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Economic Feasibility Study of Integrated Virtual Power Plants with Renewables for Railway System in Germany

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ABSTRACT

This study examines whether a traction-oriented virtual power plant can deliver cost-competitive, low-carbon electricity into Deutsche Bahn's 110 kV/16.7 Hz railway network and defines the contractual and technological conditions for bankability. The considered case study consists of a 104 MW portfolio – 60 MW wind and 40 MW PV as the primary focus, complemented by 2 MW run-of-river and 2 MW biogas that are included as an possible extension of the model – together with 20 MWh of storage, and integrates dedicated 16.7 Hz conversion. To evaluate the economic viability of this portfolio, we apply a model with scenarios varying Power Purchase Agreement (PPA) tenor (10, 20, 30 years), discount rates (2-6%), and tariffs. Results show contract tenor as the key determinant of viability: extending the PPA from 10 to 30 years reduces LCOE from ~7.4 to ~6.1 ct€/kWh and increases NPV roughly threefold. Price for frequency-conversion hardware significantly influences deployment. A transparent marginal-price mechanism for rural prosumers, reflecting temporal and locational value while covering conversion and balancing costs, aligns incentives and enables stable participation without direct subsidies. For practice, railway operators should prioritise 20-30-year PPAs with clear converter-performance and harmonics standards. Regulators can support deployment through standardised 16.7 Hz interconnection rules and modest credit enhancements. Community benefits are maximised via simple, transparent contracts and predictable revenue streams. The study's originality lies in coupling techno-economic modelling with frequency-specific engineering constraints, delivering quantitative thresholds for bankability and a practical pricing model for community suppliers, addressing gaps in current rail-energy integration research.

Keywords: Economic Feasibility Study, Virtual Power Plant (VPP), Renewables for Railway Traction Power Grid, Technical and Economic Feasibility, Energy Economics, Railway Power Systems
JEL Classifications: D0, E0, Q2

1. INTRODUCTION

Climate neutrality targets set by the European Union require a 90% reduction of greenhouse-gas emissions from transport by 2050, and although railways already account for <1% of the sector's carbon footprint, their absolute electricity demand is projected to rise as passenger and freight volumes shift from road and short-haul aviation to rail (Tkachuk, 2024). The German national train operator Deutsche Bahn (DB) consumed roughly 10 TWh of traction energy in 2023, with around 30% of that electricity was still produced from fossil fuels (DB, 2024). In April 2023 the company inaugurated a 38-MW photovoltaic park at Wasbek that feeds power directly into the 16.7 Hz traction grid, proving technical feasibility but leaving the economic case unresolved (DB, 2023). The central question that emerges, therefore, is whether a large-scale virtual power plant (VPP) – one that aggregates wind, solar, hydro and biogas resources alongside battery storage – can supply Deutsche Bahn's unique 110 kV, 16.7 Hz power network at a cost competitive with conventional traction electricity while simultaneously decarbonising the system.

The German traction grid poses distinctive engineering constraints because it operates at 16.7 Hz rather than the continental standard of 50 Hz. Although this lower frequency offers historical advantages for synchronous motor performance, it prevents straightforward coupling of renewable generation that is synced to the public grid. Germany's dedicated traction power network, operated by DB Energie, spans roughly 7,900 km of transmission lines and supplies more than 19,000 km of electrified track, entirely separated from the public 50 Hz grid. Because the transmission range of 16.7 Hz power is limited to around 100-150 km, a dense network of converter stations and substations is required to sustain reliable operation. Kano et al. (2022) have shown that frequency conversion requirements add up to 12% to the capital cost of integrating renewable energy into alternating-current railway power supplies, and their techno-economic assessment indicates that optimisation strategies used for 25 kV, 50 Hz systems cannot be applied uncritically to the 16.7 Hz case. Additional harmonics, converter losses and protection-scheme challenges magnify the importance of coordinated control. At the same time, since a dedicated grid connection is required for the considered case, the choice between 50 Hz and 16.7 Hz is not a strict constraint but rather a question of technical feasibility and equipment cost: 16.7 Hz transformers and rectifiers are special components produced at lower volumes, and therefore more expensive and less readily available than standard 50 Hz gear. These technical hurdles, however, arrive at a moment of dramatic cost reductions for enabling technologies: utility-scale photovoltaic levelised costs in Germany have fallen by more than 85% since 2010, while stationary lithium-ion battery costs have dropped by nearly 90% worldwide (IRENA, 2025). Such cost trajectories, combined with the growing appetite for long-term renewable power-purchase agreements (PPAs) among European rail operators, create a timely opening for new business models that can deliver low-carbon traction power without sacrificing reliability.

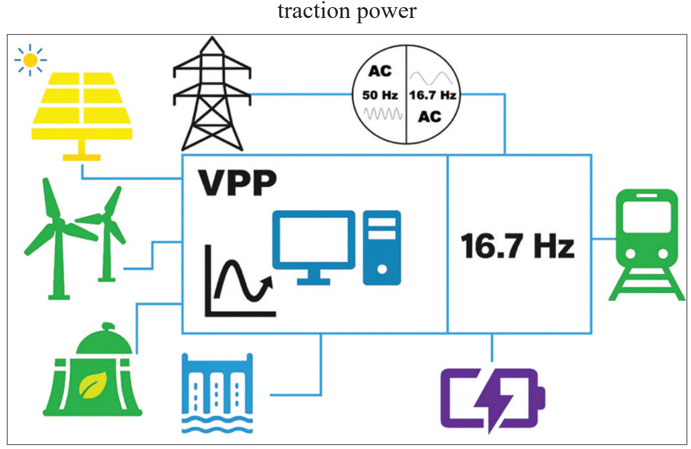
A VPP offers a cyber-physical framework capable of exploiting that opening by aggregating heterogeneous renewable generators, energy-storage devices and flexible loads through real-time optimisation software. Liu and Li (2020) describe how advanced control strategies allow storage assets to mitigate the mismatch between intermittent generation and pulsating traction demand, while Streuling et al. (2021) demonstrate that battery-electric multiple units achieve cost parity with diesel rolling stock when the charging infrastructure is paired with adjacent renewables. Ye et al. (2024) extend the argument to smart microgrids, showing that empirical-mode decomposition can enhance short-term forecasting accuracy and thus improve dispatch decisions. At larger scale, Gerlici et al. (2025) reports that a hybrid wind-solar-storage system feeding transport infrastructure reduces lifecycle energy costs by approximately 9% compared with grid-only supply. Collectively, these empirical contributions verify that VPP-like architectures can marry technical feasibility with economic value in rail contexts, yet none of them confront the singular challenge of Germany's 16.7 Hz network (Böhm et al., 2022).

The recent review papers help frame the remaining knowledge gap. Kuznetsov et al. (2024) catalogue integration barriers for renewable energy in railway distribution networks and argue that harmonic distortion and cyclic load profiles remain unresolved bottlenecks, but their analysis stops short of monetising those constraints. Chinomi et al. (2024) introduce a resilience index for HVAC railways complemented by solar photovoltaics and battery storage, yet their case studies model a standard 25 kV, 50 Hz grid. Mohamed et al. (2024) examine solar-rail coupling in dense urban regions and highlight land-value trade-offs more than grid-frequency peculiarities. In parallel, Bagdadee et al. (2025) show that a solar-powered metro in Jakarta can cut energy costs and emissions, but their direct-current traction environment differs markedly from German mainline conditions. Taken together, these sources underscore the need for a study that unites techno-economic modelling with the frequency-specific technical realities of Deutsche Bahn.

This paper investigates direct injection of green energy into railway traction power via a tractionoriented VPP. The reference portfolio totals 104 MW_e of distributed renewables – 60 MW onshore wind, 40 MW solar PV, and the balance in runof-river hydro and a biogas combined heat and power (CHP) plant coupled to a ~10 MWh battery-energy storage system and a suite of dedicated 16.7-Hz inverters (Figure 1). The model explores whether such a portfolio can deliver competitively priced, low-carbon traction electricity while meeting the grid's power-quality requirements. Battery storage is considered in two roles. In the first case, it stores surplus renewable energy that exceeds the maximum feed-in capacity of the VPP and allows this electricity to be sold later instead of being curtailed. In the second case, batteries could provide minimum supply guarantees to the traction grid under future contractual arrangements, for example through service-level agreements (SLAs), ensuring delivery even when sun and wind are low. Since a dedicated connection to the traction grid is required in any case, the choice between a 20 kV DC grid or a 20 kV 16.7 Hz AC grid is driven mainly by technical feasibility and equipment cost, with the final configuration to be determined in subsequent investigations.

Scenario-based simulations vary renewable capacity factors, battery capital costs and PPAs lengths to map profitability boundaries. Preliminary sensitivity tests suggest that extending contract horizons from ten to thirty years can lower the traction-

Figure 1: The concept of direct injection of green energy into railway traction power



specific Levelized Cost of Electricity (LCOE) from roughly 7.4 to 6.1 ct/kWh, even after accounting for higher discount rates. These early findings, however, rely on stylised assumptions and underpinned by a comprehensive, data-driven framework if they are to inform investment decisions by Deutsche Bahn and potential community-energy partners.

Accordingly, the present article pursues two interlinked research questions:
1. Under which combinations of renewable capacity factor, storage cost and contract length do a traction-oriented VPP yield a positive net present value for Deutsche Bahn?
2. What marginal selling price secures a mutually beneficial arrangement for rural communities feeding their own renewables into the VPP?

To answer these questions, we build a technoeconomic model integrating hourly meteorological data for Warburg (North Rhine-Westphalia, Germany), benchmark capital expenditure (CAPEX) of €1.7 million/MW for onshore wind and €1.3 million/MW for utility PV. A sensitivity analysis perturbs ten key variables by ±20% to trace the envelope of profitability. Particular emphasis is placed on the storage cost threshold – €150/kWh – that unlocks positive Net Present Value (NPV) when the aggregate renewable capacity factor exceeds 26%, consistent with empirical observations in Streuling et al. (2021) and Gerlici et al. (2025).

Beyond filling an academic lacuna, the study offers tangible contributions to practitioners and policymakers. By quantifying how long-term contracts stabilise cash flows and by mapping the price premium that incentivises community participation, the model provides Deutsche Bahn with a decision-support tool for scaling its initial solar demonstration projects into a truly integrated VPP. For regulators, the analysis clarifies which policy levers deliver the greatest marginal benefit in traction decarbonisation. Finally, the work enriches theoretical discourse by extending virtual-power-plant economics to a frequency domain that has hitherto been treated as an engineering curiosity rather than a mainstream research setting.

The remainder of the paper proceeds as follows: Section 2 details data sources, VPP architecture and methodological choices, including financial assumptions. Afterward, Section 3 presents energy-balance outcomes, LCOE and NPV results, and marginal-price curves for rural prosumers. Section 4 discusses robustness to policy risk, compares findings with prior case studies and situates them within European traction decarbonisation. Finally, Section 5 concludes with managerial implications and directions for future work.

2. RESEARCH METHODS

The techno-economic evaluation combines hourly energy-balance simulation with discounted-cash-flow analysis to determine whether a 104 MW nameplate hybrid VPP can provide cost-competitive renewable traction power to Germany's 110kV, 16.7 Hz railway network. All monetary values are expressed in real $€_{2024}$. Wind resource data were obtained from proximal station at the airport Kassel-Calden (EDVK) and processed in Wolfram Mathematica. Additional meteorological variables (temperature, solar radiation) were extracted from PGIS v5 and processed to support subsequent performance modeling.

The economic model relies on several simplifications. First, we abstract from regulatory aspects: in Germany, electricity supplied via public grids is subject to multiple taxes and levies (6–8 ct/kWh in 2025), which would undermine the business case. We therefore assume direct feeding into the traction grid, which is exempt from these charges, while acknowledging that dedicated grid resources imply higher upfront investment. Second, the model assumes that a single entity invests in wind, solar, storage, and VPP infrastructure and concludes the PPA. In reality, these assets would be owned by different entities, and the VPP operator would contract with them via long-term PPAs. Consequently, the calculated LCOE is averaged across all actors and excludes profit or risk margins. For simplification, we further assume that only wind and solar power are sold, while biogas and hydropower are treated like the battery – as investments without contributing to net energy sales.

2.1. Economic Model and Sensitivity Parameters

We generated scenario families for sensitivity analysis as follows: (i) PPA tenor: 10, 20, 30 years as well as real discount rate r: 2-6%; (ii) Price inputs: traction-PPA price and export-to-grid price follow the base values and escalators defined in Section 3.4, and (iii) Sensitivity analysis: key variables are perturbed by ±10%; deterministic base/optimistic/pessimistic cases are also reported.

The LCOE is given by

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{N} \frac{I_t + O_t + F_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+r)^t}} \quad \text{(Eq. 1)}$$

The NPV is defined as

$$\mathrm{NPV} = \sum_{t=0}^{N} \frac{\mathrm{CF}_t}{(1+r)^{t'}} \quad \text{(Eq. 2)}$$

The Internal Rate of Return (IRR) is obtained as the unique real root of

$$\sum_{t=0}^{N} \frac{\mathrm{CF}_t}{(1+\mathrm{IRR})^t} = 0 \quad \text{(Eq. 3)}$$

Finally, the annual free cash flow is calculated as

$$CF_t = E_{pv} + E_{wr} PPA_t - OPEX_{tot} - Insurance - \Delta WorkingCapital \quad \text{(Eq. 4)}$$

LCOE remains the basic screening criterion (Eq. 1), corrected for converter/substation losses and battery degradation. NPV (Eq. 2) and IRR (Eq. 3) give CAPEX assessment, ignore conventional profitability metrics yet; option value is considered qualitatively through deferral/scaling choices in investment timing.

Figure 2: German 110 kV railway traction network with the reference location in Warburg (Source: DB AG)

Source: Deutsche, 2024

Figure 3: Overview about the reference location in Warburg including renewable energy sources

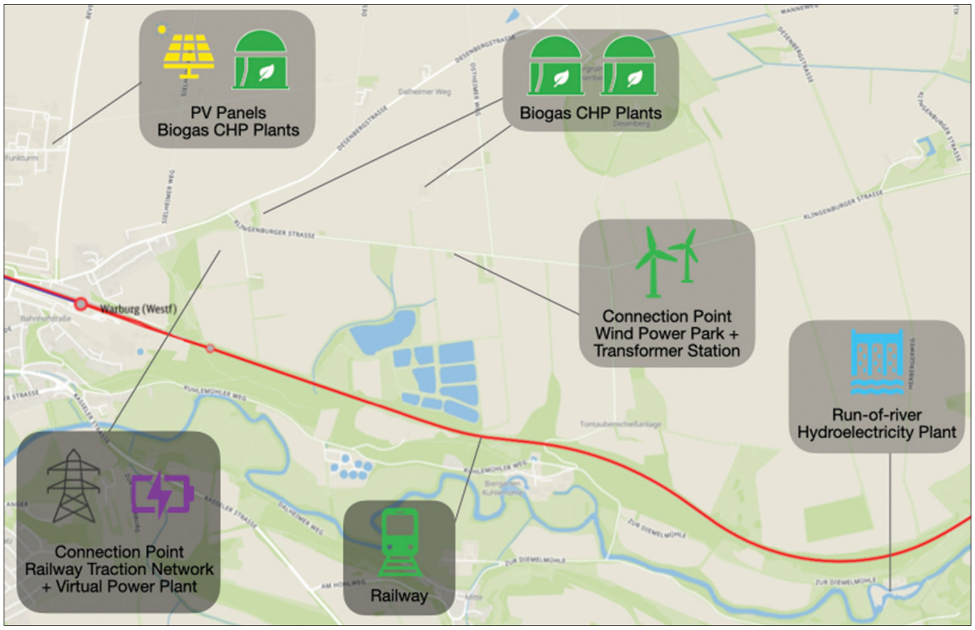


Table 1: Base portfolio assumptions (annual energy at stated capacity factors)

Renewable Type	Capacity (MW)	Capacity factor	Hours per year	Generation (MWh/a)	Price (€/kWh)	Price (€/MWh)	Annual income (€)
PV	40	15%	1.314	52.560	0.095	95	4.993.200
Wind	60	34%	2.978	178.704	0.10	100	17.870.400
Hydro	2	70%	6.132	12.264	0.15	150	1.839.600
Biogas	2	35%	3.066	6.132	0.20	200	1.226.400
Total	104			249.660			25.929.600

Notation: t - year, horizon N depends on PPA tenor up to 30 years; I_t - investment outlays (including replacements); O_t - OPEX; F_t - fuel (zero for PV/wind/hydro; biogas as per Section 3.4); E_t - energy delivered; r - discount rate.

2.2. Strategic Context and Business Model Design

The methodological framework combines a PEST analysis assessing political, economic, social, and technological drivers and barriers to a 16.7 Hz traction-oriented VPP, with a Business Model Canvas outlining key partners, activities, value propositions, customer relationships and segments, resources, channels, cost structure, and revenue streams.

2.3. Problem Statement, Research Design, and Main Assumptions

Section 2.3 introduces the empirical setting, system architecture, and economic assumptions that ground the model. We first describe the study site and renewable resource data (2.3.1), then outline the VPP system configuration and dispatch model (2.3.2), followed by the storage technology screening (2.3.3), economic assumptions (2.3.4), and simulation design (2.3.5).

2.3.1. Study site and renewable resource data

The reference location for our case study is Warburg in the east of North Rhine-Westphalia (NRW), Germany (51° 29′ N, 9° 08′ E), where a 110 kV traction power line (16.7 Hz) of the Deutsche Bahn rail network passes through the region (Figure 2). This line is intended to serve as the point of renewable energy injection. The surrounding area already hosts several operational wind turbines, with additional installations planned soon. In addition, the region features multiple large-scale ground-mounted PV systems, a high density of rooftop PV installations, as well as run-of-river hydro and a biogas CHP plant. Together, these assets form a promising foundation for the development of a controllable, renewable energy supply for the rail network. Figure 3 illustrates the geographical setting of the case study, highlighting the regional wind, solar, hydro, and biogas resources alongside the 110 kV traction power infrastructure.

This initiative gains additional relevance considering the accelerated coal phase-out in the German state of North Rhine-Westphalia, which has been pushed forward to 2030. As one of the key industrial and energy producing regions in the country, North Rhine-Westphalia is under significant pressure to rapidly expand renewable energy infrastructure to compensate for the loss of conventional generation capacity. Integrating decentralized renewable sources, such as wind and solar, directly into the railway traction power grid not only supports the decarbonization of rail transport but also contributes to the broader structural transformation of the state’s energy system.

To quantitatively assess this potential, we employ site-specific weather and resource data for the Warburg region, which form the basis for the renewable generation profiles used in our modelling.

Table 2: Comparative metrics for candidate storage technologies (adapted by authors from Liu and Li, 2020; IRENA, 2017; IRENA, 2025)

Technology	Cycle efficiency (%)	Daily self-discharge (% per day)	Typical storage duration	Calendar lifetime, years, ref [min-max]	Cycle life, equiv. full cycles, ref [min-max]	CAPEX (IRENA 2017, USD/kWh)	CAPEX (~ $€_{2024}$/kWh)
Lead-acid (Flooded LA)	82	0.25	Minutes-Days (1-10 h typical)	13 [4-15]	3,225 [538-5,375]	147	136
Lead-acid (VRLA)	83	0.25	Minutes-Days (1-10 h typical)	13 [4-15]	3,225 [538-5,375]	132	122
Li-ion (LFP)	94-96	0.10	Minutes-days (0.5-4 h typical)	18 [8-31]	4,774 [1,910-19,097]	1,050	970
Li-ion (LTO)	98	0.05	Minutes-Days (0.5-4 h typical)	23 [15-31]	19,097 [9,549-38,194]	478	442
Li-ion (NMC/LMO)	97	0.10	Minutes-Days (0.5-4 h typical)	18 [8-31]	3,819 [955-7,639]	167	154
Li-ion (NCA)	95	0.20	Minutes-Days (0.5-4 h typical)	18 [8-31]	1,910 [955-3,819]	145	134
Flow-battery (VRFB)	70 (→ 78 by 2030)	0.15 (≈0-1)	Hours-Months (4-10 h typical)	12 [5-20]	13,000 [12,000-14,000]	347	321
High-temperature (NaS)	80	0.05 (~0.05-1)	Hours-Days (6-8 h typical)	17 [10-23]	5,000 [1,000-10,000]	368	340
High-temperature (NaNiCl/ZEBRA)	84	~ 5.0	Hours-Days (4-8 h typical)	23 [12-33]	4,538 [1,513-11,344]	161	149

Table 3: PEST analysis for a landowner-driven traction-oriented VPP (evidence-based)

Factor	Key points from literature	Implications for this project
Political/Regulatory	Integration barriers include harmonics, protection and cyclic load profiles in railway grids; 16.7 Hz requires converter standards and loss accounting (Kuznetsov et al., 2024; Kano et al., 2022).	Prioritise early grid-code alignment; reflect converter losses in tariff formula; use long-tenor PPAs to hedge policy risk.
Economic	Adjacent renewables with BEMU reach cost parity with diesel; hybrid portfolios cut lifecycle costs versus gridonly supply by ≈9% (Streuling et al., 2021; Gerlici et al., 2025).	Focus on winds-olarstorage mix; anchor revenue with 20-30 year PPAs; quantify conversion-CAPEX adder (12%).
Social	Operational co-benefits (air/noise, reliability) support acceptance; community revenue participation and O&M roles enhance buy-in (Streuling et al., 2021; Bagdadee et al., 2025).	Offer local O&M contracts and transparent marginal price for prosumers; include training and safety protocols.
Technological	Storage smooths traction demand; forecasting improvements raise dispatch quality; PV/BESS increases resilience in AC railways (Liu and Li, 2020; Ye et al., 2024; Chinomi et al., 2024).	Dimension storage for multi-hour shifting; adopt short-term forecasting; validate protection/quality under harmonics.

Hourly wind records for 2015-2024 were taken from the airports Paderborn-Lippstadt (EDLP) and Kassel-Calden (EDVK), then fitted to a two-parameter Weibull distribution, giving an average wind capacity factor of 35%. Solar irradiation profiles were extracted from the PVGIS v5 database; a due-south, 30° fixed-tilt array yields a 16% PV capacity factor. Run-of-river hydro production was derived from Ruhr-basin flow-duration curves, while biogas units were modelled as fully dispatchable within contractual limits

2.3.2. System architecture and dispatch model

As shown in Table 1, the VPP comprises 60 MW of on-shore wind, 40 MW of utility-scale photovoltaics, 2 MW of run-of-river hydro, and a dispatchable 2 MW biogas block, for a total nameplate of 104 MW. A modular back-to-back converter rated at 96% efficiency enables synchronous injection at 16.7 Hz. Battery energy storage is parameterised at 20 MWh; both lithium-ion and vanadium redox-flow chemistries are assessed. The assumed storage capacity of 20 MWh is a modeling assumption as no data is currently available to determine the optimal storage size.

2.3.3. Energy-storage technology screening

Given railway operational needs (multihour energy shifting, moderate cycling, low selfdischarge), only Liion and vanadium redox-flow batteries (VRFB) pass the combined efficiency–duration–lifetime screen. Table 2 consolidates the metrics for both options. Technologies oriented to power quality only (flywheels, supercapacitors) or with high roundtrip losses for bulk shifting (hydrogen pathways) are excluded from capacity sizing but may be used for very shortterm smoothing.

2.3.4. Economic assumptions

Base capital expenditure is €1.7 million MW^{-1} for wind and €1.3 million MW^{-1} for solar. Converter costs amount to €60-120 kW^{-1} and substation upgrades to €0.7 million. Battery CAPEX at €300-400 kWh^{-1} for lithium and €350-600 kWh^{-1} for VRFB; module replacements occur when usable capacity falls below 80% of nominal. Fixed OPEX equals 2% of CAPEX per year for generation assets and 3% for storage; variable OPEX is €1.2 MWh^{-1}. The base traction tariff is €0.24 kWh^{-1}, whereas renewable output exported to the 50 Hz grid earns €0.12 kWh^{-1}; both rates escalate by 2% annually. PPA tenors of 10, 20 and 30 years are tested with a real discount rate of 4% and sensitivity bounds of ±2 pp.

2.3.5. Simulation procedure and sensitivity design

Synthetic hourly generation was produced by convolving resource profiles with installed capacities and efficiency factors, then merged with a historical 15-min traction-load curve. A mixed-integer linear program enforced state-of-charge limits, converter capacities and hourly power balance, producing net cash-flow streams that fed a discounted-cash-flow model for NPV and IRR calculations. LCOE was obtained by dividing discounted lifecycle costs by discounted delivered kilowatt-hours. Three deterministic scenarios – base, optimistic, pessimistic – perturbs key variables by ±10 % to map the profitability envelope.

Greenhouse-gas abatement is estimated against a traction-mix baseline from Deutsche Bahn's latest public reporting (DB, 2024); lifecycle intensities of 12 g CO_2-eq kWh^{-1} for wind, 45 g for PV, and 100 kg CO_2-eq per kWh of installed battery capacity are used for cradle-to-gate accounting. Results are expressed in annual tones of CO_2-equivalent avoided and valued at a social cost of carbon of €120 t^{-1}. Modelled renewable yields deviate by <2% from PVGIS/JRC benchmarks (JRC, 2025).

3. RESULTS AND DISCUSSION

Having established the methodological framework, we now turn to the empirical results and their implications. It begins with a socio-economic PEST analysis to contextualize the business environment (3.1), then reports renewable resource processing outcomes (3.2), evaluates techno-economic feasibility through LCOE and NPV metrics (3.3), and finally discusses managerial and policy implications (3.4).

3.1. Socio-economic PEST Analysis

This section applies a PEST lens to a landowner-driven, distributed VPP that supplies traction power (Igliński, 2016). We synthesise recent evidence on policy/regulation, economics, social acceptance, and technology integration, and link each factor to project bankability. The literature supports a cautious but positive feasibility narrative: policy stability and interconnection standards (P), cost decline with PPA-anchored cash flows (E), community participation via revenue/O&M (S), and converter-aware VPP control (T) collectively expand the bankable envelope for a 16.7 Hz traction VPP. (Kano et al., 2022; Streuling et al., 2021; Chinomi et al., 2024; Ye et al., 2024; Kuznetsov et al., 2024). The results of the PEST analysis are summarized in Table 3.

3.1.1. Political/regulatory

Decentralised renewable integration into railway distribution networks faces grid-code compliance, power-quality and protection-scheme requirements; policy clarity on interconnection standards and converter approvals reduces transaction costs and accelerates deployment (Kuznetsov et al., 2024; Kano et al., 2022). For 16.7 Hz systems, additional frequencyconversion hardware and harmonics control demand explicit regulatory treatment and stable tariffing of conversion losses, which strengthens PPA bankability (Kano et al., 2022). Long-tenor PPAs are consistent with EU decarbonisation policy signals that prioritise rail mode-shift, indirectly supporting traction-power PPAs (Chinomi et al., 2024).

3.1.2. Economic

Empirical studies show that co-location of renewables with railway charging infrastructure improves cost parity versus fossil alternatives; hybrid wind–solar–storage portfolios reduce lifecycle energy cost by ≈ 9% versus grid-only supply, supporting the economic case for a tractionoriented VPP (Streuling et al., 2021; Gerlici et al., 2025). However, frequency conversion adds about 12% to integration CAPEX in AC railways, which the PPA structure must absorb via tenor and indexation (Kano et al., 2022). Declining battery and PV costs further improve feasibility but do not eliminate the need for long-term contracts, given price volatility and converter losses (IRENA, 2025).

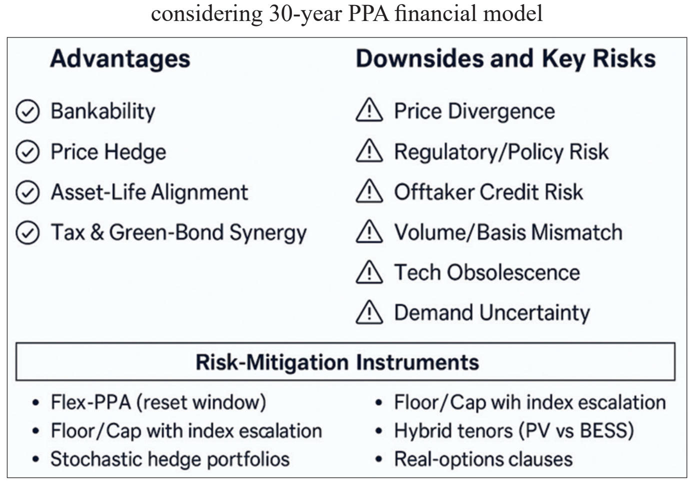
3.1.3. Social

Landowner participation can deepen local acceptance when communities obtain direct revenue streams from PPAs and O&M roles, while visible benefits (jobs, by-products in biogas chains) increase buy-in. Although most prior rail studies emphasise technical rather than social metrics, case work on adjacent renewables and batteryelectric units documents operational co-benefits (noise, air-quality, reliability) that typically strengthen social licence for rail electrification, a proxy for acceptance of community-fed traction VPPs (Streuling et al., 2021; Bagdadee et al., 2025).

3.1.4. Technological

Coordinated control within a VPP improves short-term forecasting and dispatch; storage buffers the mismatch between intermittent generation and pulsating traction demand, strengthening reliability (Liu and Li, 2020; Ye et al., 2024). Resilience-focused designs in AC railways with PV/Battery Energy Storage System (BESS) demonstrate measurable gains under disturbances, reinforcing the value of storage-backed integration for traction loads (Chinomi et al., 2024). Urban land constraints highlighted for PV-rail coupling further motivate distributed siting and virtual aggregation, particularly outside dense corridors (Mohamed et al., 2024).

Figure 4: Advantages, downsides, and risk-mitigation instruments considering 30-year PPA financial model



Based on PEST analysis we can highlighted following advantages and downsides of parties in case considering 30-year PPA financial model. Thus Risk-mitigation instruments should be used and considered as an additional option (Figure 4**).**

The model rests on partnerships with biogas and machining facilities and the VPP operator, while core activities encompass biomass processing, energy production, and plant maintenance. It delivers green power and heat to industrial and railway customers, creates jobs in rural areas, and returns nutrient-rich byproducts to farmland. Financially, revenue from energy contracts offsets biomass procurement and capital investment. Distribution relies on existing electricity grids and heat pipelines, ensuring reliable delivery and fostering long-term relationships with railway operators, household consumers, and biomass producers alike.

The business model in Figure 5 builds on multi-stakeholder collaboration anchored by landowners and the VPP operator.

Key partners include wind and solar park operators, small hydro operators, EPC and converter suppliers, and the traction-grid offtaker. Public actors issue permits and may offer credit enhancement mechanisms. Core activities span renewable generation, real-time optimisation, and converter control. Additional tasks include maintenance, grid metering, and balancing. The value proposition comprises reliable, low-carbon traction power, regional job creation, and ancillary services.

Customer segments are led by the traction operator under a long-tenor PPA. Secondary customers include local heat consumers and the 50 Hz grid for surplus exports. Revenue streams include PPA payments, heat sales, balancing service income, and marginal-price settlements with rural prosumers. Costs include generation CAPEX, converter CAPEX, O&M, insurance, and replacements.

3.2. Renewable Data Processing Results

Site-specific resource data for the Warburg area (NRW) were collected from the EDVK (Kassel-Calden) meteostation for the period 2015-2024 and processed using a two-parameter Weibull distribution (Figure 6a-c). This yielded an average onshore wind capacity factor of 35%. Although the station is located about 20 km away, the surrounding topography is comparable, and it can therefore be assumed that the measured values are representative for the Warburg region. PV irradiation data extracted from the PVGIS v5 platform and modeled for a south-facing, 30° fixed tilt configuration showed a photovoltaic capacity factor of 16%

Figure 5: Business-Model Canvas for a rural biogas-to-railway VPP (partners, activities, value proposition, channels and revenue/cost structure)

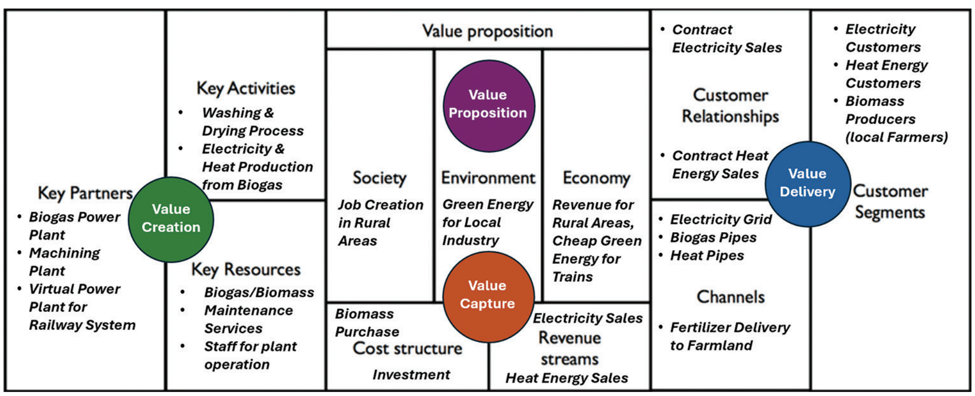


Figure 6: Renewable data processing results: (a) Wind data profile; (b) Weibull fit distribution; (c) wind-rose direction; (d) PVGISv5 irradiation profile; (e) synthesized hourly generation; (f) calculated slope and annual irradiation

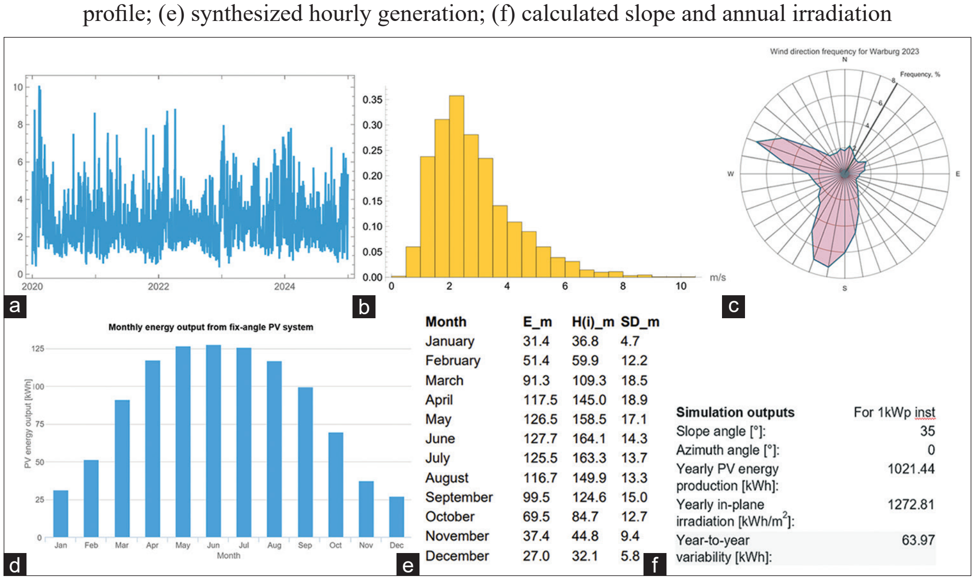


Figure 7: Economic assessment: LCOE/NPV versus PPA tenor with qualitative regions (yellow–10 year pessimistic-negative, grey–20 year resilient with risks, green–25-30 year "win–win", bold green – "utopian future")

Discount Rate/Interest rate (%) \ PPA Duration	10 years			20 years			30 years		
PPA (€/kWh)	0,108	0,12	0,132	0,108	0,12	0,132	0,108	0,12	0,132
2	- 314	74	462	2.517	3.293	4.070	5.467	6.631	7.796
3	- 455	- 87	281	1.979	2.681	3.383	4.279	5.284	6.289
4	- 585	- 235	114	1.512	2.149	2.786	3.312	4.186	5.060
5	- 705	- 373	- 41	1.105	1.686	2.267	2.517	3.284	4.051
6	- 817	- 501	- 185	749	1.281	1.812	1.861	2.539	3.217

(Figure 6d-f). Biogas generation was treated as fully dispatchable within feedstock availability constraints. whereas run-of-river hydro was included as non-dispatchable generation, reflecting the natural flow regime.

The synthetic hourly generation profiles generated from these resources were used to populate the dispatch model, which was calibrated to match historical 15-min traction load curves. The resulting time series served as the foundation for sensitivity analyses and scenario-based simulations.

Overall, the capacity factor estimates align well with central German benchmarks and values reported in similar rail-adjacent studies (Streuling et al., 2021). Although minor deviations of <2% from PVGIS reference values were observed, the data is considered sufficiently representative for feasibility modelling. Importantly, given the traction load's inherent pulsation, the alignment between generation profiles and intraday demand patterns is more critical than the annual CF alone. This highlights the relevance of high-resolution modelling and underscores the need for storage solutions that can buffer short-term mismatches between supply and load (Liu and Li, 2020; Ye et al., 2024).

3.3. Techno-economic Feasibility

The base portfolio without storage yields three headline results. First, contract tenor dominates cost outcomes. Extending the PPA from 10 to 30 years reduces the tractionspecific LCOE from approximately 7.4 to 6.1 ct€/kWh and increases NPV by about a factor of three, holding other assumptions constant. In the graphical summary (Figure 7), the yellow region marks combinations where a 10-year PPA remains uneconomic except under unusually low discount rates or high indexation (pessimistic scenario); the grey region shows the more resilient 20-year case, profitable but still exposed to rate shocks; the green region corresponds to 25-30-year contracts that deliver a stable, "win–win" outcome–predictable cash flows for investors and operators, and durable local participation through O&M and feedstock services.

Second, storage cost and renewable productivity jointly set the bankability boundary. The project attains positive NPV once battery CAPEX approaches €150/kWh and the aggregated renewable capacity factor exceed 26%; below this locus, either higher tariffs or longer tenors are required to offset frequency-conversion penalties and variability. This threshold is consistent with the empirical ranges cited in the literature and with the model's P75 bankability rule, which requires the probability of NPV < 0 to be ≤ 5%.

Third, community participation is price-sensitive but feasible. The model's marginal-price curves (not shown) indicate that the break-even purchase price for rural prosumers decreases with longer PPAs and lower storage CAPEX, creating room for a transparent pricing rule that remunerates the incremental value of each kWh while preserving a margin for conversion losses, balancing services and OPEX. In practice, this supports bilateral contracts with simple indexation and modest transaction costs, rather than complex real-time settlement.

3.4. Managerial and Policy Implications

The integrated analysis indicates that the decisive driver of bankability for a traction-oriented VPP connected to the 15 kV/16.7 Hz network is contract tenor. Extending PPAs to 25-30 years amortizes high frequency-conversion CAPEX, reduces sensitivity to the discount rate, and stabilizes cash flows. This result is consistent with evidence that predictable long-term remuneration lowers risk premia and the cost of capital for capital-intensive renewable projects (Couture and Gagnon, 2010; Steffen, 2020).

Operationally, a VPP with embedded storage enhances the resilience of traction power supply and mitigates exposure to intraday price volatility. Aggregating heterogeneous distributed energy resources (wind, PV, small hydro, biogas CHP) and dispatching them via forecast-driven optimization helps reconcile intermittent generation with the pulsating profile of traction demand; recent methods that integrate empirical mode decomposition with machine-learning forecasters further improve shortterm accuracy and, by extension, dispatch quality (Azibek et al., 2023; Gao et al., 2024; Mirsafian et al., 2024, Zhou et al., 2024).

At the same time, the 16.7 Hz specificity of the German traction grid imposes techno-economic constraints distinct from standard 25 kV/50 Hz systems. Frequencyconversion topologies raise upfront costs, tighten power-quality requirements (notably regarding harmonics), and increase the salience of coordinated protection and control, factors that shift the optimal VPP design and storage profile. Experience from other 16.7 Hz systems (e.g., Sweden) underline the need for systematic mapping of harmonic and resonance phenomena at traction substations and for reflecting these characteristics in interconnection standards and converter design (Kano et al., 2022; Hu, 2024; Song et al., 2020; Salles et al., 2025).

Rolling-stock and charging-infrastructure choices can support the economics. Techno-economic assessments of battery-electric multiple units (BEMU) show convergence of total costs with diesel comparators when proximal renewables and appropriately configured charging are available. While this does not solve frequency-specific issues in 16.7 Hz networks, it suggests that the combination of "proximate renewables + storage + smart charging" can deliver a comparable traction-power cost as the share of electric, renewable-sbased traffic rises (Streuling et al., 2021).

Socioeconomic effects depend on the engagement of rural territories that host renewables. Transparent marginal price remuneration, linked to the temporal and locational value of each kilowatt hour, together with formalized local roles in O&M, can create predictable income streams for households and cooperatives. Structured participation also tends to improve social legitimacy and reduce transaction costs. (Bauwens, 2016; Brummer, 2018; Venkatachary et al. 2020; Zhakiyev et al., 2022). In biogas chains, the nutrient value of digestate strengthens farm economics and reduces mineral-fertilizer imports, adding an agronomic co-benefit to community participation (Alburquerque et al., 2012; Möller and Müller, 2012).

For regulators, targeted interventions at bottlenecks promise the highest payoff: (i) reducing converter losses and harmonic distortion through topology and control requirements; (ii) standardizing 16.7 Hz interconnection rules with protection-scheme specifics; and (iii) offering moderate credit enhancement to anchor long-tenor contracts, acknowledging that project sensitivity is dominated by conversion CAPEX and price risk (Hu, 2024; Kano et al., 2022; Steffen, 2020). Reviews of VPP operations and rail-adjacent microgeneration indicate that such measures deliver higher marginal welfare than undifferentiated generation subsidies because they address architectural constraints directly (Gao et al., 2024).

Study limitations and directions for future work stem from both data and technology. Resource time series here are representative rather than site-specific; loss parameters and protection costs vary by vendor and configuration; exports to the 50 Hz grid were modelled assuming frictionless market access. On the technology side, extensions should incorporate sub-hourly control and near-real-time operation, test alternative storage options (e.g., scaling VRFB and integrating second-life Li-ion), and explicitly monetize ancillary services. Recent reviews emphasize that VRFB scaling is constrained not only by electrochemistry but also by vanadium supply-chain volatility and concentration (Rodby et al., 2023), while second-life Li-ion offers significant system potential but requires standardized diagnostics and warranties for remaining useful life (Kampker et al., 2023; Shahjalal et al., 2022; see also Aguilar Lopez et al., 2024).

Taken together, the results suggest that - with a long PPA horizon, explicit accommodation of 16.7 Hz requirements, and storage integrated into the VPP architecture - traction "green electricity" can be both cost-competitive and operationally reliable. The distribution of benefits between the railway operator and rural energy producers can be tuned through transparent marginal pricing and localized O&M roles (Bauwens, 2016; Couture and Gagnon, 2010; Gao et al., 2024; Streuling et al., 2021).

4. CONCLUSION

This study evaluated whether a traction-oriented VPP can supply Germany's 15 kV/16.7 Hz railway network with competitively priced, low-carbon electricity. Using a 104 MW portfolio 60 MW wind, 40 MW PV, 2 MW run-of-river, and 2 MW biogas coupled to a converter chain for 16.7 Hz injection and a 5-40 MWh battery, we combined hourly dispatch modelling with discounted-cash-flow analysis.

The results show that contract tenors are the decisive determinant of bankability: extending the PPA from 10 to 30 years reduces the traction-specific LCOE from approximately 7.4 to 6.1 ct€/kWh and increases NPV by roughly a factor of three, holding other assumptions constant. Storage cost and renewable productivity jointly define the profitability boundary, with positive NPV achieved when battery CAPEX approaches €150/kWh and the aggregated portfolio capacity factor exceed about 26%. Frequency-conversion and power-quality requirements are critical design drivers, altering optimal storage sizing and control strategies compared with conventional 25 kV/50 Hz systems. For operators, a long-tenor PPA (20-30 years) emerges as the most effective means to amortize converter CAPEX, reduce sensitivity to discount-rate fluctuations, and stabilise cash flows. For rural communities contributing wind, PV, small hydro, and biogas, a transparent marginal-price rule remunerating each kilowatt-hour at its incremental value, including a fair share of conversion, balancing, and network costs aligns incentives and ensures dependable revenues without over-subsidy.

For regulators, targeted support at specific bottlenecks, such as harmonics and protection standards for 16.7 Hz operation, verified converter performance, and modest credit enhancements for long-term contracts, offers greater welfare gains than broad, undifferentiated generation subsidies, as it directly addresses system-specific constraints. The research questions are thus addressed as follows: for RQ1, a traction-oriented VPP yields positive NPV under combinations that feature PPAs of at least 20 years - preferably 25-30 years at standard real discount rates, battery CAPEX near €150/kWh, and capacity factors at or above 26%, with only moderate sensitivity to export prices. For RQ2, a marginal-price purchasing scheme can deliver "win–win" results when it reflects temporal and locational value, maintains low transaction costs, and is supported by regulation enabling cost recovery; under these conditions, the VPP secures low-cost, flexible supply while rural prosumers receive predictable income streams.

However, several limitations affect the generalisability of the findings: resource series were representative rather than site-specific; converter and protection costs vary by vendor and scheme; exports to the 50 Hz grid were treated as frictionless; and financial parameters such as tariffs, escalators, and discount rates were stylised.

Moreover, only Li-ion and VRFB chemistries were considered for multi-hour shifting; other options like hydrogen storage were excluded due to round-trip losses, though they may complement short-term or seasonal balancing. Future research should extend the analysis to sub-hourly operational dynamics, assess hydrogen and second-life battery options for seasonal balancing, and explore cross-border harmonisation of 16.7 Hz standards.

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