Enhancing energy efficiency and environmental sustainability through regional battery-powered train energy transfer systems

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EXTENDED ABSTRACT

The urgent need to decarbonize both the energy and transportation sectors stems from their combined responsibility for over 60% of global greenhouse gas emissions [1]. As climate change accelerates, international frameworks such as the Paris Agreement and regional policy initiatives like the European Green Deal have set ambitious targets for achieving net-zero emissions by mid-century. In particular, the EU aims to reduce net greenhouse gas emissions by at least 55% by 2030 and reach climate neutrality by 2050. These goals require systemic shifts across infrastructure, including energy production, storage, and mobility systems. Consequently, there is a growing demand for distributed, low-carbon solutions capable of addressing grid limitations while enabling resilient, renewable-powered energy access, especially in rural or environmentally protected regions [2], [3], [4]. While renewable energy adoption is expanding rapidly, challenges persist in matching generation with demand, particularly in remote areas where building grid extensions, even for clean energy, is economically infeasible or ecologically disruptive. Simultaneously, the electrification of regional rail offers a promising platform not

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only for clean transportation but also for innovative energy distribution [5], [6], [7]. This work proposes a novel concept: battery-powered regional trains acting as mobile energy carriers that transport passengers and energy simultaneously. Inspired by the principles of Vehicle-to-Grid (V2G) [8] and Vehicle-to-Vehicle (V2V) [9] systems, this model envisions trains charged via renewables at depots or nodes with excess supply, then delivering clean energy to low-access or off-grid areas to power station operations, auxiliary infrastructure, microgrids, or even recharge other vehicles. The concept is particularly well suited for regional rail lines that traverse topographically diverse or partially electrified corridors. A case study modeled using MATLAB simulations on the Borlänge–Malung railway in Sweden exemplifies this approach, based on train performance and demand scenarios developed within the Horizon Europe FutuRe Flagship Project [10]. With significant elevation differences, traction energy consumption for uphill trips is found to be approximately 40% higher than for downhill returns. In conventional planning, this asymmetry would necessitate sizing batteries for worst-case (uphill) demand, resulting in oversizing and added environmental burden. However, by enabling energy transfers between downhill and uphill trains, either directly or via rail-side energy hubs, battery capacity can be optimized, avoiding the cost and emissions associated with redundant storage capacity. This energy-balancing approach is topography-aware and dynamically adaptive to route-specific operational demands. To assess operational feasibility, the proposal incorporates modeling of traction energy, battery aging, and auxiliary energy demand. Battery degradation is simulated using a Rainflow counting algorithm applied to time-series state-of-charge (SOC) profiles under various speed and energy-use conditions. This method, combined with depth-of-discharge–based cycle-life curves [11], [12], [13], offers reliable projections of battery life, enabling right-sizing of energy storage and avoiding premature replacements. Notably, the carbon footprint of lithium iron phosphate (LFP) battery manufacturing is estimated at around 55 kgCO_2eq per kilowatt-hour[14], reinforcing the need to avoid excess capacity that would otherwise inflate upstream emissions. Furthermore, auxiliary energy demands, particularly for Heating, Ventilation, and Air Conditioning (HVAC) systems, are non-negligible and fluctuate significantly based on weather conditions and passenger load. A one-dimensional thermal simulation conducted as part of the FutuRe project shows that HVAC energy consumption is highly sensitive to variations in both occupancy and ambient temperature. For instance, at 28°C, an empty train requires less than one-third the ventilation and cooling energy of a fully loaded one, along with an estimated 8% reduction in traction energy. These variations not only affect battery sizing but also offer potential for surplus energy reallocation in real time. Accurate prediction of auxiliary loads allows for more dynamic energy management and identifies opportunities to supply other users, such as e-bike or EV charging stations in isolated locations, without overburdening system resources. From an energy systems perspective, these mobile energy carriers provide flexibility at multiple levels. In remote locations, where even renewable power plant construction could damage delicate ecosystems, trains offer a non-intrusive alternative for clean energy delivery. During periods of low demand, they can store surplus energy; during peak hours, they can discharge to relieve grid stress and reduce dependency on fossil-based balancing sources. The system is especially valuable in regions where electricity consumption is limited to narrow time windows, such as seasonal tourism destinations or mobile research sites, where permanent grid infrastructure is not justified. Moreover, Europe's grid average emissions remain relatively high at 244 g CO_2 eq/kWh (2019–2022) [15], making renewable-charged trains a cleaner intermediary that reduces transmission losses and improves localized carbon performance. Incorporating V2G and V2V functionalities into rail infrastructure, however, introduces technical challenges. These include the need for standardized charging interfaces, predictive scheduling, real-time energy exchange coordination, and robust battery health monitoring systems. In conclusion, this extended abstract proposes a shift in how battery-electric trains are conceptualized, not as passive consumers of electricity but as intelligent, mobile contributors to sustainable energy networks. In addition to providing clean transportation, these trains have the potential to deliver decentralized, on-demand, and environmentally sensitive energy services. With the integration of topography-based routing, auxiliary load prediction, and advanced battery lifecycle modeling, this concept could enable future decentralized, zero-carbon mobility and energy systems, especially in areas where traditional infrastructure is neither feasible nor desirable.

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