.

[5] Streuling C, Herwartz-Polster S, Pagenkopf J, Schenker M, Böhm M, Polster J et al. Versorgungskonzept und Integration von Erneuerbaren Energien in neuartige Tank- und Ladeinfrastrukturen: Forschungsbericht 63. Dresden; 2024.

[6] Pagenkopf J, Schirmer T, Böhm M, Streuling C, Herwartz S. Marktanalyse alternativer Antriebe im deutschen Schienenpersonennahverkehr, NOW GmbH, https://elib.dlr.de/134615/ 2020.

[7] Fernández S. D5.2 Development of alternative propulsion based on ESS: Confidential; 2023.

[8] Schenker M, Moser I, Böhm M (eds.). Holistic Modeling and Optimization of Hydrogen-Powered Trains for Zero-Emission Railway Operation; 2025.