

Research Paper

Hybrid Catenary-Battery Trains for Non-Electrified Sections and Emergency Use

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Abstract

The hybrid catenary–battery system offers a promising solution for railways operating in non-electrified sections and during emergencies, ensuring uninterrupted operation, enhanced safety, environmental sustainability, and cost efficiency. This study addresses the challenge of determining an appropriate battery size and introduces a novel rule-based Energy Management Strategy (EMS) with coasting mode to minimize energy consumption while meeting operational requirements. The novelty of this work lies in (i) a straightforward sizing method based on worst-case emergency scenarios and (ii) the integration of coasting-mode operation into a rule-based EMS for hybrid catenary–battery trains. Simulation results show that the proposed approach achieves up to 12.56% energy savings on 3% gradient tracks while fully supplying auxiliary loads, compared with baseline operation that provides only partial coverage. These results demonstrate a practical and scalable framework for designing efficient, reliable, and resilient railway transport systems.

Keywords: Hybrid railway; Catenary; Battery; Energy management; Coasting mode

1. Introduction

The integration of hybrid catenary and battery systems in railways, especially on non-electrified track sections and during emergencies, is pivotal for improving operational efficiency and reliability. This hybrid approach enables trains to draw power from overhead catenary systems where available and switch to battery power in areas without electrification or in the event of catenary failures. According to Aroua *et al.* [1], dual-mode trains are widely used in Europe with accounting for nearly 57%.

A primary advantage of hybrid systems is their ability to maintain service continuity in non-electrified zones. Trains equipped with both catenary and battery systems can transition seamlessly between power sources, eliminating

the need for extensive electrification in less populated or economically viable areas. This flexibility is particularly advantageous for light rail vehicles and trams operating in urban environments where full electrification may not be feasible or cost-effective [2], [3]. For example, the JR East EV-E301 hybrid regional train operates using catenary power on electrified sections and switches to battery power on non-electrified tracks, demonstrating the practical application of this technology [4].

Additionally, hybrid systems are crucial in emergency situations, such as catenary failures, which can cause significant disruptions. By integrating battery storage, trains can continue to operate even when the catenary system is compromised, minimizing service interruptions



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and enhancing safety [5], [6]. Hybrid systems provide a reliable backup power source, allowing for emergency operations and a safe return to the nearest station [7].

Beyond operational reliability, these systems contribute to environmental sustainability by reducing reliance on fossil fuels, especially in regions where diesel-powered trains dominate. The combination of lithium-ion batteries with catenary systems has proven effective in lowering emissions and improving energy efficiency in rail transport [8]. Furthermore, hybrid systems can capture and store regenerative braking energy, further enhancing overall energy efficiency and making them a more sustainable option for modern railways [9].

Economically, hybrid catenary and battery systems reduce the need for large-scale electrification, which is often costly. In regions where the investment in electrification may not justify the expected ridership, these systems offer a more cost-effective alternative [10], [11]. Moreover, the operational flexibility of hybrid systems leads to lower ongoing costs, as they can adapt to varying demand and infrastructure conditions [11]. Some railway operators, such as SNCF in France and Trenitalia in Italy, prefer to use dual-mode trains rather than track electrification due to the difficulty in some track sections [1].

Recent research has highlighted the operational and sustainability benefits of hybrid catenary-battery systems. Schenker *et al.* optimized battery electric multiple units (BEMUs) by combining overhead line equipment with onboard energy storage, achieving substantial energy savings on partially electrified routes [12]. Ghaviha *et al.* demonstrated the potential of speed profile optimization for catenary-free electric trains with lithium-ion batteries, showing that such systems can operate up to 20 km at 100 kph without catenary [13]. Pugi and DiCarlo explored multi-modal battery-operated trains for partially electrified lines, suggesting pantograph-based recharging to enhance reliability [14]. Magelli *et al.* showed that hybridizing diesel trains with regenerative braking improves energy efficiency [15]. While these studies make important contributions, they primarily emphasize energy savings, speed optimization, or alternative recharging methods. However, none of them

systematically address the challenge of battery sizing for hybrid catenary-battery trains under both non-electrified and emergency operation scenarios, nor do they propose a simple, implementable EMS that balances energy consumption and operational reliability. This gap motivates the present study.

In addition to catenary-battery hybrid systems, fuel cell-battery hybrids have also been proposed as alternatives to diesel traction. While both configurations aim to reduce emissions and improve efficiency, their operational contexts and technology readiness levels differ significantly. Fuel cell-battery trains, such as the Alstom Coradia iLint and the JR East KuMoYa E995, demonstrate the feasibility of hydrogen-powered rail, but face challenges related to hydrogen infrastructure, energy efficiency, and system costs. In contrast, catenary-battery hybrids leverage existing overhead line infrastructure where available, while using batteries to bridge non-electrified sections or ensure operation during emergencies. Table 1 provides a benchmark comparison between catenary-battery and fuel cell-battery systems, highlighting the advantages of the former in terms of infrastructure costs, efficiency, environmental benefits, and operational flexibility.

In vehicles that use hybrid power sources, an Energy Management Strategy (EMS) is important to distribute the load power between the energy sources used [16], [17]. Some common EMS methods used in hybrid trains are frequency management, rule-based, Potryagin's minimum principle (PMP), linear quadratic, and dynamic programming (DP) [18]. In this study, the rule-based method is chosen since it is simple and implementable. Furthermore, its performance has been proven by researchers, such as in [19], [20].

This study addresses the gap in existing research by focusing on the determination of an appropriate battery size for hybrid catenary-battery railway systems specifically designed for both non-electrified sections and emergency operation. Unlike prior works that mainly optimize energy efficiency or explore speed profiles, our approach emphasizes a straightforward and practical sizing method combined with a tailored rule-based EMS. The novelty of this study lies in: (i) proposing a systematic yet simple method to determine the

Table 1. Comparison between catenary–battery and fuel cell–battery systems

Factor	Catenary-Battery Hybrid	Fuel Cell – Battery Hybrid	Refs.
Infrastructure & Maintenance Costs	Leverages existing catenary infrastructure, avoiding full electrification by using batteries in catenary-free zones. Lower long-term maintenance compared to hydrogen infrastructure.	Requires costly hydrogen production, storage, and refueling infrastructure; higher maintenance burden.	[13], [21]
Energy Efficiency	High efficiency is achieved by directly using grid electricity when under catenary; batteries store regenerative braking energy, reducing consumption.	Lower efficiency due to multiple energy conversions (H ₂ production, storage, and fuel cell conversion).	[22], [23]
Environmental Impact	Can operate with near-zero emissions if the grid uses renewable sources; avoids diesel and reduces urban emissions.	Only green if hydrogen is renewable; grey hydrogen production still emits CO ₂ .	[6], [21], [22]
Operational Flexibility	Can run seamlessly on electrified and non-electrified sections; batteries charge while under catenary, reducing downtime.	Limited by hydrogen refueling infrastructure, it requires significant planning for fueling stations.	[6], [22]
Energy Storage & Management	Requires smaller battery capacity since catenary power is available; easier to balance charging/discharging.	Requires larger onboard storage and continuous hydrogen supply; complex system integration.	[22], [23], [24]
Technology Readiness	Already commercialized (e.g., JR East EV-E301).	Mostly at prototype/demonstration stage (e.g., Alstom Coradia iLint, experimental locomotives).	[6], [24]

battery capacity required for hybrid trains to ensure service continuity in both normal and emergency conditions, and (ii) developing an implementable rule-based EMS that minimizes energy consumption while maintaining operational reliability. The rest of this paper is organized as follows: Section II introduces the train model and traction performance; Section III presents the proposed approach for battery sizing and EMS; Section IV discusses the testing results and analysis; and Section V concludes the study.

2. Hybrid Electric Railway

2.1. Train Model

The specifications of the train set in this study are listed in [Table 2](#). It consists of two cars, a motor car (MC) and a trailer car (TC). The first refers to the car with a traction motor, while the second is without. The MC has a higher mass than the TC since it has a propulsion system in its body. The trainset has four traction motors (M) and is targeted to pass a gradient of up to 3%. It has two power sources, a catenary and a battery, since it passes an unelectrified track. Besides that, the battery is used as an emergency power supply when the catenary supply fails.

The general structure of the trainset propulsion system is depicted in [Figure 1](#). The catenary is in TC, including the transformer. The high power from the catenary, 25 kV, is stepped down by the transformer and then sent to the rectifier to form a DC voltage. The DC-bus voltage is 3000 VDC and connected to VVVF (Variable Voltage Variable Frequency) and SIV (Static Inverter). VVVF is a variable frequency inverter that drives the traction motor, while SIV is the static frequency inverter for the auxiliary load. The DC-bus is also connected to the battery via EMS and a DC-DC converter. The EMS manages the power flow between the catenary and the battery, while the DC-DC converter is the interface for the DC-bus and battery with different voltages.

Based on the specifications, in [Table 2](#), the trainset is modeled using the simple dynamic model as illustrated in [Figure 2](#). The train dynamic model is based on Newton's motion law as following Eq. (1) to Eq. (5) [25].

$$F_{trac} = M_t Acc + (F_{roll} + F_{aero} + F_{grade}) \quad (1)$$

$$F_{roll} = f_r M_t g \cos(\alpha) \quad (2)$$

$$F_{aero} = \frac{1}{2} C_w A \rho_{air} v_t^2 \quad (3)$$

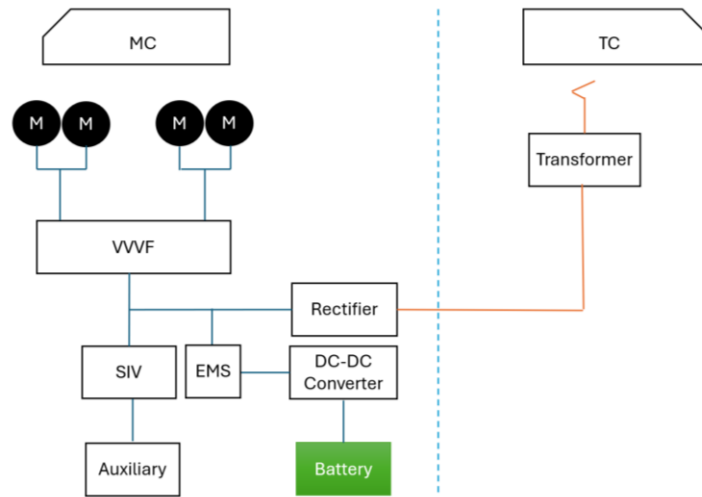


Figure 1. Propulsion system structure

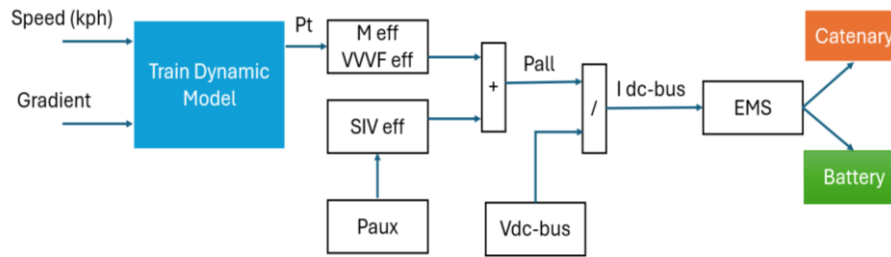


Figure 2. Trainset simple model

Table 2. Trainset general specifications

Parameters	Value
Car mass	41 (MC) – 40 (TC) ton
Passenger normal load mass	7.05 ton
Number of traction motors	4
Maximum gradient	3 %
Power sources	Catenary and Battery
Catenary voltage	25 kV AC
Battery voltage	600 V DC
Catenary operation mode	
Design speed	220 (kph)
Operation speed	200 (kph)
Acceleration (normal load, grade 0%)	0.4 (m/s ²)
Battery operation mode	
Design speed	40 (kph)
Operation speed	30 (kph)
Acceleration (normal load, grade 0%)	0.34 (m/s ²)

$$F_{grade} = M_t g \sin(\alpha) \quad (4)$$

$$P_t = F_{trac} v_t \quad (5)$$

where, F_{trac} , F_{roll} , F_{aero} , and F_{grade} are traction force, rolling resistance, aerodynamic resistance, and gradient resistance, respectively. M_t and Acc

are the trainset mass and acceleration, respectively. The trainset mass is the sum of the car mass and the passenger mass. P_t and v_t are the trainset's power and speed, respectively. Other variable names and values are described in

Table 3.

The input of the train dynamic model is speed and gradient, then based on (1) to (5), the output is the trainset required power. In this study, since the focus is on the power and energy flow, the detailed model of motor control is not used. The traction motor, VVVF, SIV, DC-DC converter, rectifier, and transformer are modeled with the same constant efficiency, which is 0.9.

Table 3. Train dynamic model parameters

Variables	Names	Value
f_r	Friction coefficient	0.002
g	Gravitational acceleration	9.80 m/s ²
α	Angle of inclination	1.718° (3%)
C_w	Air resistance coefficient	0.5
A	Windward area	9 m ²
ρ_{air}	Air density	1.225 kg/m ³
P_{aux}	Total auxiliary power	132 kW
V_{DC-bus}	DC bus voltage	3000 VDC

2.2. Traction Performance

Based on the train's general specifications, [Table 2](#), the train performance is calculated to determine the ability of the train to reach the determined performance. [Figure 3](#) and [Figure 4](#) are drawn using (1) to (4), which illustrate the train traction result based on the determined mass and acceleration, accounting for the effect of resistance.

[Figure 3](#) shows the train performance when using a catenary supply. Where F_{trac} , R_t , and Acc are traction force as in (1), total resistance ($F_{roll} + F_{aero} + F_{grade}$), and train acceleration, respectively. The numbers 0 and 3 in R_t and Acc are for 0% and 3% gradient, respectively. The power required is up to 873 kW to get the determined speed of 220 kph in the 0% gradient. It has a constant traction

force and acceleration until a speed of 85 kph. When the gradient is 3%, the same power can reach a maximum speed of 105 kph, and the acceleration decreases from 0.4 m/s² to 0.12 m/s².

The train performance with the battery as a supply is depicted in [Figure 4](#). It shows that based on the train specifications, [Table 2](#), in the track without a gradient, the maximum speed is up to 60 kph. The power required is 44 kW, with the weakening point for traction force and acceleration at 5 kph. However, when the gradient of 3% was applied, the maximum speed became 6 kph. It is very slow. If the determined distance is 10 km, the duration required to cover it is (10 km/ 6 kph), which is 1.67 hours. This duration is too long. Hence, it needs to be upgraded to improve performance.

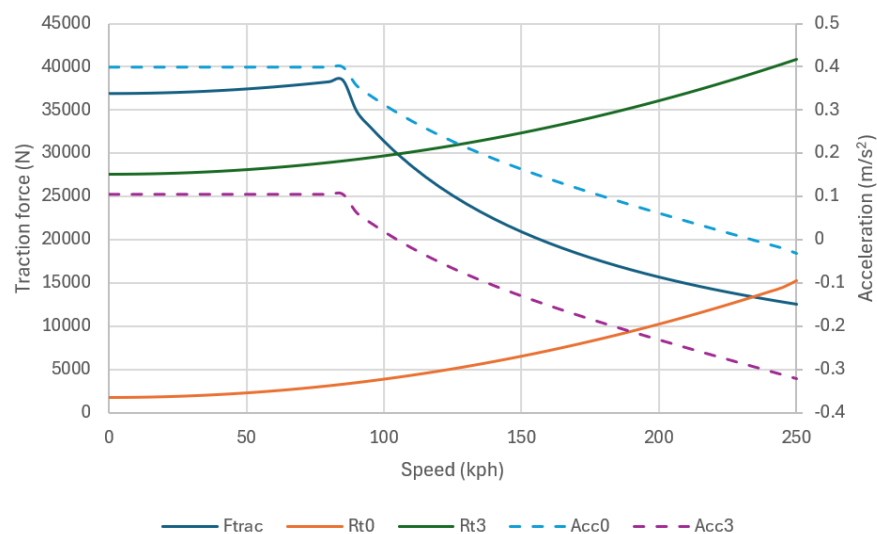


Figure 3. Train performance with catenary source

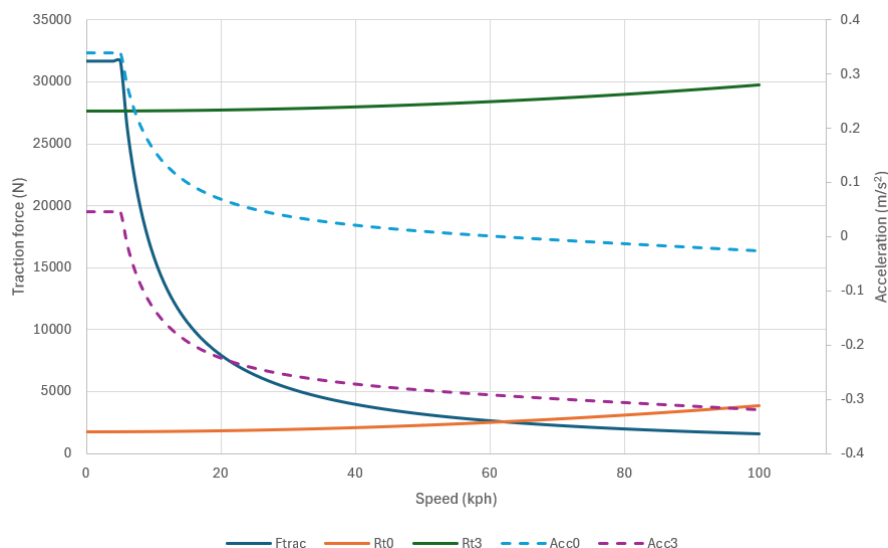


Figure 4. Train performance with a battery source

3. Proposed Battery Sizing and Hybrid Energy Management

The purpose of the hybrid catenary-battery in this trainset system is to handle unelectrified track paths and emergency conditions where the catenary supply fails. Hence, the proposed method focuses on solving these two issues.

3.1. Emergency Operation

Emergency is the priority; hence, its design is the first step. Based on the train performance when supplied by the battery according to the requirement in Table 2, its speed is too slow in the gradient condition. The longer it takes to reach the destination in emergency conditions, the more stressed the passenger becomes. Moreover, it increases the power consumed by the auxiliary. When the auxiliary power is integrated for a long time, it gives high energy and increases the energy consumption from the battery. Based on the catenary supply condition, when passing in a 3% gradient, its speed is reduced by up to 50%; therefore, the gradient speed of the battery supply is also designed to be half of the operational speed, which is 15 kph. With this speed, the traveling time for 10 km is (10 km/15 kph), which is 0.67 hours or only 40.2 minutes.

The upgraded speed makes a new train performance graph, as shown in Figure 5. The weakening speed is 13 kph with the non-gradient speed up to 100 kph, and when in the 3% gradient,

the speed is 15 kph. In this condition, the total power consumed from the propulsion system is up to 193 kW. The total power, including auxiliary power, will be higher.

The battery energy is calculated as Eq. (6).

$$E_B = \left(\frac{E_{avg} * D}{\eta_t} \right) * (2 - 75\%DoD) \quad (6)$$

Where E_B , E_{avg} , D , and η_t are battery energy, average energy consumption, traveling distance, and total system efficiency. The battery Depth of Discharge (DoD) is 80%, for a safety margin, the formula uses 75% DoD.

3.2. Drive Cycle

The train performance is generally a torque control that gives a view of propulsion performance for the given resistance. However, for this study to show the hybrid capability to handle emergency conditions and non-electrified tracks, the drive cycle, which is the speed vs. time, is used. Figure 6 and Figure 7 show the conditions when the battery supply is used in the non-gradient and 3% gradient tracks, respectively. It was created based on the train performance graph in Figure 5. The drive cycle for the catenary supply without and with a gradient is depicted in Figure 8 and Figure 9, respectively. It is created based on the train performance, as Figure 3. The drive cycle distance for the battery and catenary supply is 10 km and 50 km, respectively.

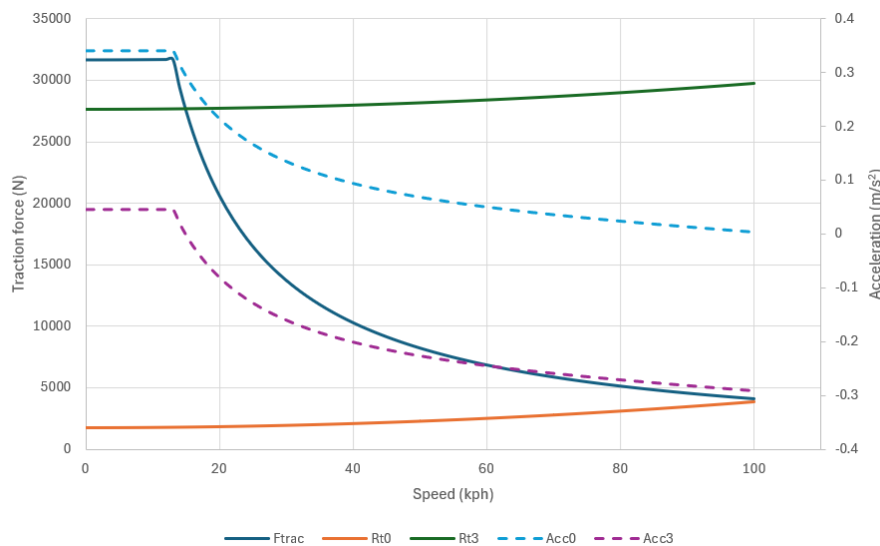


Figure 5. Train performance with an upgraded speed on the gradient track

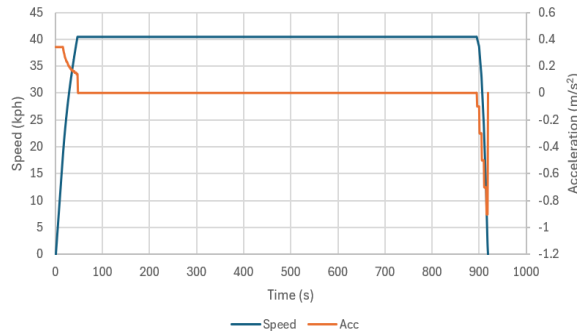


Figure 6. Battery supply: drive cycle no gradient

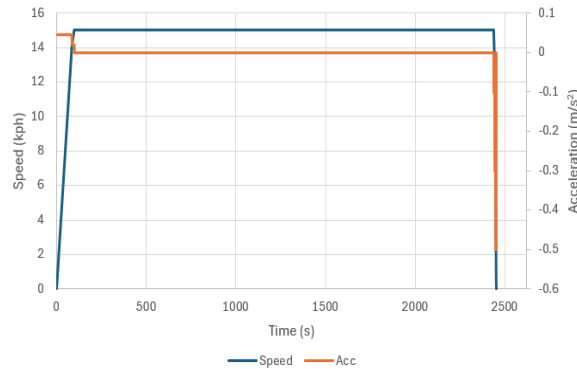


Figure 7. Battery supply: drive cycle 3% gradient

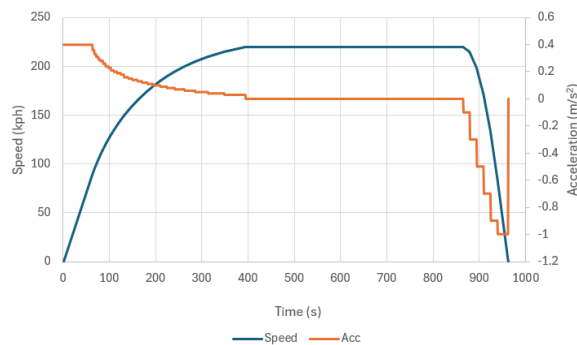


Figure 8. Catenary supply: drive cycle no gradient

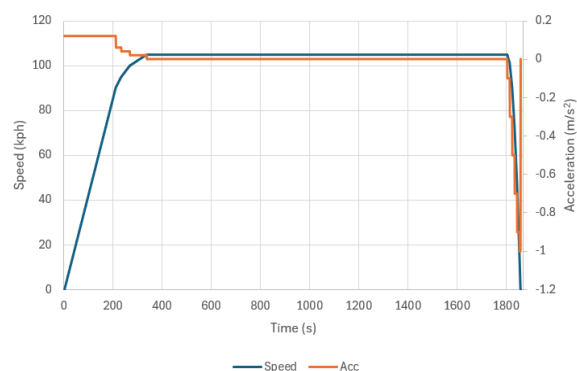


Figure 9. Catenary supply: drive cycle 3% gradient

3.3. Proposed Rule-based EMS with coasting

The rule-based EMS has been widely adopted as a baseline strategy for hybrid railway

applications due to its simplicity and proven effectiveness [19], [20]. In this study, the baseline EMS is adapted and modified to account for the specific train and track conditions under consideration. The proposed strategy is illustrated in Figure 10. To maximize energy recovery, regenerative braking power is first directed to the battery. If the battery state of charge (SoC) reaches its upper limit (100%), the surplus energy is redirected to the catenary, thereby preventing overcharging. Unlike some conventional EMS implementations, the battery is not employed to support peak power demand during acceleration. Instead, its capacity is preserved to guarantee sufficient energy availability for emergency operation scenarios, ensuring that the train can still complete the required distance in case of catenary power loss.

The novel contribution of this work lies in integrating a coasting mode into the rule-based EMS. During operation, coasting is strategically activated to reduce traction power demand and improve overall system efficiency. This addition extends beyond conventional rule-based methods reported in [19], [20], which do not incorporate coasting.

4. Results and Discussion

4.1. Testing Condition

4.1.1. Emergency Operation

The emergency operation is when battery-only mode is used. To determine the battery size, the drive cycle for battery supplies with a 3% gradient is used since it is an extreme condition. The distance for this test is 10 km. The auxiliary power only uses 50% of the total.

4.1.2. Normal Operation

The normal operation means that the catenary-only mode is used. This operation is to determine the power requested from the catenary during train operation. Both with and without a gradient will be tested. The distance for this test is 50 km.

4.1.3. Hybrid Mode

In the hybrid mode, both the catenary and battery are used. The power distributed for the catenary and battery is determined by the EMS algorithm. The rule-based EMS is used and determined based on the track condition. To test the hybrid mode, two cases are used:

Case 1:

The non-electrified track is between two stations (inter-station) with 10 km. For illustration, the train moves from stations A, B, and C, the non-electrified track is between stations B and C, with a maximum distance of 10 km. Figure 11 shows the condition in the track without a gradient, where the maximum speed of the catenary and battery supply is 220 kph and 40 kph, respectively. The inter-station test is also done for a 3% gradient with the maximum speed of 105 kph and 15 kph for catenary and battery supply, respectively, as shown in Figure 12. The total distance for this test is 60 km.

Since the battery size is determined based on the emergency condition with half of the auxiliary power only, this test also applies 50% auxiliary power when the battery supply is connected. This

can be set up in the station before moving to the next station, and it is not a big issue since the train is in an idle condition.

Case 2:

The second case is when the non-electrified track is in the middle of the track before the next station. The total distance of this test is 60 km (station A to B), with 50 km for the electrified track and the rest, 10 km, non-electrified. In this condition, the coasting operation method is proposed to reduce energy consumption.

The coasting mode means the train is freely moving when the supply power is turned off. In this scenario, the train will have no power. The coasting is activated at a distance of 50 km at a speed of 220 kph (non-gradient track, Figure 13). Figure 13 shows that the train decelerates constantly by 0.14 m/s^2 starting from 929 s. It can

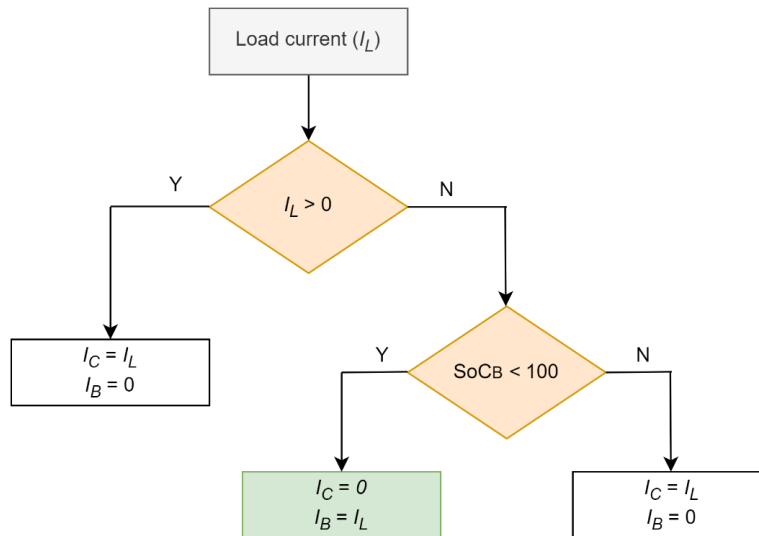


Figure 10. Simple rule-based EMS

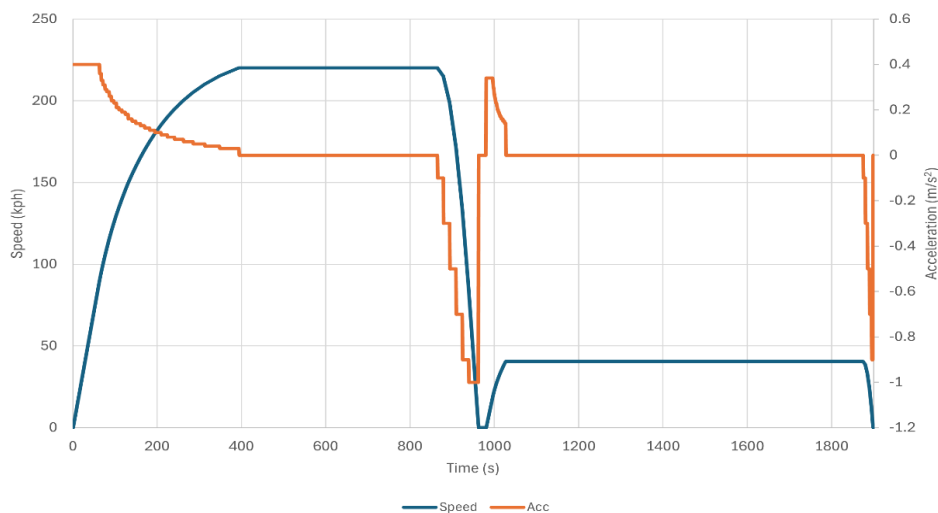


Figure 11. Hybrid mode: drive cycle no gradient

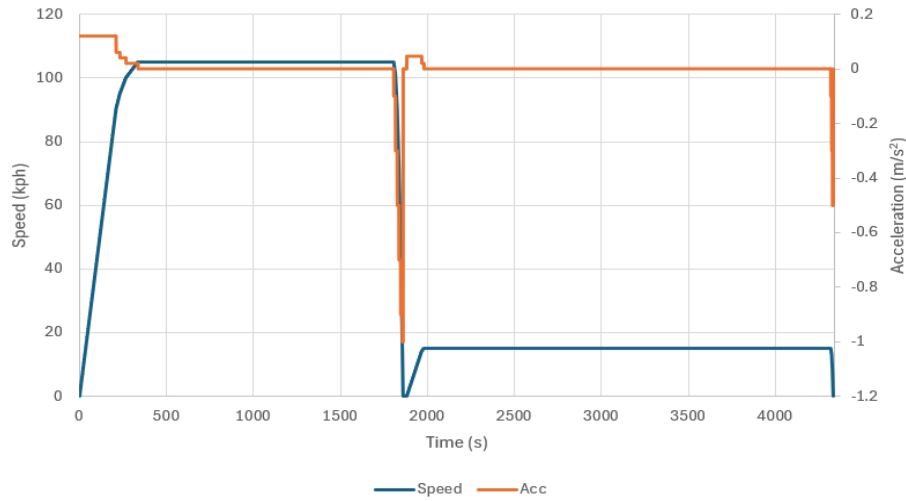


Figure 12. Hybrid mode: drive cycle 3% gradient

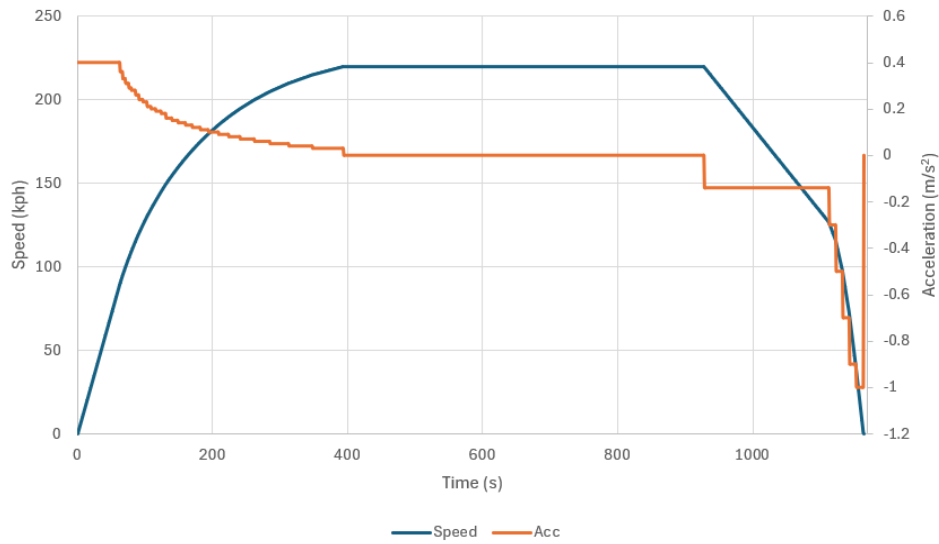


Figure 13. Coasting mode: no gradient

reach 58.965 km at a time of 1114 s. Then the break is applied, and the train can reach a distance of 60 km from the station. During coasting, the battery supplies the auxiliary load.

The same scenario is applied with a 3% gradient, and the train cannot reach 60 km distance, as shown in [Figure 14](#). This happens since the top speed when the train starts to move without power freely is lower than that with no gradient. Under these conditions, the train reaches 50 km at 1840 s, then the catenary power is lost. The train gets a constant deceleration of 0.05 m/s² resulting from the resistance at this speed. The speed reaches 15 kph at 58.330 km at a time of 2341 s. The battery is then connected to supply the system. If not, the train will continue to decrease and cannot reach the next station within 60 km. In

Case 2, full auxiliary power can be handled by the battery, since it only has a small portion of energy for the propulsion function. When coasting takes place, the battery supplies the auxiliary.

4.2. Emergency Operation Test

Based on the worst-case operation using a battery supply with a 3% gradient, this test is done using the drive cycle as in [Figure 7](#). The result is then used to calculate the battery specification:

$$\begin{aligned}
 E_B &= \left(\frac{E_{avg} * D}{\eta_t} \right) * (2 - 75\%DoD) \\
 &= \left(\frac{14.49 * 10}{0.9} \right) * 1.25 \\
 &= 201.3 \text{ kWh}
 \end{aligned} \tag{7}$$

The battery capacity can be calculated as Eq. (8).

$$\begin{aligned}
 C_B &= E_B / V_B \\
 &= 201.3 / 600 \text{ (kWh/V)} \\
 &= 335.5 \text{ Ah}
 \end{aligned}
 \tag{8}$$

The final battery specifications, 201.3 kWh, 600 V, and 335.5 Ah, were then used in the simulation. The battery was then tested to run the train on the gradient track (3%) with a distance of 10 km. [Figure 15](#) shows the battery performance. The test starts at a battery SoC of 100% and ends at an SoC of 20%. Besides the energy for traction, in this condition, the battery also supplies 50% of auxiliary power. It was also tested in a non-gradient track, and the result is depicted in [Figure 16](#).

Comparing [Figure 15](#) and [Figure 16](#), it can be seen that in the gradient track, the traveling time is longer since the maximum speed is lower. More details on the maximum power and energy consumed are provided in [Table 4](#). The maximum power of the gradient track is lower, since it has lower acceleration and top speed than the non-gradient track. However, the total energy required by the train on the gradient track is higher. The energy from regenerative braking is only small since it has a low maximum speed and deceleration value.

4.3. Normal Operation Test

In normal operation, all of the power requested by the train set is supplied by the catenary. [Table](#)

[5](#) summarizes the maximum power and energy consumption for both with and without the gradient track. It can be seen that the gradient track has higher values for both maximum power and energy consumed. The difference in the consumed energy between the non-gradient and 3% gradient is up to 137%. The large gap is caused by the significant mass of the train, which results in higher energy consumption on gradient tracks.

4.4. Hybrid Mode Test

Case 1:

In this case, the non-electrified track is between stations, hence the train can stop first before moving to the non-electrified track. The test uses the drive cycle from [Figure 11](#) and [Figure 12](#) for non-gradient and gradient tracks, respectively. The results are summarized in [Table 6](#). It can be seen that the energy consumption of the 3% gradient is higher than that of the non-gradient track.

Table 4. Power and energy in battery operation

Track profile	Max power (W)	Energy consumed (kWh)
No gradient	339.060	31.79
3% gradient	272.245	161.9

Table 5. Power and energy in catenary operation

Track profile	Max power (W)	Energy consumed (kWh)
No gradient	1.641.665	306.8
3% gradient	1.706.750	728.5

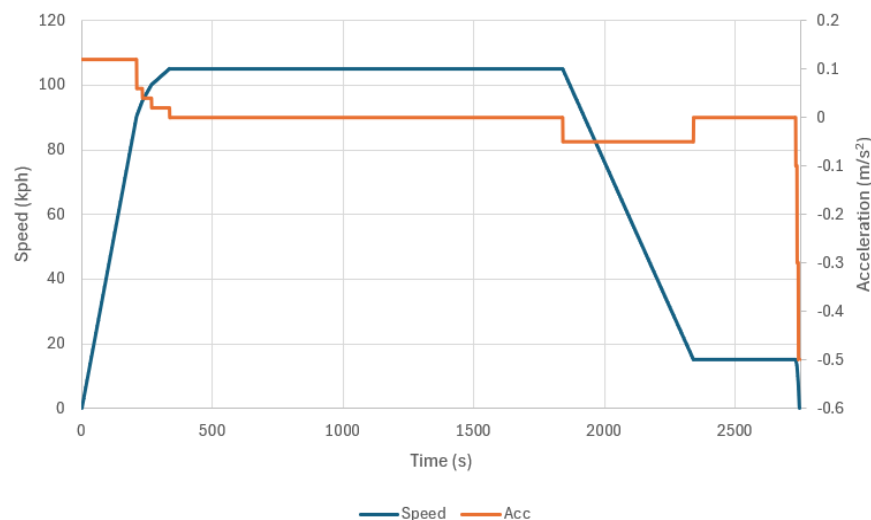


Figure 14. Coasting mode: 3% gradient

Table 6. Energy consumption in hybrid mode

Track profile	Catenary energy (kWh)	Battery energy (kWh)	Total (kWh)
No gradient	306.8	32.2	339.0
3 % gradient	728.5	169.1	897.6

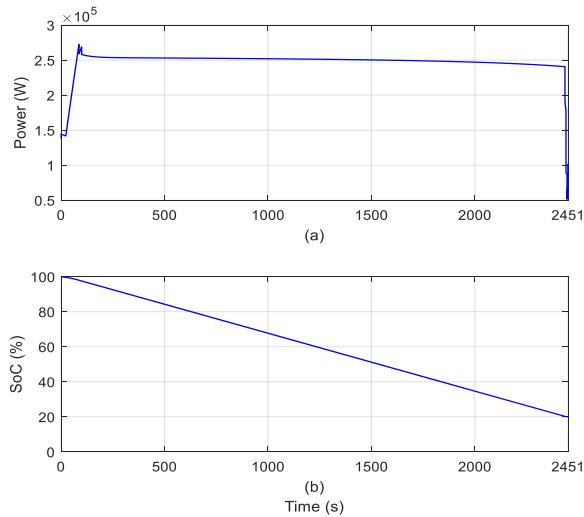


Figure 15. Battery performance in the gradient track

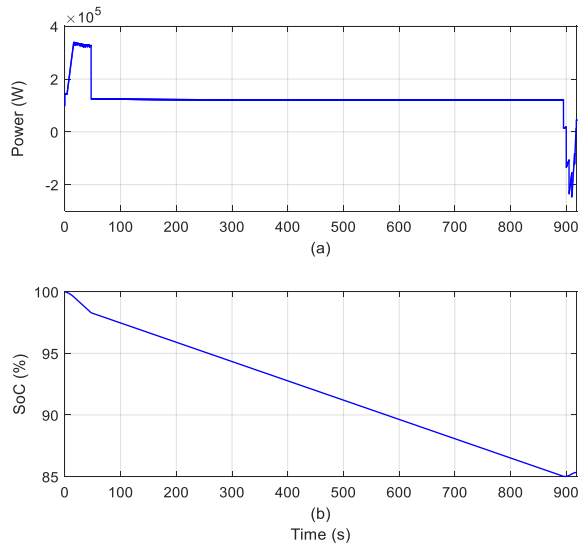


Figure 16. Battery performance in the non-gradient track

The power-sharing graph for the non-gradient and gradient tracks is depicted in [Figure 17](#) and [Figure 18](#), respectively. From [Figure 17](#), it can be seen that, in the beginning, the catenary is activated and the battery is disconnected. The reverse condition is applied when the train reaches the middle station. Both the power given by the catenary and battery is higher than the power requested by the train, since the efficiency of the system is applied.

The rule-based EMS design allows the battery to absorb the regenerative brake power. However,

it can not be seen when the braking happens at a time between 800 s and 1000 s. This is due to the battery being in full condition (100 % SoC). The regenerative braking in the last station only gives a small amount of power since it happens at a low speed and deceleration. The same condition happens for the track with a 3% gradient, [Figure 18](#). However, it has higher power due to the higher traction force required to move the train on the gradient track. In this condition, the SoC of the battery at the final station is 20%.

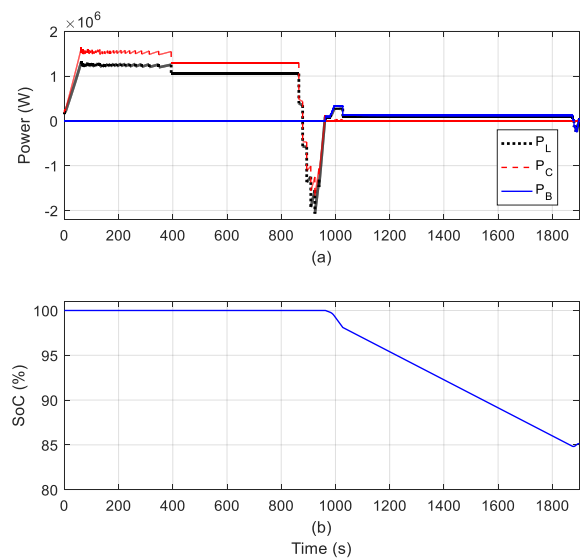


Figure 17. Hybrid mode performance: non-gradient

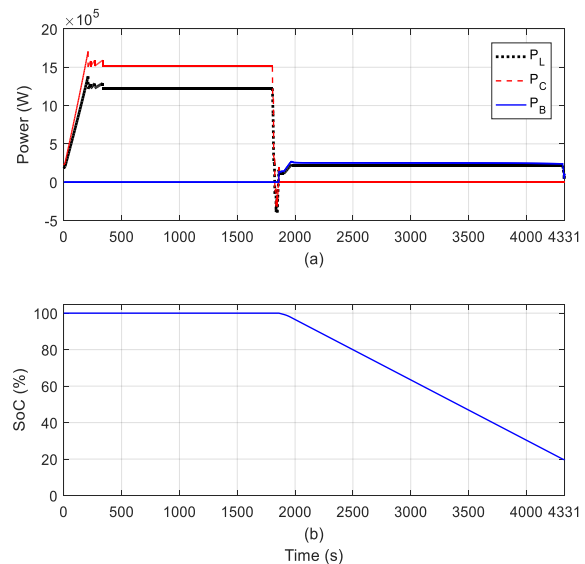


Figure 18. Hybrid mode performance: gradient

Case 2:

In case two, the coasting mode is applied to reduce the total energy consumption. This mode is used when the non-electrified track section is between stations or when the train does not stop in the middle station, if it is assumed as Case 1. The drive cycle uses Figure 13 and Figure 14 for non-gradient and 3% gradient, respectively. In the coasting condition, both auxiliary power is supplied by the battery. In this case, the auxiliary power is 100% work.

The results of this test are summarized in Table 7. It can be seen that the same as before, the track with a gradient has higher power consumption. Compared to Case 1 with the same track and distance, the difference is only in the coasting mode; Case 2 has lower energy consumption for the same scenario. In the non-gradient track, the energy reduction is up to 0.80%, while in the 3% gradient, the reduction is up to 12.56%.

The power-sharing graph for linear and gradient tracks is depicted in Figure 19 and Figure 20, respectively. Both coasting modes are activated when the covered distance is 50 km. In Figure 19, the battery only supplies the auxiliary power until the train stops. The battery's SoC decreases from 100% to 96%, and then when the brake is applied, the battery is charged by the regenerative power. The final battery SoC is 97.70%. Hence, the delta SoC is 2.3%, meaning that it only consumes 2.3% of the battery SoC.

In the gradient track, when coasting is activated at 50 km, the battery is connected to supply 100% of the auxiliary power. When the speed reaches 15 kph, the battery helps to supply the propulsion system. Hence, the train can continue to move and reach the final destination. At these conditions, the battery SoC decreases from 100% to 79.60% at the end of travel. The regenerative braking power is too small since the brake happens at a low speed with low deceleration. Hence, the delta SoC of the battery is 20.40%.

Comparing Case 1 and Case 2, the coasting mode can give energy savings. However, the coasting mode is related to the train operation, which is the responsibility of the train driver.

Therefore, in some railway operators, such as SNCF in France and Deutsche Bahn in Germany, the Driving Advisory System (DAS) is given as a recommendation for the driver [1].

4.5. Discussion

To situate our results within the broader context of hybrid railway technologies, we compare the energy reduction achieved in this study (up to 12.56% with coasting mode on gradient tracks) with findings from related works. The author in [26] showed that integrating an on-

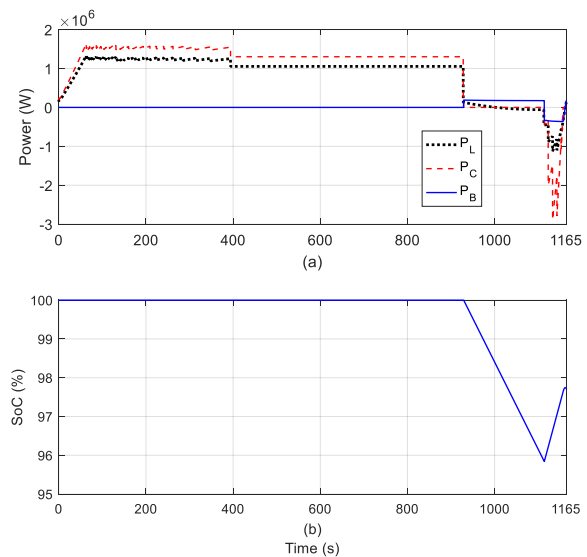


Figure 19. Coasting mode performance: non-gradient

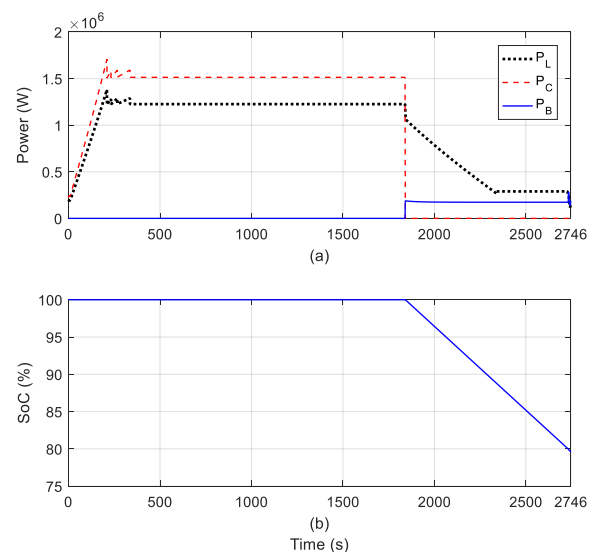


Figure 20. Coasting mode performance: gradient

Table 7. Energy consumption in a hybrid with coasting mode

Track profile	Catenary energy (kWh)	Battery energy (kWh)	Total (kWh)
No gradient	331.5	4.80	336.3
3% gradient	740.9	43.97	784.87

board battery energy storage system equivalent to just 0.6% of the train's energy demand increased the train mass by only 0.07% but still resulted in 2.11% energy savings under simulation conditions. Schenker *et al.* [12], on the other hand, reported more substantial savings, achieving an 8.3% reduction in catenary energy consumption on a partly electrified German route, along with a 23.3% recuperation factor for regenerative braking. Compared to these studies, our observed energy savings (12.56%) are higher than the results of [26] and somewhat greater than those of [12]. The differences arise primarily from the integration of a coasting strategy within a rule-based EMS, the modeling assumptions regarding auxiliary loads, and the operational scenarios simulated. These findings suggest that incorporating coasting mode into EMS design can yield efficiency gains that complement or even exceed those reported in prior studies, while also maintaining emergency readiness and operational reliability.

While the simulation results demonstrate the feasibility of the proposed hybrid catenary–battery system, several challenges must be considered for real-world implementation. First, integration with existing rail infrastructure requires compatibility with both electrified and non-electrified sections, including substations, catenary switching systems, and station layouts. Second, battery performance and lifecycle are critical; real-world operating conditions such as temperature variations, frequent charge–discharge cycles, and aging can reduce effective capacity and increase maintenance costs. Third, the weight and space requirements of large battery packs may affect train design, particularly for retrofitting existing rolling stock. Fourth, operational coordination is needed to align the hybrid system with signaling, safety, and driver advisory systems, ensuring smooth transitions between catenary and battery operation. Finally, economic feasibility depends on balancing the reduced energy consumption and emissions against the higher initial investment in batteries and control systems. Addressing these challenges requires not only optimized energy management strategies, as proposed in this paper, but also close collaboration between railway operators, infrastructure providers, and technology suppliers to ensure practical deployment.

For operators, the proposed system offers several practical implications. First, the observed 12.56% reduction in energy consumption on gradient tracks translates directly into lower operating costs, especially in regions where electricity tariffs for traction are significant. Second, by reserving battery capacity for emergency conditions, the system enhances service reliability, ensuring trains can reach the next station during catenary failures without causing severe schedule disruptions. Third, while the initial capital investment in batteries and control systems may be substantial, the combination of reduced energy costs, extended asset resilience, and avoidance of full-scale electrification can provide favorable long-term economics. Finally, operational strategies such as coasting mode can be integrated with driver advisory systems, aligning train schedules with efficiency goals without compromising punctuality.

5. Conclusion

The hybrid catenary–battery railway model and its effective hybrid operation mode have been successfully proposed and validated in simulation. The battery size was determined as the minimum required to cover emergency distance conditions, ensuring cost-effectiveness while maintaining operational reliability. A simple hybrid operation incorporating a coasting mode was developed and tested, achieving up to 12.56% energy reduction on 3% gradient tracks. The proposed EMS also enables the battery to fully supply auxiliary loads, representing a significant improvement over the baseline operation, where only partial coverage was possible. Beyond simulation, the study highlights important considerations for real-world applications. Integration with existing infrastructure, battery lifecycle, and degradation, and the trade-off between capital investment and operating cost will be critical factors for deployment. For railway operators, the proposed system implies lower long-term energy costs, enhanced schedule reliability during catenary failures, and reduced reliance on full electrification, making it a practical pathway toward sustainable and resilient rail transport. Future work will focus on experimental validation, the application of advanced EMS

optimization methods, and comprehensive cost-benefit analyses to support large-scale adoption.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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