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INNOVATIVE ENERGY RECOVERY SYSTEM DESIGN FOR LOCOMOTIVES: ADVANCING TECHNOLOGY MANAGEMENT FOR SUSTAINABLE RAIL TRANSPORTATION

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ABSTRACT

In Sri Lankan railway, dynamic braking energy from Diesel-Electric Multiple Units (DEMUs) are currently wasted as heat, unlike electrified railways around the world, which recover and reuse this energy. This research proposes to design an innovative and sustainable system to harvest and reuse dynamic braking energy in S14 DEMUs operating on the upcountry railway line, planning to reduce operational costs and support environmental sustainability. Based on past research studies, energy losses during a 20-hour round trip from Badulla to Colombo were estimated around 3.5 MWh. Braking intervals and energy peaks were analyzed to identify optimal energy recovery points. A Lithium Iron Phosphate (LFP) battery system was selected for its proven safety, reliability and feasibility in transport applications. The suggested innovative design integrates a 1 MWh battery pack, capable of utilizing dynamic braking energy, primarily during the downhill section. The stored energy is then reused to power up the auxiliary systems during the return journey. This solution provides significant economic benefits. Over a 10-year period of battery lifetime, each train could save more than Rs. 87 million and reduce diesel consumption by approximately 550,800 liters. These savings not only reduce fuel costs but also reduce carbon emissions, contributing to a greener, more sustainable rail transport system. This novel system's expansion over the upcountry railway fleet could have a multiplied *positive impact on the economy and environment. The results show that innovative energy recovery in non-electrified railroads is both economically feasible and ecologically sound.*

Keywords: Battery Storage, Diesel Electric Multiple Units, Dynamic Braking, Innovative System, Sustainable System

1. Introduction

In today's railway industry, rising energy costs, growing environmental concerns, and the push for sustainable development are driving efforts to reduce emissions and improve efficiency. Modern railways have a lot of potential to save energy by using technologies like regenerative braking, energy storage systems (ESS) on board and along the tracks, reversible power grids, and advanced energy management methods (Roch-Dupré et al., 2017; García-Garre & Gabaldón, 2019).

The initial part of this study measured dynamic braking wastage in class S14 DEMUs on the upcountry line, revealing that a Badulla–Colombo round trip wastes about 3.5 MWh as heat; 2.4 MWh during Badulla to Colombo journey and 1.1 MWh on the return (Madhumal et al., n.d.). Based on these results, the study explores innovative methods to recover and reuse part of this lost energy, targeting to improve efficiency, cut costs, and enhance sustainability by reducing environmental impact.

1.1. Aim of the Study

To assess potential cost savings and explore long-term sustainability benefits, it is essential to develop an innovative, efficient, and sustainable energy recovery system capable of capturing the energy released during dynamic break in DEMUs.

1.2. Objectives of the Study

This study aims to assess various energy storage and dynamic braking techniques to determine the feasibility of implementing an energy recovery system for non-electrified locomotives. It further focuses on designing an innovative battery storage system capable of storing and reusing the energy recovered during braking. The performance of the proposed system will be evaluated in terms of its impact on fuel efficiency, cost reduction, and emission control. Finally, the study will provide recommendations for scaling up the system to support future locomotive fleets.

1.3. Scope of the Study

This study presents a novel system design that integrates with current dynamic braking to recover energy without changing the core locomotive design, building on earlier findings on energy loss in Class S14 DEMUs. In order to promote sustainability in non-electrified rail networks, this innovation seeks to increase fuel efficiency, lower emissions, and provide long-term cost savings.

2. Literature Review

Globally, regenerative braking is a proven method for energy recovery in rail transport, though its application in Sri Lanka remains limited. This review examines related global practices and technologies, particularly battery-based energy storage systems such as LFP, emphasizing their efficiency, safety, and adaptability for sustainable rail energy reuse.

2.1. Introduction to Railway Industry

Over two centuries, the locomotive industry has evolved significantly, though the fundamental technology of low friction iron wheels on iron rails remains the same but the implementation is vastly different (Smith, 2001). Additionally, it was discovered that diesel-electric locomotives have an overall efficiency of about 40%, whereas diesel-hydraulic locomotives show a comparable range of efficiency (Rasul et al., 2013). Fully electric locomotives, exhibit a much higher efficiency, with values ranging from 85% to 90% (Rasul et al., 2013). Considering efficiency, many countries prioritize railway electrification and deploy fully electric locomotives for passenger and freight transport.

Before the COVID-19 outbreak, Sri Lankan Railways (SLR), operated approximately 310 trains on a daily basis, including 45 long-distance trains and 12 intercity services, transporting around 290,000 passengers each day (Kulatunga et al., 2015). In addition, SLR maintains a network of 1,420 kilometers of rail tracks, operates 175 locomotives and 900 carriages in regular service, and manages an extensive railway signaling system (Kulatunga et al., 2015). Currently, the locomotive fleet SLR is presented in Table 1.

Table 1: Locomotive Fleet of Sri Lanka Railways (*Sri Lanka Railways*, n.d.)

Locomotive Type	**Locomotive Model**											**Total**
Diesel Multiple Units	S8	S9	S10	S11	S12	S13	S13A	S14	S14A			130
	20	15	15	19	23	12	4	18	4			
Diesel Electric Locomotives	M2	M4	M5B	M5C	M6	M7	M8	M8A	M9	M10	M11	98
	13	14	4	7	14	11	8	2	6	9	10	
Diesel Hydraulic Locomotives	W3	W2A	Y									39
	10	2	27									

The MTU V12 4000 series engines that power the S10, S12, and S14 DEMUs also have similar features. In contrast, Cummins engines are installed in the S11 and S13 DEMUs. There are many different engine models with different specifications for both electric and hydraulic locomotives.

2.2. Regenerative Braking, Energy Recapturing and Reutilization

To halt a moving train, its kinetic energy is converted into heat through friction. This is achieved by pressing brake pads or blocks against the wheels or discs. In additionally, dynamic brakes generate electrical energy by converting the kinetic energy of a train's rotating wheels, which slows it down, which involves switching the propulsion machine's operating mode from motor to generator (Travis D. Painter B.S., 2006). Dynamic braking may be finely controlled in downward motion more than air brakes because it is powered by electrical energy rather than friction (Frilli et al., 2016). Dynamic braking, has the significant advantage of saving brake maintenance costs (Frilli et al., 2016). This method is specifically applied in electric and in hybrid vehicles to get the maximum utilization of available energy. In fully electrified rail tracks the energy produced during regenerative energy can be fed back into the power supply system and reused by other trains on the same track (Rasul et al., 2013). If there are no trains available, it can be stored in batteries for later use (Rasul et al., 2013). These storage batteries can be installed either onboard the train or by the side of the track (wayside storage; Rasul et al., 2013).

2.3. Battery Storage Systems, Battery Chemistries and Safety in Battery Storage Systems

Sri Lanka has shorter tracks and less varied terrain than nations like Brazil, the USA, Australia, and Canada, which have long, varied rail routes. Lack of resources and technology limits this further. Therefore, these systems need to be customized with innovations to the local environment with affordable Energy Storage Systems (ESS).

Optimal placement, sizing, and operation of ESS can significantly enhance the overall performance of the network (Das et al., 2018). Four primary types of Energy Storage Systems (ESS) are commonly used worldwide, namely; battery, flywheel, super capacitor, and hydraulic accumulator with Battery Energy Storage Systems (BESSs) further classified into onboard systems, which store regenerative braking energy which can achieve 15% to 30% savings in traction energy after optimization (Zhang et al., 2015). With onboard ESS achieving 18.6% – 35.8% savings in Brussels, 24% in Madrid, and 8% in Japan (Khodaparastan et al., 2019).

In 2002, first hybrid diesel-electric switcher locomotive, “The Green Goat” has been shown to operate with reductions in fuel consumption of 30% to 80% and a reduction in harmful emissions of 80% to 90% compared to conventional locomotives (Rasul et al., 2013). A hybrid locomotive consists of several major components and differs from traditional locomotive; design of a hybrid locomotive is illustrated by Figure 1.

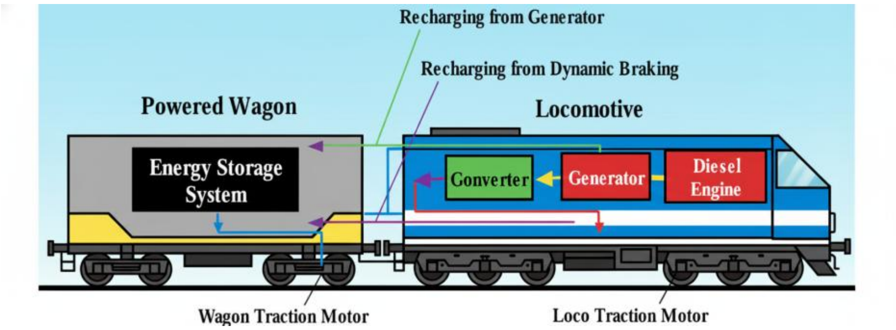

Figure 1: Conceptual-Design for Hybrid-Powered Freight Train (Rasul et al., 2013)

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Study on locomotive operating in a mountain pass in North America revealed that the entire dynamic brake energy capacity was 900 kWh per train (Travis D. Painter B.S., 2006). Assuming a 30% energy recovery rate, it was projected that each train might save 20 gallons of diesel, and daily savings of 680 gallons of fuel (Travis D. Painter B.S., 2006). HITACHI has been actively developing battery-powered railway systems since 2001 to enhance energy efficiency and reduce CO_2 emissions (Rasul et al., 2013). Studies discovered that up to 80% of regenerative braking energy could be recovered, resulting in a 20% reduction in fuel consumption (Rasul et al., 2013).

A simulation study on a Croatian mountain rail route showed that retrofitting a 1.6 MW diesel-electric locomotive with lithium-ion batteries reduced fuel use by 16.47% and greenhouse gas (GHG) emissions by 16.6% (Cipek et al., 2019). A study investigate that stationary Li-ion battery systems provide the best energy recovery (~57% efficiency) and the highest cost-effectiveness with a payback period of around 6 years (Cicconi & Kumar, 2023). Super capacitors, although offering high power density, are not cost-effective for high-speed trains, storing up to 19.2 kWh onboard and 186 kWh stationary and recovering less energy compared with stationary system recovering up to 222 kWh per braking cycle and onboard system (Li-ion) storing 164 kWh per cycle (Cicconi & Kumar, 2023). Because of its exceptional safety, thermal stability, and affordability, LFP has become a top contender for energy storage in rail systems, especially in regenerative braking applications. A comprehensive review of existing research on various battery chemistries and their applications was conducted, and Table 2 illustrates the results.

Table 2: Integrated Summary of Battery Chemistry Technologies (Evro et al., 2024; Tomaszewska et al., 2019; Godinez-brizuela et al., 2023)

Battery Type	Energy Density (Wh/kg)	Cycle Life	Charge /Dis - charge	Cost ($/kWh)	Key Advantages	Key Disadvantages	Application Insights
Lithium Iron Phosphate (LFP)	100–160	4000–8000	High Power	240	High safety, long life, low cost, thermal stability	Lower energy density than NMC	Grid storage, heavy-haul rail, industrial use
Lead-Acid (VRLA)	25–40	300–500	Low	150	Low cost, widely available	Heavy, limited cycle life	Starter batteries, emergency systems
Nickel-Metal Hydride (NiMH)	70–90	2000–5000	High power	500	Good lifespan, decent energy density	High self-discharge rate	Hybrids, power tools
Nickel-Cadmium (NiCd)	50–70	2000–3000	Moderate	350	Durable, reliable	Contains toxic cadmium, expensive	Aircraft, backup systems
Lithium Polymer (Li-Po)	100–155	400–600	High	Mid Value	Lightweight, flexible form factor	Risk of swelling, moderate life	Drones, RC devices, compact electronics

In battery module design, reliable cell-to-cell and module-to-module connections are essential (H. Xu et al., 2020). Figure 2 shows the basic starting point of this method, integrated into the battery storage design, with deeper analysis planned for later stages.

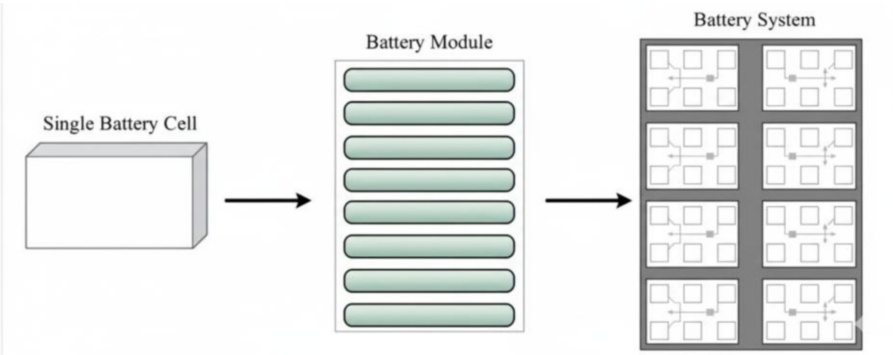

Figure 2: Step-by-Step Battery Pack Modelling Process (H. Xu et al., 2020)

Due to high-energy demands, harsh operating conditions, and constant vibration and temperature fluctuations in rail operations, battery system safety is critical for hybrid locomotives. (Ceraolo et al., 2018). Advanced BMS, thermal control technologies, sturdy packaging, and rigorous adherence to charging protocols are all necessary to ensure safety (Ralls et al., 2023). Fire protection methods like fire-resistant coatings, gypsum boards, insulation, and concrete encasement are recommended (Mira et al., 2021). Around 40% of car accidents involve frontal impacts, and train collisions are also common (P. Xu & Xiao, 2022). When positioning the battery pack, it is essential to ensure structural strength particularly in crash zones, while maintaining system balance and center of gravity. (Gopal Samavedam, 2002). These factors must be incorporated into battery pack design to ensure safety, and the current study's storage recommendations reflect them.

2.4. Research Gap

Research around the world shows that regenerative braking can save energy, lower emissions, and enable sustainable rail operations mainly on lengthy, steep routes. In order to improve efficiency and sustainability, dynamic brake energy recovery and storage systems for diesel-electric locomotives that are affordable, secure, and innovative system design are needed for Sri Lanka's short, low-gradient lines.

3. Methodology

Building on the 3.5 MWh of identified energy waste, this study refines strategies to use a portion for class S14 DEMU auxiliary power through detailed braking pattern analysis. The auxiliary power requirements include 25 kW for train lighting, fans, and buffet equipment, 10 kW for each of the two air-conditioned compartments, and 5 kW for each of the two driver and guard cabins. (Madhumal et al., n.d.). For a 20-hour journey, the total auxiliary load of 55 kW (25kW + 2*10kW + 2*5kW = 55kW), consumes approximately 1.1 MWh. The auxiliary power peaks at around 100 kW during engine start-up, then stabilizes between 50–60 kW during normal operation (CRRC QINGDAO SIFANG CO., 2019f). Maximizing battery efficiency requires careful consideration of charging and discharging factors, which can be further optimized later using a Battery Management System (BMS).The greatest energy loss occurs during dynamic braking on the Badulla-to-Colombo trip, with around 2.5 MWh (Madhumal et al., n.d.). Topography greatly impacts energy recovery, with steep downhill sections offering the highest potential. Analysis, which focuses on peak generation periods with the train timetable is shown by Table 3.

Table 3: Integrated Analysis of Train Timetable and Quantified Energy Generation During Dynamic Braking Across Time Periods (Madhumal et al., n.d.; *Sri Lanka Railways*, n.d.)

Energy Dissipation Time Period (hr: min: s)	Time of Dissipation	Total energy (kWh)	Avg. Power Dissipation (kW)	Train Station	In Time	Out Time
In 5.45 AM – Out 4.30 PM				Badulla		5:45
9.18.5 - 9.24.35	6Min 30ec	91.4074213	105.4701	Hali Ela	6:00	6:01
9.33.27 - 9.47.5	8Min 52 Sec	159.4715	87.72882	Uduwara	6:09	6:10
9.48.34 - 9.55.48	1Min 29 Sec	84.2640975	87.370608	Demodara	6:23	6:24
10.2.1 - 10.2.13	6Min 13 Sec	0.71806107	26.92729	Ella	6:39	6:40
10.2.33 - 10.9.41	20 Sec	91.8881327	96.611354	Kithal Elle	6:45	6:46
10.11.15 - 10.18.22	1Min 34Sec	101.298414	108.27621	Heel Oya	6:54	6:55
10.20.9 - 10.29.9	1Min 47Sec	128.765652	107.30471	Kinigama	7:04	7:05
10.32.41 - 10.45.1	3Min 32 Sec	168.393549	102.40148	Bandarawela	7:11	7:14
10.56.21 - 10.59.38	11Min 20 Sec	32.0518897	73.214976	Diyatalawa	7:28	7:29
11.10.59 - 11.13.30	11Min 21Sec	40.6849798	121.24663	Haputale	7:41	7:43
11.17.11 - 11.20.10	3Min 41Sec	31.3798714	78.887945	Idalgashinna	7:59	8:00
11.20.48 - 11.30.40	38Sec	142.785622	108.53637	Ohiya	8:20	8:21
11.33.44 - 11.40.11	3Min 4Sec	99.6114003	115.82721	Pattipola	8:36	8:37
11.41.54 - 11.46.19	1Min 43Sec	69.8579	118.62662	Ambewela	8:45	8:46
11.48.15 - 12.5.9	1Min 56Sec	243.514279	108.06847	Perakumpura	9:05	9:06
12.7.41 - 12.12.47	2Min 32Sec	93.5110784	137.51629	Nanu Oya	9:16	9:22
12.13.22 - 12.18.45	35Sec	80.3795954	111.98396	Great Western	9:39	9:40
12.20.35 - 12.28.3	1Min 50Sec	108.633137	109.11811	Talawakelle	10:08	10:12
12.50.2 - 12.51.56	1Min 59Sec	15.0834838	59.540068	Kotagala	10:25	10:26
12.55.54 - 12.57.22	3Min 58Sec	14.249416	72.866332	Hatton	10:37	10:39
12.58.1 - 12.58.56	39Sec	8.43374022	69.003329	Nawalapitiya	11:42	11:46
13.3.45 - 13.9.24	4Min 49Sec	63.9433398	84.880539	Ulapane	11:58	11:59
13.10.6 - 13.11.46	42Sec	10.2121127	45.954507	Gampola	12:18	12:19
13.10.6 - 13.11.46	1Min 40Sec	3.86514176	43.482845	Kandy	12:38	12:50
13.24.59 - 13.25.48	13Min 13Sec	8.04540023	73.886329	Peradeniya	12:58	13:00
13.26.13 - 13.26.45	25Sec	3.49357337	49.128376	Kadugannawa	13:16	13:17
13.27.34 - 13.28.36	49Sec	7.46213744	54.160675	Rambukkana	13:56	13:59
13.32.14 - 13.33.41	3Min 38Sec	12.409195	64.185491	Polgahawela	14:10	14:11
13.34.9 - 13.34.49	28Sec	6.18565064	69.58857	Veyangoda	14:41	14:42
14.31.43 - 14.55.3	56Min 54Sec	339.249036	109.04433	Gampaha	14:53	14:54
14.56.56 - 14.58.15	53Sec	15.7914047	89.951039	Ragama	15:04	15:05
15.6.57 - 15.14.17	8Min 42 Sec	100.34912	102.62978	Colombo Fort	15:27	

Because of its frequent dynamic braking and steady downhill gradients, the Badulla to Gampola journey, which lasts roughly 6.5 hours, is found to be the best for battery charging. A thorough analysis of cumulative energy generation reveals that this segment recovering about 1,768.6 kWh (~ 1.7 MWh). As evaluated in the literature review, LFP batteries are selected as the main energy storage solution in this study. From 1.7 MWh energy harvested, with 70% system efficiency, 1.19 MWh is available for battery charging. Considering the 13.5-hour return trip, the base auxiliary load is 0.7425 MWh, which, with a 20% margin for demand variations, becomes 0.891 MWh. accounting for 90% LFP battery discharge efficiency, the required stored energy is 0.99 MWh (recoverable energy (1.19 MWh) > auxiliary demand (0.99 MWh).

The S14 DEMU's engine compartment is unsuitable for battery installation due to high temperatures, mechanical vibrations and shocks, limited crash safety, and lack of advanced cooling systems. However, passenger compartments typically experience less constant vibration and heat stress (Gopal Samavedam, 2002). Hence, Battery systems can be assembled particularly in air-conditioned compartments. Weight distribution analysis confirmed the feasibility of integrating a BESS into passenger compartments while meeting SLR safety limits. The train, comprising 2 engine and 7 passenger compartments, was evaluated using manufacturer data and standard passenger weights (70kg per person) to ensure battery systems remain within compartment (50 tons) and total DEMU weight (500 tons) limits. {CRRC QINGDAO SIFANG CO., 2019f; CRRC QINGDAO SIFANG CO., 2019a}. Results are presented in Table 4.

Table 4: Gross Weight Per Compartment (CRRC QINGDAO SIFANG CO., 2019b; CRRC QINGDAO SIFANG CO., 2019c; CRRC QINGDAO SIFANG CO., 2019d; CRRC QINGDAO SIFANG CO., 2019e)

Compartment Type	Seating/Standing Capacity	Total Passengers	Total Passenger Weight (Tons)	Tare Weight (Tons)	Gross Weight (Tons)
Air-Conditioned	44 / 0	44	3.08	37.64	40.72 *2 = 81.44
Second Class Reserved	48 / 0	48	3.36	33.42	36.78
Third Class Reserved	72 / 0	72	5.04	32.85	37.89
Second Class Ordinary	48 / 78	126	8.82	33.42	42.24
Third Class Ordinary	72 / 84	156	10.92	32.85	43.77
Third Class Buffet	50 / 92	142	9.94	33.71	43.65
Engine Compartment	-	-	-	74.00	74.00*2 =148.00

With a safe residual capacity of 66.33 tons, the fully loaded DEMU weighs approximately 433.77 tons. With AC compartments permitting up to 9 tons, each passenger compartment has a 7–13-ton margin. Similar to chassis-based storage techniques covered in the literature, under-seat and undercarriage areas, which are outside crash zones, offer enough room for battery installation while maintaining structural integrity and efficient thermal management. Figure 3 illustrates the proposed battery placement using a CAD model, categorizing areas into crash (red), buffer (black), and safe (green) zones. The corners of the compartment and the undercarriage are high-risk crash zones, and the buffer zone is still partially vulnerable to debris. According to research, the green safe zone offers the best, safest place for battery integration by combining structural strength with efficient airflow and AC cooling.

Figure 3: Different Zones of the Passenger Compartment Based on Safety Concerns

For feasible BESS, based on battery manufacturers key data on chemistry, voltage, capacity, charge/discharge rates, thermal traits, cycle life, and pack sizing. Each LFP cell has a voltage of 3.2 V and a capacity of 314 Ah, yielding 1004.8 Wh of energy per cell. The battery module is designed with a capacity of 314 Ah and a voltage of 51.2 V, which requires 16 cells connected in series. (SHENZHENLEFU, XIAMEN LEFOR, n.d.). With battery capacity fixed, all cells are connected in series to form the module. To achieve 1 MWh at 600 A and 1500 V, each battery module provides 16,076.8 Wh (51.2 V × 314 Ah). By configuring 64 modules in 32 series and 2 parallel connections, the total battery pack energy reaches 1.029 MWh, with a pack voltage of 1638.4 V. In order to forecast performance, facilitate system integration, and direct future BESS improvements for rail applications, the battery pack's real-world behavior was modeled using the MATLAB Simulink Battery Design toolbox based on literature findings. (Chirag Patel, 2019). Figure 4 shows the simulated innovative BESS.

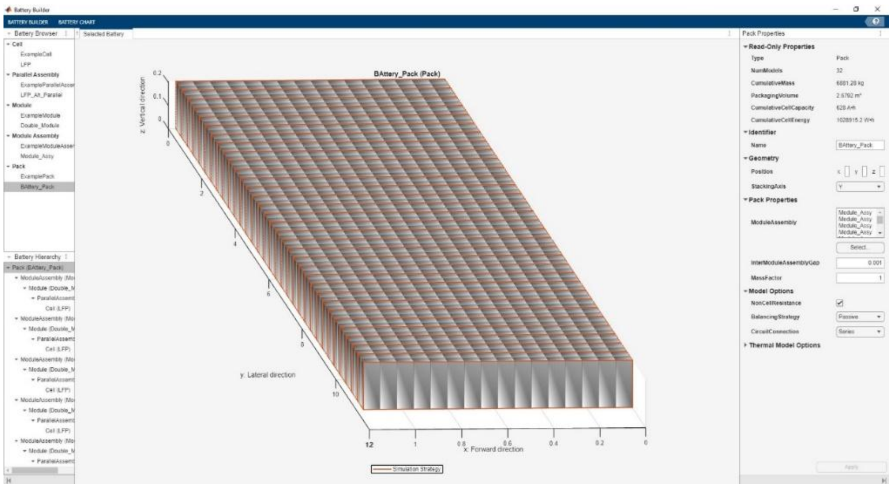

Figure 4: Battery Pack Design Developed using MATLAB

The BESS was divided into four battery packs for even weight distribution, with two packs installed in a single AFC compartment. Each pack weighs about 2,492 kg, totaling 4,984 kg per compartment, and measures 7,200 mm × 850 mm × 250 mm as per the MATLAB simulation results. Figure 5 shows the pack layout within the compartment.

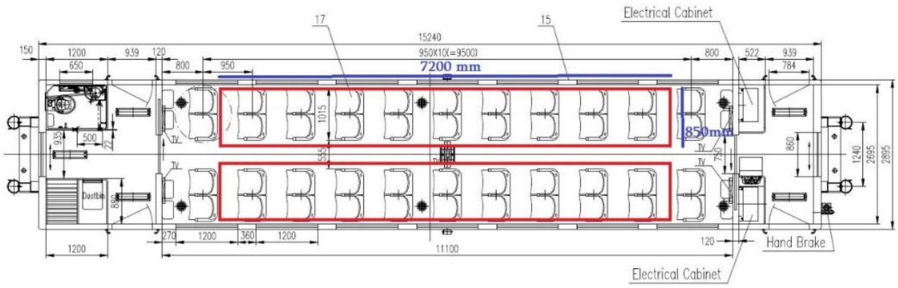

Figure 5: Battery Layout within the Dimensional Layout of S14 AFC Compartment

4. Results/Analysis and Discussion

This study highlights the potential for long-term cost savings and emission reductions through implementing battery-assisted energy storage. The S14 DEMU's engine, driving the main generator for traction and auxiliary systems like lighting, ventilation, and buffet services, with a specific fuel consumption of about 205 g/kWh (MTU, 2012). AFC compartments use independent Deutz F6L 912 engines for cooling, consuming 222 g/kWh (Company, n.d.). Diesel density is assumed at 850 kg/m^3 for calculations (Petroleum, 2022), as exact values for Sri Lanka Railways are not readily available.

4.1. Fuel Consumption for Auxiliary Requirements

The diesel fuel density is 0.85 kg/L, with the main engine's specific fuel consumption (SFC) at 205 g/kWh (0.205 kg/kWh) and the AFC engine's SFC at 222 g/kWh (0.222 kg/kWh). This translates to 0.2412 L/kWh for the main engine and 0.261 L/kWh for the AFC engine. Assuming constant auxiliary loads of 35 kW for the main engine and 20 kW for the AFC engine, fuel consumption is 8.44 L/hr and 5.22 L/hr respectively, resulting in a total auxiliary fuel consumption of 13.66 L/hr.

4.2. Cost Savings Achieved through Battery Based System

The battery modules are priced at USD 121,428, with additional costs for packaging, cooling, and system integration (50% worst-case) (*Techno-Economic Analysis of Cooling Technologies Used in Electric Vehicle Battery Thermal Management: A Review*, n.d.), bringing the total to USD 182,142 (LKR 54,642,600 at 1 USD = LKR 300). Diesel-powered auxiliary systems currently consume 13.66 L/hr, costing LKR 78,954.81 per 20-hour journey. With a 6.5-hour battery backup using dynamic braking energy, per-trip costs drop to LKR 25,660.31, saving LKR 47,294.50 per journey and LKR 14,188,347 annually (300 operating days), resulting in a BESS payback period of 3.85 years. Based on 10-year battery lifespan, total savings exceed LKR 87 million. Additional benefits, such as reduced engine runtime, lower maintenance, less auxiliary generator downtime, and potential residual value from battery recycling or resale, further enhance the economic and operational advantages of the system.

4.3. Attainable Sustainability Goals through System Implementation

By reducing dependency on diesel-powered auxiliary systems, the proposed BESS provides significant long-term environmental advantages in addition to financial savings. This improves the sustainability and environmental responsibility of railway operations by reducing fuel consumption, greenhouse gas emissions, and other pollutants. The system is expected to save about 550,800 L of diesel over a ten-year period.

This substantial fuel saving correlates with a proportional reduction in diesel combustion-related emissions. The S14 DEMU falls under the Tier 1 emission standard category (CRRC QINGDAO SIFANG CO., 2019f). Using the EPA's 2020 National Emissions Inventory, Tier 1 U.S. line-haul locomotives are assumed to have emission levels similar to the S14 DEMU (Agency et al., 2022). Table 5 showing cumulative emission reductions.

Table 5: Green House Emission Savings over the period of 10 years according to Environmental Protection Agency's, 2020 National Emissions Inventory (Agency et al., 2022)

Pollutant	EPA (g/gal)	Converted (kg/L)	Total Reduction
Carbon Dioxide (CO_2)	10,150	2.68135	1,476,888 kg ≈ 1,476.9 metric tons
Nitrogen Oxides (NO_x)	120.5	0.03183	17,532 kg ≈ 17.53 metric tons
Carbon Monoxide (CO)	26.624	0.00703	3,872 kg ≈ 3.87 metric tons
Particulate Matter (PM)	2.95076	0.00078	429.6 kg ≈ 0.43 metric tons
Sulphur Dioxide (SO_2)	0.0939	0.000025	13.77 kg ≈ 0.01 metric tons

While lowering sulfur dioxide, nitrogen oxides, and particulate matter enhances public health and adherence to air quality regulations, lowering carbon dioxide emissions aids in the fight against climate change. By increasing energy efficiency and creating a robust, ecologically aware, and future-ready network, installing the novel battery storage system contributes to a sustainable transition to low-emission railroads.

5. Conclusion and Implications

This study shows that it is possible to recover 1.7 MWh of dynamic braking energy from class S14 DEMUs in Sri Lanka during the Badulla–Gampola descent. Nearly 70% of this energy could be stored by a properly operated 1 MWh LFP BESS. AFC undercarriage spaces can be safely integrated while preserving axle load limits and enhancing stability, according to structural and weight analyses. According to economic analysis, an investment of Rs. 55 million could be recovered in less than four years, saving over Rs. 87 million in diesel over a ten-year period. This would also prevent the use of 550,800 L of fuel and more than 1,470 metric tons of CO_2 and other pollutants, thereby promoting low-emission, sustainable rail operations.

Instead of focusing on sophisticated battery modeling or thermal management, this study was driven by general design principles and focused on sizing and operational requirements. Simplifying assumptions were necessary due to limited field data and monitoring infrastructure. However, the research establishes a foundation for sustainable energy innovation in railways. Future directions include high-resolution real-time data acquisition, Artificial Intelligence driven predictive braking strategies, terrain- and load-aware optimization, and hybrid auxiliary systems powered directly by braking energy. These innovations, combined with detailed battery performance assessments, can enhance energy recovery, reduce operational costs, and strengthen environmentally responsible, technology-driven railway management.

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Appendix

Supporting documents used for research including raw data, source codes, CAD designs and other essentials:
https://drive.google.com/drive/folders/1hSZ-haNy3v0AMRdgR9dVlDOuDEI3OCXQ?usp=drive_link