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**FEASIBILITY ANALYSIS OF HARVESTING DYNAMIC
BRAKE ENERGY IN DIESEL-ELECTRIC MULTIPLE
UNITS FOR SUSTAINABLE OPERATION IN THE SRI
LANKAN CONTEXT**

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(208852E)

MEng/PG Diploma in Manufacturing Systems Engineering

Department of Mechanical Engineering

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Thesis/Dissertation submitted in partial fulfilment of the requirements for the degree
Master of Engineering in Manufacturing Systems Engineering

Department of Mechanical Engineering

University of Moratuwa

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August 2025

DECLARATION

I declare that this is my own work, and this Dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. I retain the right to use this content in whole or part in future works (such as articles or books).

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The supervisors should certify the Dissertation with the following declaration.

The above candidate has carried out research for the MEng in Manufacturing Systems Engineering Dissertation under my supervision. I confirm that the declaration made above by the student is true and correct.

Name of Supervisor: Dr. Lihil Uthpala Subasinghe

Signature of the Supervisor:

Date:

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ABSTRACT

Dynamic braking helps regulate train speed and avoids it from becoming too high, especially when they are going downhill. Sri Lanka's non-electrified railway system loses energy because Diesel-Electric Multiple Units (DEMUs) turn braking energy into heat. However, electrified railways recover and reuse braking energy. This study's goal is to perform feasibility study on the use of this wasted energy, which will make things more sustainable, lower costs, and lower carbon emissions.

The first step of this study is to figure out how much energy is lost by S14 DEMUs running on Sri Lanka's upcountry railway line. Study looked at data from onboard loggers, circuit diagrams, operation manuals, and previous tests of the brakes. The results show that a 20-hour round trip from Badulla to Colombo dissipates about 3.5 MWh of energy. Additionally, dynamic braking intervals and patterns were identified to study on feasibility analysis.

Feasibility analysis continued on sustainable energy recovery system to store and reuse a portion of this wasted energy for auxiliary power in the S14 DEMU without altering its existing structure. A Lithium Iron Phosphate (LFP) battery storage system was chosen because of its use in the past and in the railway and automotive industries. A 1 MWh battery pack was added to utilize 1.7 MWh where charging was best during the first 6.5 hours from Badulla to Gampola, where the brakes work best.

The system is expected to save more than 105 million LKR and cut diesel use by 550,800 liters over a period of 10 years. This will lower emissions and support sustainability. These results point to a feasibility study that is cost-effective and will help make non-electrified railway networks more energy-efficient and environmentally friendly.

Keywords: Dynamic braking, Diesel electric multiple units, Energy recovery, Battery storage, Sustainable system

TABLE OF CONTENTS

Declaration	i
Acknowledgement	ii
Abstract	iii
Table of Contents	iv
List of Figures	vii
List of Tables	x
List of Abbreviations	xi
Chapter 1	1
1. Introduction	1
1.1. Background	1
1.2. Aim, Objective and Scope	2
1.2.1. Aim	2
1.2.2. Objective	2
1.2.3. Scope	2
1.3. Thesis Overview	3
Chapter 2	5
2. Background and Literature Review	5
2.1. Introduction to Railway Industry	6
2.2. Braking and Regenerative Braking	8
2.3. Comparative Analysis of Regenerative Braking in Sri Lankan Locomotives against Global Standards and the Need for Energy Quantification	10
2.4. Energy Recapturing, Storage, and Reuse	11
2.5. Different Battery Storage Systems and Battery Chemistries	17
2.5.1. Battery Storage Systems	17
2.5.2. Battery Chemistries	30
2.6. Safety in Battery Storage Systems	37
2.7. Research Gap	42
2.8. Review Summary	44

Chapter 3	46
3. Methodology	46
3.1. Data Collection on Dynamic Braking and Energy Wastage	46
3.2. Data Preparation and Refining	48
3.3. Energy Quantification and Results Obtained	55
3.3.1. Quantified Data	55
3.3.2. Evaluation of Quantitative Data Supporting System Development	60
Chapter 4	67
4. Feasibility study on system design	67
4.1. Synchronization of Regenerative Energy Dissipation with System Demands and Analytical Considerations for Feasibility Analysis	67
4.2. Design of the Battery Storage System Considering Safety, Performance Parameters, and Available Technological Solutions	70
4.2.1. Constraints and Risks in Locomotive Engine Compartment vs Safety and Structural Advantages of Passenger Compartments	70
4.2.2. Quantitative Weight Distribution Analysis and System-Level Impact Assessment of Battery Integration	72
4.2.3 Development of Battery Storage Model Based Simulation on Key Parameters	79
Chapter 5	86
5. Results and discussion	86
5.1. Cost Comparission of the New System Implementation	87
5.1.1. Estimation of Fuel Consumption – Baseline for Auxiliary Systems	88
5.1.2. LFP Battery System Sizing and Supplier Recommendations	88
5.1.3. Overall Cost comparison (Current System and Suggested System)	91
5.2. Attainable Sustainability Goals through System Implementation	92
Chapter 6	95
6. Conclusion	95
6.1. Research summary	95

6.2.	Publications	96
6.3.	Limitations and Challenges	96
6.4.	Future Work and Research Directions	98
	References	100
	Appendix	106

LIST OF FIGURES

	Page
Figure 1.1: Class S14 DEMU operating on Sri Lanka's upcountry railway line	3
Figure 2.1: Electrified railway track with an electric locomotive in operation [10]	6
Figure 2.2: Block diagram of the power car of a DEMU [15]	9
Figure 2.3: Schematic of a diesel based hybrid locomotive powertrain [9]	10
Figure 2.4: Conceptual design for hybrid powered freight train [9]	13
Figure 2.5: NS 999 undergoing testing at Rose Yard, located in Altoona, Pennsylvania [29]	19
Figure 2.6: Installed battery ISO container and intra pack battery trays mounted on the NS 999 locomotive [29]	20
Figure 2.7: Battery ISO container for the NS 999, produced by DropBox, Inc. [29]	20
Figure 2.8: Key design parameters of the battery pack layout studied [26]	22
Figure 2.9: Simplified flow diagram of the battery system used in the life cycle assessment study (BMS – Battery Management System; BMB – Battery Management Board; IBIS – Integrated Battery Interface System) [26]	23
Figure 2.10: Stages of the battery supply chain, raw material processing, component manufacturing, and final assembly [33]	26
Figure 2.11: Interconnection layout for prismatic battery cells [35]	27
Figure 2.12: Structural arrangement of a pouch cell module [35]	27
Figure 2.13: Configuration design of a prismatic cell module [35]	27
Figure 2.14: Step by step battery pack modeling process [36]	28
Figure 2.15: Framework for optimizing the design of an air cooled battery module [36]	29
Figure 2.16: Battery chemistry comparison [23]	32
Figure 2.17: Conceptual layout showing the structural components of a Lithium-Ion battery cell [40]	33

Figure 2.18: Emerging trends and innovation directions in Lithium-Ion battery systems [9]	34
Figure 2.19: Visualization of the global increase in Electric Vehicle (EV) and Plug-in Hybrid Electric Vehicle (PHEV) [47]	36
Figure 2.20: Trend analysis showing the growth in academic publications and citations related to Lithium-Ion batteries (LIBs) [47]	36
Figure 2.21: Summary of fire risk assessment [49]	38
Figure 2.22: a) Low-speed indentation tests employing a 30 mm diameter indenter on cylindrical cells in a 0% State Of Charge (SOC); deformation shape seen just before the cell electrically fails when the impactor is applied (b) In the U-direction at 1.8 mm displacement and (c) In the V-direction at 2.35 mm displacement [52]	40
Figure 3.1: Main electrical power circuit of the DEMU [56]	47
Figure 3.2: Graphical representation of data collected from the on board data logger	48
Figure 3.3: Simplified circuit of the traction motor / resistor grid during dynamic braking	49
Figure 3.4: Variation of armature voltage with excitation current (field current) in a separately excited DC motor [60]	50
Figure 3.5: Variation of armature voltage with the speed (armature rotation) [61]	51
Figure 3.6: Variation of armature voltage (V_a) with excitation current (I_e) of the traction motor (characteristic curve of traction motor) [59]	52
Figure 3.7: Refined curve created by using MATLAB plot and curve fitting functions	53
Figure 3.8: Altitude variation along the Badulla–Colombo railway route [63]	61
Figure 4.1: 3D CAD model of the passenger compartment of S14 DEMU (without seats)	76
Figure 4.2: Different zones of the passenger compartment based on safety concerns	77
Figure 4.3: Cross section of S14 DEMU passenger compartment without seats and areas where battery storage can be assembled	78
Figure 4.4: Cell chemistry details given by the battery manufacturer [70]	80
Figure 4.5: Battery module details given by the battery manufacturer [70]	80

Figure 4.6: Battery pack design developed using MATLAB	83
Figure 4.7: Battery pack optimization from MATLAB	83
Figure 4.8: Battery module assembly layout within the dimensional layout of S14 AFC compartment	84
Figure 4.9: Top view of the S14 AFC compartment after installing two battery packs	85
Figure 4.10: Isometric view of the S14 AFC compartment after installing two battery packs	85

LIST OF TABLES

	Page
Table 2.1: Locomotive fleet of Sri Lanka railways [11]	7
Table 2.2: Specifications of Lithium-Ion cells and the complete battery system for the hybrid locomotive [21]	21
Table 2.3: Comparative overview of seven battery design strategies [26]	24
Table 2.4: Integrated summary of battery chemistry technologies [9][21][26][32][38][39][40][41][42][43]	31
Table 2.5: Comparative analysis of various Thermal Management Systems (TMSs) [49][50]	39
Table 2.6: Structural safety and crashworthiness of battery cell types [37]	41
Table 3.1: Part of quantified data	56
Table 3.2: Set of quantified data during dynamic braking application from Badulla to Colombo (including time of application and power dissipation)	57
Table 3.3: Set of quantified data during dynamic braking application from Colombo to Badulla (including time of application and power dissipation)	58
Table 3.4: Quantified data as a summary	59
Table 3.5: Train schedule from Badulla to Colombo [11]	64
Table 4.1: Compartment tare weights (without passengers [66][67][68][69])	74
Table 4.2: Passenger weight calculations [66][67][68][69]	74
Table 4.3: Combined gross weight per compartment (including passengers)	74
Table 5.1: Emissions made as per the environmental protection agency's , 2020 national emissions inventory [77]	94
Table 5.2: Green house emission savings over the period of 10 years	94

LIST OF ABBREVIATIONS

Abbreviation	Description
AI	Artificial Intelligence
APTA	American Public Transportation Association
BEDEL	Battery-Hybrid Diesel-Electric Locomotive
BEL	Battery Electric Locomotive
BESS	Battery Energy Storage System
BMB	Battery Management Board
BMS	Battery Management System
CAD	Computer Aided Design
CATL	Contemporary Amperex Technology Co., Limited
CFD	Computational Fluid Dynamics
CTC	Cell-to-Chassis
CTP	Cell-to-Pack
DEMU	Diesel-Electric Multiple Units
DfD	Designing for Disassembly
DRL	Deep Reinforcement Learning
EPA	Environmental Protection Agency
EV	Electric Vehicles
GHG	Green House Gas
HVAC	Heating, Ventilation, and Air Conditioning
IBIS	Integrated Battery Interface System
LFP	Lithium Iron Phosphate
MBD	Model-Based Design
ML	Machine Learning
MPC	Model Predictive Control
MTU	Motoren- und Turbinen-Union
NCA	Nickel-Cobalt-Aluminum
NS	Norfolk Southern
RDM	Robust Design Methodology

SAC	Soft Actor-Critic
SLR	Sri Lanka Railway
SOC	State of Charge
TIM	Thermal Interface Material
TIM	Thermal Interface Materials
UK	United Kingdom
USA	United States of America
WESU	Wayside Energy Storage Unit
ZEBL	Zero-Emission Boost Locomotive

CHAPTER 1

INTRODUCTION

1.1. Background

The railway industry is searching for ways to cut emissions and improve energy efficiency because energy prices are going up, environmental concerns are growing, and there is more focus on sustainable development. One of the most important things that people all over the world are looking into is how to make the best use of energy while trains are running.

Modern railways have 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 [1][2]. Many studies have looked into these methods, and many of them have led to real-world applications that successfully recover braking energy and send it back into the system for reuse [3][4].

However, in countries like Sri Lanka, where the railway routes are short and the elevation changes are tiny, these kinds of regenerative energy recovery methods have not been studied. It wasn't been possible to measure or use the energy lost during dynamic braking in Diesel-Electric Multiple Units (DEMUs) yet [5]. This braking energy is currently just turned into heat and let out through resistor banks, which is a significant waste of energy that could be used again.

Previous studies have shown that one of the best ways to make rail systems more energy efficient is to improve the way they capture and store energy [6]. To use these ideas in Sri Lanka, first we need to find and measure the energy losses that happen during normal train operations.

1.2. Aim, Objective and Scope

1.2.1 Aim

To perform feasibility study on efficient and sustainable energy recovery system to capture the energy released during dynamic braking in DEMUs.

1.2.2 Objective

- Evaluate dynamic braking and energy recovery methods to determine the feasibility of energy storage in non-electrified locomotives.
- Gather and study data on regenerative braking in S14 DEMUs, then create optimized data models that connect braking patterns with energy dissipation for feasibility study.
- Develop a battery storage solution to effectively capture and reuse a part of the recovered braking energy.
- Evaluate system performance in terms of fuel, cost, and emission savings, and propose scalability for future locomotives.

1.2.3 Scope

- The study examines Class S14 DEMUs functioning on Sri Lanka's upcountry railway line due to their significant dynamic braking intervals.
- The study focuses on the S14 DEMU for feasibility analysis, with findings also applicable to S12 DEMUs due to their similar braking systems and operating conditions.
- The study examines energy recovery based on existing driving behaviours and braking actions without altering the locomotive's fundamental design or operating methods.
- Long-term forecasts encompass cost reductions, enhancements in fuel economy, and decreases in emissions, so enhancing future sustainability efforts in non-electrified railway systems.



Figure 1.1: Class S14 DEMU operating on Sri Lanka's upcountry railway line

1.3. Thesis Overview

This dissertation focuses on whether it is possible to reutilize braking energy from DEMUs, with an emphasis on those that run along Sri Lanka's upcountry railway line. The study's purpose is to perform feasibility analysis on working and long-lasting energy recovery system that works well in the area because these rails are not electrified.

The study begins with a close look at how energy recovery technologies are used across the world. This gives previous research information that need to uncover gaps and opportunities which could be used in Sri Lanka. Next, we need to find out how much energy is lost when Class S14 DEMUs perform dynamic braking. This is done by carefully looking at the locomotive operational data, electrical circuit diagrams, technical documents, and test results from the past.

Using MATLAB's curve-fitting function, the study finds key connections between how braking power engages in energy wastage. These ideas help to perform feasibility study on an energy storage system from the start, by setting up the correct battery pack. At initially, battery specs were based on information from battery manufacturers. After that, MATLAB's battery design toolkit was used to develop proper battery storage design which also can be further optimized in later stages. A Computer Aided Design (CAD) model of the passenger compartment helps in planning where to put

and store the battery storage system in the train by integrating facts discovered within the research.

The suggested system is crucial because it can work without modifying the underlying structure of the DEMU. Suggested system includes a regenerative braking system that uses some of the energy that would have been wasted to power other devices on board. We chose a battery-based energy storage system because it has been widely and successfully used in transportation industry.

In order to assess the feasibility and economic viability of the proposed system, this research looks at long-term estimates of how much energy it will save and experimental confirmations. The results show that costs and emissions will go down by a significant amount over the next 10 years and within a payback period of less than 4 years. The dissertation ends with a summary of the main findings and suggestions for further work, with a focus on making non-electrified railway operations more sustainable.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

With an emphasis on non-electrified networks like those in Sri Lanka, this section provides a thorough analysis of the current understanding of braking energy and energy recovery in the railway sector. An overview of the railway industry is given at the outset, stressing its significance and the increasing focus on sustainable practices. After that, the idea of braking specifically, dynamic and regenerative braking is thoroughly examined, along with how these techniques work to control train energy and speed.

To determine how regenerative braking has been applied globally and the various contemporary strategies available in the Sri Lankan context, a comparative analysis has been provided. Waste energy recapture from regenerative braking has revealed an obvious gap considering Sri Lankan context compared to the global applications. That comparative analysis outlines the urgent need to quantify energy loss from braking energy for Sri Lankan DEMUs, in order to develop sustainable responses.

The review further addresses the concepts and technologies associated with energy recapture, namely the concept of storage and reuse associated with rail transport systems. The literature review assesses different battery storage systems and chemistries, particularly, LFP, along with other possible battery chemistries based on energy density, life cycle, and applicability to rail. Safety standards, thermal management and operational reliability of battery systems in mobile settings are also addressed in this section.

Section ends with review findings, the research identifies a significant research gap. That is, no proper studies have been performed to measure the braking energy waste for any of Sri Lanka's non-electrified trains. In addition, there are no readily available practical ESS ready to be fitted to these trains and then demonstrate the recovery and reuse of lost energy. The section concludes with a list of relevant key points and details how this study extends existing work to provide a practical and sustainable solution for energy recovery and reuse in Sri Lanka's rail sector.

2.1. Introduction to Railway Industry

Locomotive engines at Sri Lanka Railway Department come as: diesel hydraulic, and diesel electric, with most being diesel electric. Historically, steam locomotives were predominant until the advent of diesel-electric locomotives, which use diesel engines for electric transmission. Over nearly 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 [7].

Because of their high capacity, dependability, and safety, railroads continue to be the greatest choice for moving heavy loads over long distances, even in the face of the expansion of road transportation. High-autonomy electric locomotives provided by electrified rail systems make rail transportation a more environmentally friendly option for freight transportation than trucks, airplanes, and ships [8]. 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; fully electric locomotives, on the other hand, exhibit a much higher efficiency, with values ranging from 85% to 90% [9]. Because of this significant disparity in energy efficiency, many nations have made electrifying their railway networks a top priority and are increasingly using fully electric locomotives for both passenger and freight transportation. Figure 2.1 shows an electrified rail operation.



Figure 2.1: Electrified railway track with an electric locomotive in operation [10]

Sri Lankan Railways (SLR), one of the oldest railway systems in Asia, which is more than 160 years old by now. Beginning from the steam engines then it moved to diesel-hydraulic locomotives and diesel-hydraulic multiple units. There after DEMUs came into action. Before the COVID-19 outbreak, 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 [5]. 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 [5]. The locomotive and carriage fleet has recently expanded with the addition of new DEMUs, locomotives, and carriages. Currently, the locomotive fleet considering the capacity of SLR is presented in table 2.1:

Table 2.1: Locomotive fleet of Sri Lanka railways [11]

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									

As mentioned earlier, approximately 60% of the total locomotive fleet is in daily operation. However, Sri Lanka currently does not have any electrified rail tracks, Electric Multiple Units (EMUs), or fully electric locomotives. Within the locomotive fleet, Diesel Multiple Units (DMUs) can be categorized into two types: Diesel-Electric Multiple Units (DEMUs) and Diesel-Hydraulic Multiple Units (DHMUs). With the exception of the Class S8, which is classified as a DHMU due to its fully mechanical hydraulic transmission system, all other DMUs in operation are DEMUs.

To elaborate on the engine configurations, the MTU V12 396TC13 and MTU V12

396TC14 engines are fitted to the S8 and S9 classes, respectively. Both are part of the MTU V12 3900 series and have a lot in common. 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 diesel electric and diesel hydraulic locomotives.

2.2. Braking and Regenerative Braking

To halt a moving train, its kinetic energy must be dissipated, typically by converting it into heat through friction. This is achieved by pressing brake pads or blocks against the wheels or discs. Most trains use compressed air systems, known as air or pneumatic brakes, to control the brake application, release, and holding. This system is widely used all around the world [12].

Apart from the conventional braking “Dynamic braking” is also used by the trains. Dynamic brakes dissipate electrical energy by converting the kinetic energy of a train's rotating wheels, which slows it down. Dynamic braking may be finely controlled in downward motion more than air brakes because it is powered by electrical energy rather than friction [4]. The traction motor's reduced turning ability caused by the dynamic brake grids causes the vehicle to slow down. Regenerative braking, as opposed to traditional dissipative braking, has the significant advantage of saving brake maintenance costs by converting a significant portion of the train's kinetic energy into electric power without releasing it onto the pneumatic brakes' friction surfaces [4]. The history of electric traction motors in locomotives and the history of dynamic brakes in locomotives are closely related with each other [12].

Regenerative braking, which involves switching the propulsion machine's operating mode from motor to generator, is an interesting technology for efficiency improvement. It is possible for both; electric locomotives and diesel electric locomotives equipped with electric traction motors [13]. This method is specifically applied in electric vehicles and in hybrid vehicles that we use in our day today life, in order to get the maximum utilization of available energy. High-tech components like

sensors, additional storage units, and inverter circuits can be used to improve the efficiency of EVs [14]. Nevertheless, these technologies have the potential to complicate EVs and raise the overall cost of EV production [14]. Battery-powered EVs can effectively increase their driving range by utilizing regenerative braking. A similar application can be used for diesel-electric locomotives and DEMUs during the dynamic braking process. Figure 2.2 illustrates the major components inside a DEMU.

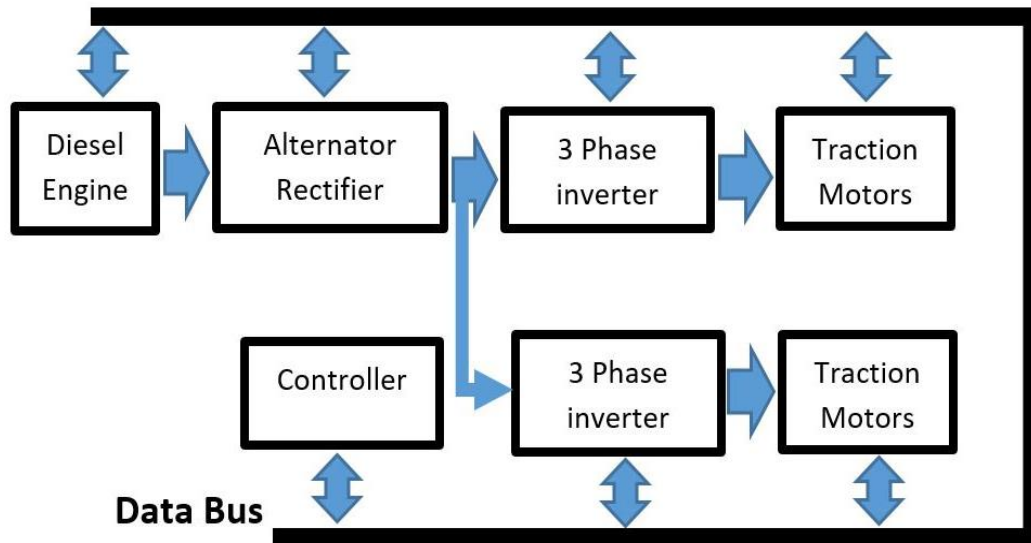


Figure 2.2: Block diagram of the power car of a DEMU [15]

In the fully electrified rail tracks the energy produced during braking (regenerative energy) can be fed back into the power supply system and reused by other trains on the same track that are accelerating at the time [9]. If there are no trains available to use this energy immediately, it can be stored in batteries for later use [9]. These storage batteries can be installed either onboard the train or by the side of the track (wayside storage) [9].

Another study shows that in diesel-based hybrid locomotive systems, the primary power source is a diesel engine supported by battery packs during periods of high power demand, where the diesel engine drives an electrical generator that either powers the traction motors or charges the energy storage system when surplus energy is available, and during dynamic braking, this generator recovers energy to recharge the batteries, allowing additional power during peak loads and enabling the use of a smaller, more efficient diesel engine, as illustrated in Figure 2.3 [9].

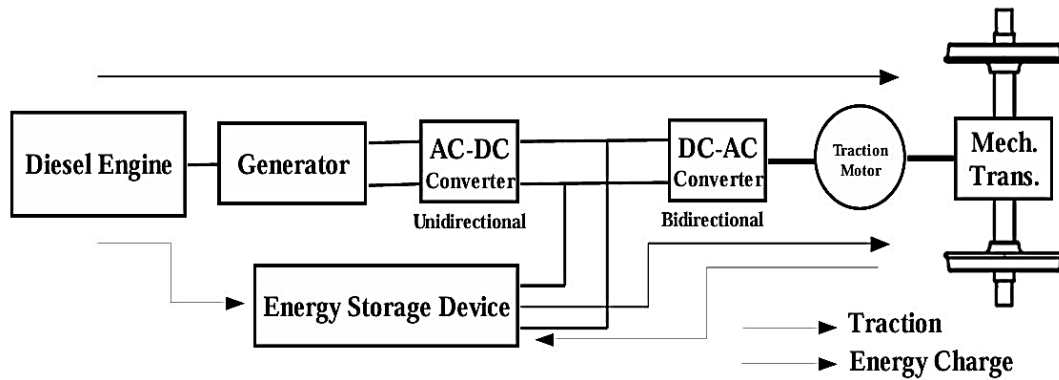


Figure 2.3: Schematic of a diesel-based hybrid locomotive powertrain [9]

2.3. Comparative Analysis of Regenerative Braking in Sri Lankan Locomotives against Global Standards and the Need for Energy Quantification

In locomotives, engines that usually move the train switch from motors to generators during regenerative braking, which changes mechanical energy into electrical energy. In Diesel Hydraulic Locomotives, dynamic braking happens when a flywheel rotor makes the hydraulic clutch move in a way that acts as a brake, especially in W-class engines used in the upcountry region [5].

Most railroad locomotives in Sri Lanka have the capability of dynamic braking, where the energy converted during braking is dissipated as heat through resistor grids instead of being utilized. This process, particularly used in upcountry regions for train control, involves converting kinetic energy into heat, which is wasted. Drivers in suburban areas often forget to use dynamic braking, which wears out the brakes and makes them less effective. So, even though regenerative braking could save energy, the Sri Lankan railway system doesn't get any of these benefits due to existing operation system.

The use of energy recovery technologies in electrified railways, as described in the literature, does not fit with the situation in Sri Lanka. Sri Lanka has problems because it does not have as much technology and resources as other countries do. Most of the research has been done in Brazil, the USA, Australia, and Canada, where diesel electric locomotives mostly move goods. These countries have longer tracks and a lot of variation in terrain. These conditions are different from those in Sri Lanka, where the

rail tracks are shorter and the terrain is less varied. Because of this, these technologies need to be changed to fit Sri Lanka's unique conditions, which include short distances and less varied terrain. Also, Sri Lanka needs to find ESS that are cost-effective and can be used effectively.

The first step in analysing energy recovery and storage systems is to figure out how much energy is being wasted and other energy-related data. This quantification provides a clear understanding of energy losses, enabling the optimization of energy recovery and storage methods. To date, no major research or investigation has been conducted to quantify the energy wastage occurring during the dynamic braking process specifically in the Sri Lankan context. This research initial focus is on quantifying energy wastage data in order to address this gap and lay the groundwork for effective energy recovery and storage solutions.

2.4. Energy Recapturing, Storage, and Reuse

The current trend in railway development has resulted in a growing interest in the energy optimization of railway systems, particularly with regard to the braking phases. Interactions between the electrical infrastructure and the loads represented by railway vehicles, as well as all the sub-systems connected to distribution and smart energy management, such as ESS are specially highlighted [4]. ESS deployment is a key strategy for optimizing a distribution network's energy efficiency. Optimal placement, sizing, and operation can significantly enhance the overall performance of the network [16]. Modern battery-powered electric vehicles still face numerous challenges [17]:

- (1) Methods for increasing the energy density of the batteries used for regenerative braking
- (2) Strategies for maximizing the driving range of EVs and extending the life of their batteries
- (3) Strategies for meeting the energy needs of EVs in both steady and dynamic states

The same issues can be applied for locomotives. When the track is not electrified, the energy from regenerative braking needs to be stored on board.

Several case studies from global railway industry leaders demonstrate the practical applications and benefits of energy recapturing, storage, and reuse technologies in locomotive systems.

A series of studies conducted on electrified rail systems demonstrated that various energy recapturing and storage strategies such as train timetable optimization (up to 14% savings), speed profile optimization (7.31%), and their integration (up to 21.17%) along with technologies like onboard ESS (8% –35.8%), wayside ESS (up to 30%), flywheels (31%), and reversible substations (up to 13%), significantly improve system efficiency, while energy storage options including lithium-ion batteries, super capacitors, and flywheels offer high efficiency (85% – 95%), long cycle lives (3,000 – 50,000 cycles), and diverse energy densities, and also contribute to voltage regulation by reducing sags up to 30% and peak power demand by 20% [18]. Although these findings are specific to electrified networks, they provide valuable insights into the energy-saving potential of regenerative braking and its supporting technologies.

Another study, which examines the feasibility of converting diesel-electric freight locomotives to battery-electric models in USA. This has identified that a 14 MWh battery pack (103 tons) can cover the average daily freight distance of 150 miles, while a larger 44.5 MWh pack (293 tons) extends the range to 425 miles (three times the average) and despite the added battery weight, battery-electric trains still consume 50% less energy than their diesel counterparts [19]. The conversion of freight locomotives to battery-electric or hybrid model is both technically feasible and economically viable, it can reach battery price reductions to \$50/kWh making the transition even more cost-effective, potentially saving \$250 billion over 20 years while significantly cutting CO₂ emissions and enhancing grid resilience though achieving these benefits will also require appropriate charging infrastructure and electricity tariff adjustments [19].

In 2002, Rail Power Technologies (Canada) introduced the first hybrid diesel-electric

switcher locomotive, “The Green Goat”. During field tests, the locomotive has been shown to operate more quietly and easily with reductions in fuel consumption of 30% to 80% and a reduction in harmful emissions of 80% to 90% compared to conventional switcher locomotives [9]. Accordingly, a hybrid locomotive consists of several major components and differ from traditional locomotive; such a conceptual design of a hybrid locomotive is illustrated by figure 2.4.

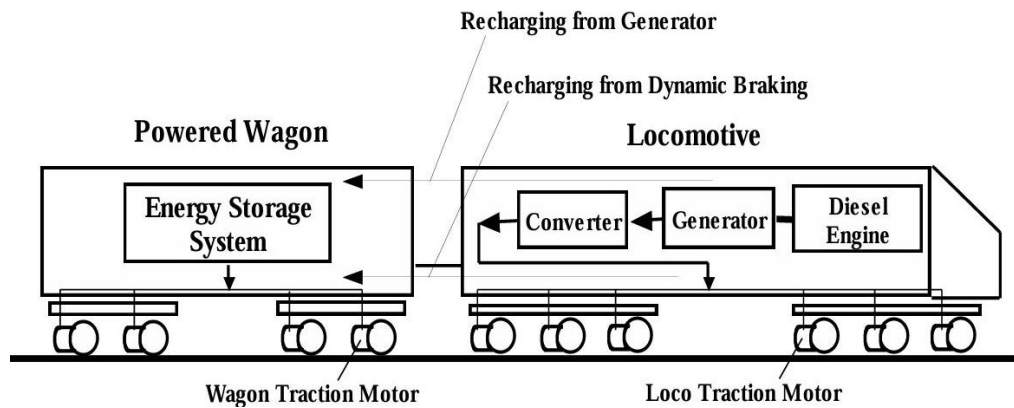


Figure 2.4: Conceptual design for hybrid powered freight train [9]

A case study conducted on a railroad locomotive operating in a mountain pass in North America revealed significant insights into energy wastage during dynamic braking. The study found that the total dynamic brake energy potential was 900 kWh per train [12]. Assuming a 30% energy recovery rate, it was estimated that 20 gallons of diesel could be saved per train and daily savings of 680 gallons of fuel, with a primary focus on reducing emissions [12].

Another research study revealed that integrating a Regenerative Electronic Stability Control (RESC) system into hybrid vehicles resulted in energy savings of at least 3%, with calculated energy consumption and recovery rates between 4kWh to 5 kWh per 100 km depending on the transmission and RESC configuration findings that could similarly be applied to hybrid locomotives for improved energy recapturing, storage, and reuse [20].

Another simulation-based study conducted on a realistic mountainous rail route in Croatia demonstrated that the economic and environmental benefits of hybridizing a conventional 1.6 MW diesel-electric locomotive by refabricating it with a BESS, revealing that the battery-hybrid diesel-electric locomotive achieved a fuel saving of

453 liters per round trip equivalent to a 16.47% reduction in fuel consumption compared to the original 2750 liters and resulted in approximately a 16.6% decrease in GHG emissions [21]. The size of Croatia is comparable to that of Sri Lanka, this finding is particularly relevant and can be effectively incorporated into this study.

HITACHI has been actively developing battery-powered railway systems since 2001 to enhance energy efficiency and reduce CO₂ emissions [9]. Using a bank of 48 lithium-ion battery modules (each rated at 1 kWh), regenerative energy captured during braking is stored and reused. Studies discovered that up to 80% of regenerative braking energy could be recovered, resulting in a 20% reduction in fuel consumption [9].

Another study based on MATLAB simulation on the Altaria intercity train along the Madrid–Cartagena route in Spain found that the hybrid Alvia service reduced fuel consumption by 12% compared to the conventional Altaria diesel service, with the help of braking energy recovery improving efficiency by 10% [2]. In addition to that, it found that hotel loads such as Heating, Ventilation, and Air Conditioning (HVAC), lighting, and onboard services which account for 10% –30% of total energy use could also be partially powered using energy recaptured through regenerative braking [2]. This study proposed two energy efficiency strategies for diesel-electric locomotives: first, using ESS like super capacitors and batteries to recover braking energy, which improved fuel efficiency by 9.5% and 7.3% respectively, resulting in annual savings of approximately €95,000 per train (Super capacitors) and €73,000 per train (batteries); and second, downsizing the diesel engine from 2.2 MW to 1.4 MW with ESS support, allowing hybrid operation that maintains power output while reducing fuel consumption [2]. Hybridization enables energy recovery from braking and efficient load balancing between diesel generators and onboard ESS, which helps reduce fuel consumption and cut emissions by 10% – 15% on low to medium-traffic railway routes [2].

Studies show that optimizing train timetables, particularly when combined with speed profile adjustments; not only reduces peak power demand by shifting acceleration cycles but also significantly improves regenerative energy utilization, as demonstrated in the Beijing Metro case study, which achieved a 21.17% energy reduction compared

to conventional scheduling and a 6.35% improvement over speed profile optimization alone; furthermore, while timetable optimization can yield up to 14% energy savings and reversible substations can contribute up to 13% by feeding recovered braking energy back to the grid, these benefits are only feasible in electrified rail systems where energy recapture and redistribution depend on an interconnected electrical infrastructure [18].

A simulation-based study using MATLAB - Simscape and Modelica, validated on the “ETR 1000” high-speed train operating along the Florence–Rome railway line, showed that without an ESS, 50% of braking energy is wasted through onboard resistors; in this case by implementing an ESS enables recovery of up to 57% of that energy, significantly reducing overall energy loss [21].

A study on the Wanshengwei to Chebeinan section of Guangzhou Metro Line 4 showed that super capacitor based energy storage, using the “BCAP3000” model with an 8.08 kWh capacity, is highly effective for capturing regenerative braking energy approximately 7.4 kWh per event; thanks to its high power density, fast charge/discharge rate, long lifespan, and compatibility with the 1500 V traction network, and is particularly well-suited for metro systems where both power demand and regenerative energy levels are relatively low [22].

Another research on the Brazilian railway system for iron ore transportation, considering geographical features and 28-hour round trips over 12 trips per month, discovered that energy consumption without recovery was 78,740.54 kWh, while with energy recovery, it was 59,948.42 kWh [13]. This reached an energy savings of approximately 23.87%; further this finding clearly highlights the potential energy savings from regenerative braking [13].

Another study has shown that battery systems can absorb up to 63.3% of regenerative braking energy (depending on battery chemistry), contribute up to 23.1% of the total traction energy in battery-assisted locomotives, and enable overall energy savings of 12% – 20% per train cycle through the integration of regenerative braking [23].

Based on a research project on evaluating the performance of a Battery Electric Locomotive (BEL) operating in a hybrid consist with two “Tier 4 Wabtec ET44C4”

diesel locomotives over 17 round trips on a 375-mile route between Barstow and Stockton, California, validated that battery-electric hybrid locomotives are both technically and economically feasible for freight operations, achieving \$18,600 in net cost savings over three months, 12% fuel and emissions reductions [24]. In addition to that that research confirmed further improvements in battery charging and energy management could enhance efficiency and long-term benefits [24].

Energy storage technologies in railway systems primarily include wayside energy storage systems and onboard energy storage systems, with examples such as a 2 MW/400 kWh nickel-metal hydride battery installed at Washington DC Metro's West Falls Church substation in 2013; comparative studies show reversible substations have high infrastructure costs but medium energy recovery, off-board ESS offer medium costs with high recovery, and onboard ESS provide low infrastructure costs, high energy recovery, and enable catenary-free operation [25]. Based on another study it has revealed that battery electric train conversions achieve up to 30% energy savings compared to diesel locomotives, while flywheel-based kinetic energy storage in New York City Transit demonstrated substantial annual savings (\$679,142) and emission reductions (873.4 metric tons CO₂), with a payback period of 5.33 years on a \$3.43 million investment [25]. Additionally, diesel-to-battery-electric conversions reduce fuel costs by 50–60%, saving approximately \$600,000 annually per locomotive and cutting diesel fuel consumption by 2.5 million gallons fleet-wide [25]. It is clear that these studies highlight that by linking regenerative braking with advanced energy storage technologies such as onboard batteries, flywheels, and reversible substations can reduce energy consumption by 14–30%, yielding significant environmental benefits and multi-million-dollar savings for rail operators[25].

With these studies, it is evident that huge amount of energy can be recovered through the proper re capture of the regenerative braking.

2.5. Different Battery Storage Systems and Battery Chemistries

In recent years, battery storage systems have become a major part of modern energy solutions across many technical fields, such as transportation, renewable energy, and in industrial power systems. The increasing demand for cleaner energy, improved

energy efficiency, and the reduction of the use of fossil fuels has driven significant development in battery technologies and their applications. Starting from electric vehicles in the automotive industry up to the level of stabilizing power grids in the energy sector, battery storage systems now play an important role in making energy use more sustainable and reliable.

The selection of proper battery storage system depends largely on the specific application, operational conditions, and performance requirements. Different kinds of battery chemistries; such as lithium-ion, lead-acid, nickel-metal hydride, and emerging technologies like solid-state and flow batteries offer many kinds of advantages and limitations in terms of energy density, lifespan, charging efficiency, environmental impact, and cost.

This section explores about the different types of battery storage systems and their underlying chemistries, with a focus on their practical applications in key industries. They are specially considered with their role in electric traction systems, automotive electrification, and large-scale energy storage, providing a foundation for understanding their suitability in harnessing regenerative braking and energy storage and utilization in railway operations.

2.5.1 Battery Storage Systems

The field of electric mobility (e-mobility) has developed at a fast rate over the past three decades, with battery costs reducing up to 98% and storage capacity increasing by a factor of three to four times, these levels exceed earlier expectations, and in general, these advancements aim to produce batteries that can store maximum energy in a compact and lightweight form, which are also low-cost, long-lasting, made from non-toxic and sustainably sourced materials, and capable of being charged and discharged safely and efficiently [26].

From the context of the present study, it is clear that train braking systems generally combine regenerative and resistive braking. Regenerative braking is used to recover energy, but if the battery storage system cannot absorb the excess energy, a braking

chopper is activated at a predetermined voltage to divert the excess energy to resistors, where it is eventually released as heat, resulting in energy loss.

There are four common types of ESS; battery, flywheel, super capacitor, and hydraulic accumulator with BESSs further classified into onboard systems, which store regenerative braking energy which can achieve 15% to 30% savings in traction energy after optimization [27]. However, battery energy storage stands out as the most promising due to its versatility in both onboard and stationary applications but the widespread use of batteries are limited due to drawbacks such as high cost, limited lifespan, low power density, and environmental concerns [27]. The most flexible and practical solution for effective, scalable, and sustainable energy storage in contemporary rail and transportation systems is optimized battery systems, despite obstacles like limited lifespan and cost [27]. In contrast, flywheels offer high power density but suffer from complex control and short-duration storage, super capacitors offer fast charge-discharge cycles with up to 25% energy savings but face scalability issues, and hydraulic systems effectively convert kinetic to hydraulic energy but involve bulky components and complex mechanical setups[27].

A study, based and validated using simulation models developed in MATLAB-Simscape and Modelica, uses the “ETR 1000” high-speed train on the Florence-Rome railway line as a case study to compare different energy storage system technologies. This 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 [28]. However onboard Li-ion systems reduce transmission losses but harness less energy due to weight and space limitations [28]. 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 to Li-ion systems, with stationary Li-ion batteries recovering up to 222 kWh per braking cycle and onboard Li-ion systems storing 164 kWh per cycle [28]. Through overall analysis, the installation of ESS can reduce total traction energy demand by 10% - 15%, with stationary solutions outperforming onboard systems due to their higher energy storage capacity [28]. In this study both wayside and onboard storage

systems are considered, as the rail, system is electrified, enabling the application of wayside storage.

Norfolk Southern (NS) and Penn State University evaluated lead-carbon and lithium-ion (Li-NMC) batteries for hybrid locomotive applications, concluding that Li-NMC is the most suitable due to its higher energy density, longer cycle life, 26-hour runtime, and minimal degradation (0.2% per cycle), compared to lead-carbon batteries which degraded by 50% in one year and lasted only 4.5 hours; performance was validated through simulations [29]. Hybrid Pulse Power Characterization, and both Software- and Hardware-in-the-Loop testing, with field trials showing energy savings of 8% – 15% and higher efficiency in hilly terrain (15%, 8.1 MWh) than flat terrain (8%, 3.6 MWh), though successful implementation requires advanced thermal management and remains economically unviable without subsidies unless battery costs fall to \$500/kWh and fuel prices reach \$4.00/gal [29]. Figure 2.5 to figure 2.7 shows the battery storage system discussed above.



Figure 2.5: NS 999 undergoing testing at Rose Yard, located in Altoona, Pennsylvania [29]



Figure 2.6: Installed battery ISO container and intra pack battery trays mounted on the NS 999 locomotive [29]



Figure 2.7: Battery ISO container for the NS 999, produced by DropBox, Inc. [29]

Wayside ESS installations in cities like Dresden and Cologne (Germany) have resulted in a 30% reduction in grid power consumption, demonstrating the effectiveness of both onboard and trackside energy storage in improving system efficiency [18]. ESS implementations across various metro networks have demonstrated significant energy savings, with onboard ESS achieving 18.6% –35.8% savings in Brussels, 24% in Madrid, and 8% in Japan [18]. A study conducted on the Beijing Subway Batong Line

demonstrated that a proposed control strategy for wayside super capacitor energy storage systems significantly improved energy efficiency by dynamically adjusting charge and discharge thresholds to recover braking energy, that would otherwise be wasted as heat in resistors [30]. While also stabilizing traction voltage; compared to batteries, super capacitors provide higher power density for quick energy absorption, longer lifespan, and simpler voltage-based state-of-charge monitoring, whereas batteries offer higher energy density but suffer from shorter lifespans due to cycling degradation [30]. Hence, battery storage systems remain more practical and applicable.

A simulation study on a Croatian mountain rail route showed that retrofitting a 1.6 MW diesel-electric locomotive with durable, high-energy lithium-ion batteries reduced fuel use by 16.47% and cut greenhouse gas (GHG) emissions by 16.6% which was discussed earlier [21]. Table 2.2 gives more detailed explanation regarding the battery model used there,

Table 2.2: Specifications of Lithium-Ion cells and the complete battery system for the hybrid locomotive [21]

	No. of Cells	E (kWh)	Max Energy (Ah)	Max Power (kW)	Mass (kg)
Cell	1	0.06	15.9	0.4	0.63
Battery	15000	900	1192.5	6000	9450

The Totarabank case study in New Zealand demonstrates that Hybrid Energy Storage Systems (HESSs), combining batteries and super capacitors, improve efficiency, performance, and battery lifespan through reduced cycling stress, with advanced probabilistic planning and meta-heuristic optimization methods like the Moth-Flame Algorithm enabling better micro-grid scheduling and up to 20% cost savings though temporal energy arbitrage using LiFePO₄ batteries is not currently viable under local tariffs in New Zealand yet this system was designed for stationary grid and renewable energy applications, making it only partially relevant to locomotive use cases [31].

Modern battery systems are equipped with advanced features that allow them to

interact intelligently with their host applications such as electric vehicles, drones, photovoltaic systems, and power grids so their design must account for how these features behave under various operating conditions, while also carefully considering the integration of mechanical, electrical, and electronic components [26]. With this the overall battery layout plays a critical role in determining system cost, thermal management efficiency, ease of manufacturing, and end-of-life recyclability.

A research study investigated a novel lithium-ion battery pack layout for hybrid vehicles, including two arrays of cells and dual parallel air-cooling channels, and optimized its design using Computational Fluid Dynamics (CFD) simulations by analyzing temperature distribution and airflow velocity maps [26]. These also incorporate vibration analysis of the final assembly demonstrating how simulation-driven approaches can effectively guide both thermal management and structural design in advanced battery systems [26]. Figure 2.8 illustrates battery pack design consisted of key design parameters. These insights can be combined with future stages of battery system development of this research, where the driver's driving patterns are linked with BESS to optimize the overall system performance, which is not considered in the current context.

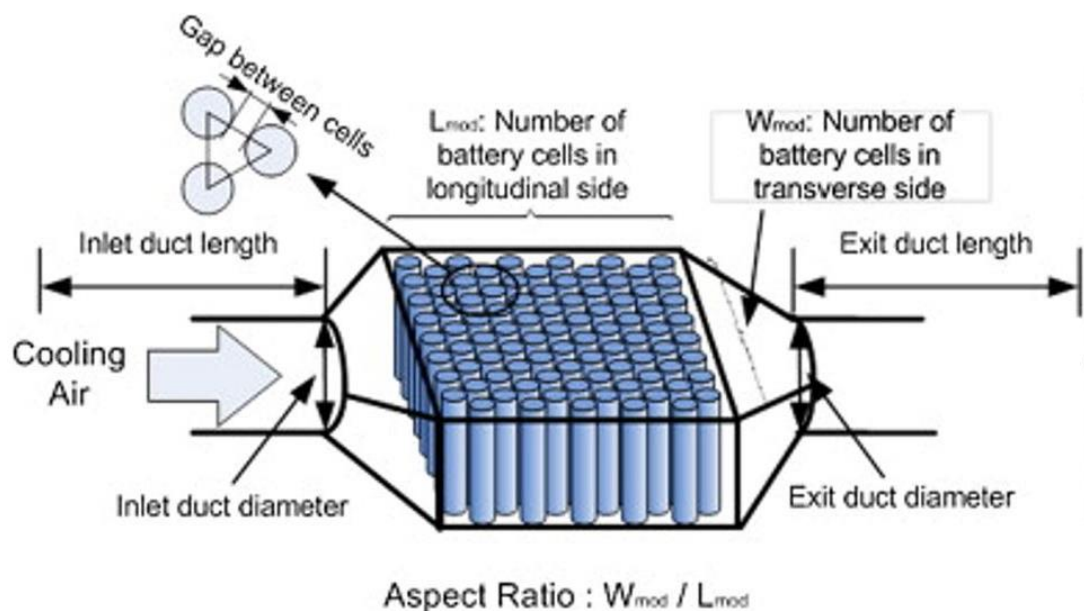


Figure 2.8: Key design parameters of the battery pack layout studied [26]

Both the assembly and disassembly process must be carefully taken into consideration in order to lower the overall cost and environmental impact of battery systems. Another study finds that battery packs account for about 30% of the total cost of an electric vehicle, so increases in assembly efficiency can directly reduce the price of final product. Design for Disassembly (DfD) which makes efficient disassembly, is crucial for component recycling and reuse, making it a crucial component in reducing lifecycle costs and ensuring sustainable end-of-life management [26]. Figure 2.9 shows the key parameters that has to be addressed during battery assembly process.

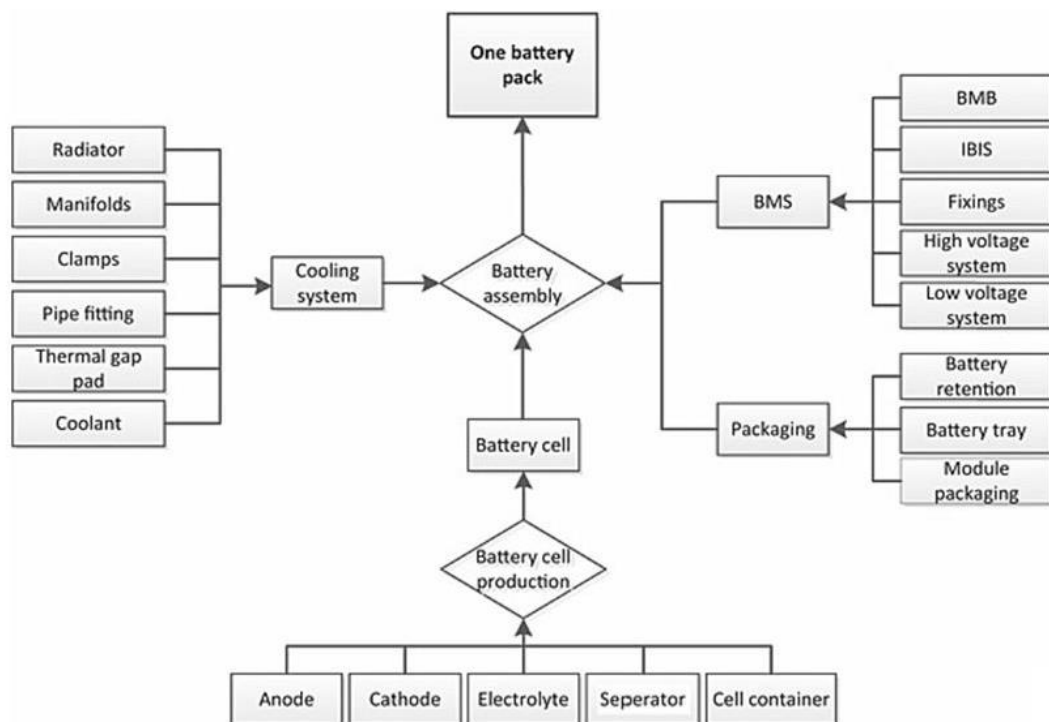


Figure 2.9: Simplified flow diagram of the battery system used in the life cycle assessment study (BMS – Battery Management System; BMB – Battery Management Board; IBIS – Integrated Battery Interface System) [26]

Furthermore, varieties of battery design methodologies are available to address challenges discussed above. The best design approach can be selected by proper examination of the benefits and drawbacks of each approach. But to perform that there should be clear understanding of the battery storage system, including all important factors that could affect the design. Although these methods are promising, their use

is outside the major scope of this study and might be investigated in later phases. Table 2.3 discusses several of these techniques.

Table 2.3: Comparative overview of seven battery design strategies [26]

Design Method	Key Features	Challenges and Constraints
Experience-Based Design	Relies on engineering expertise and 2D/3D CAD tools; treated as a configuration process.	Lacks algorithmic optimization and simulation integration; dependent on trial-and-error.
Simulation-Driven Design	Uses numerical and analytical tools with fewer physical prototypes for validation.	Often assumes worst-case boundary conditions; may overlook system-level interactions.
Design for X (DfX)	Improves assembly/disassembly; focuses on lifecycle, cost, and environmental impact.	Does not consistently include simulations or energy management strategies.
Thermal Focused Design	Explores cooling layouts and techniques validated by simulations and experiments.	Primarily addresses thermal aspects; limited multi-objective optimization.
Optimization-Based Design	Combines multi-objective and multi-physics analysis with surrogate models and evolutionary algorithms.	May neglect lifecycle or energy control strategies; complex setups can be time-consuming.
Model-Based Engineering	Enables full-system modeling and control simulation; useful for energy and strategy evaluation.	Doesn't use real-time data; lifecycle and manufacturing aspects often excluded.
ML-Assisted Design	Data-driven, high accuracy in state estimation, supports user-centered design.	Requires large datasets, offline training, and powerful computing; may limit design creativity.

According to earlier studies, battery technology innovations are crucial because they increase driving range, reduce charging times, lower costs, improve safety and dependability, and reduce their environmental impact [32]. Similar information needs to be reviewed for better storage options if battery storage systems are used in rail transportation.

Battery pack manufacturing is a complex and vital process that involves transitioning from individual cells to modules and finally to complete packs, requiring strict quality control, safety protocols, traceability, and scalability, along with integrated in-process

inspections, end-of-line testing, and compliance with industry certification standards to ensure reliable mass production [33]. According to Bob Galyen's five key principles for effective battery design, a well-designed battery must prioritize safety, deliver the required power and energy performance, have a lifespan that matches the intended application (such as over 11 years for electric vehicles), be cost-effective once safety, performance, and durability are ensured, and minimize environmental impact through recyclability to help conserve critical materials [34]. To make sure of safe, dependable, and effective battery operation in modern applications, the BMS and its supporting electronic controls are important because they protect battery cells from overcharging, over discharge, and voltage or current spikes while also preserving cell balance [34]. A battery pack is made of some components which work together, including cells that store energy, modules that provide mechanical support and electrical connections, a BMS that monitors voltage, temperature, and balances the cells, a thermal management system to prevent overheating or freezing, and a protective enclosure that guards against mechanical shocks, vibrations, and environmental conditions [34]. These factors also to be addressed when designing battery storages in this research. However, this can be taken in to deeper extents and for the scope addressed under this research some major parameters have to be considered.

Battery sizing is mainly based on both voltage and capacity, where series configurations define the total pack voltage, parallel configurations determine the overall capacity (Ah) and energy storage (kWh), and the choice of battery chemistry, such as Lithium Nickel Manganese Cobalt Oxide; NMC (Nominal Voltage 3.7 V), LFP (Nominal Voltage 3.2 V), or Lithium Titanium Oxide; LTO (Nominal Voltage 2.2 V) also decide the voltage levels [34]. In addition to that the power-to-energy ratio varies by application, with stationary storage systems favouring high energy and lower power [34]. However this needed to be addressed when sizing the battery storage by considering space availability with in the S14 DEMU when providing the recommendations for the battery pack in the next part of this research.

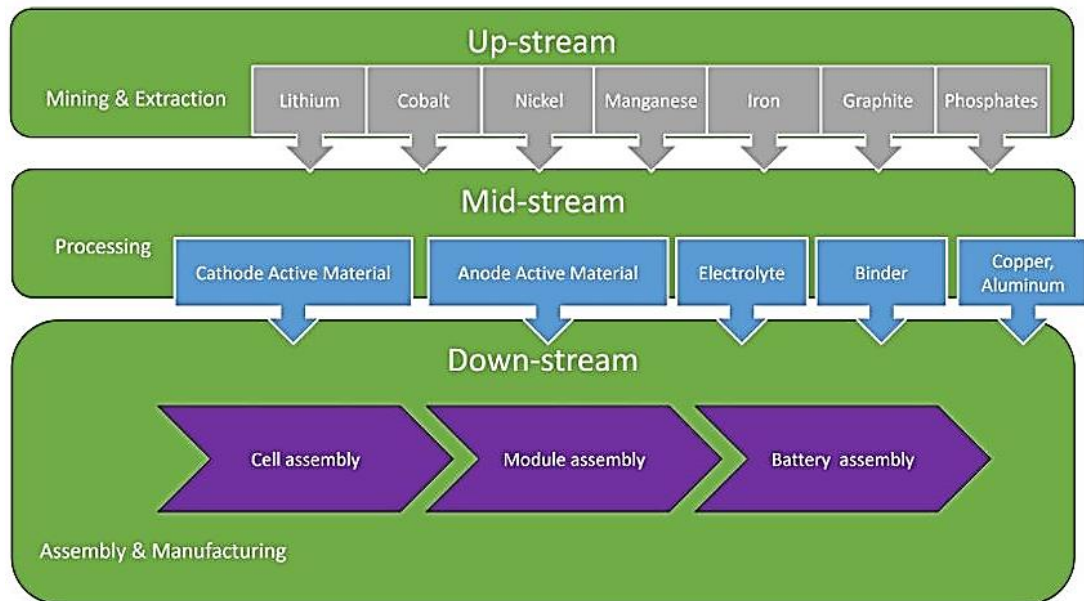


Figure 2.10: Stages of the battery supply chain, raw material processing, component manufacturing, and final assembly [33]

Figure 2.10 illustrates various stages of battery pack design and manufacture which elaborates the complexity of the whole process. Two major ways of battery pack design are Cell-to-Pack (CTP) and Cell-to-Chassis (CTC) methodologies, which widely used in the electric vehicle industry and hold potential for locomotive battery storage systems, with CTP technology by Contemporary Amperex Technology Co., Limited (CATL) enhancing energy density by 15% – 20% and reducing components by 40% through the elimination of traditional modules to lower production costs [35]. In other hand CTC integrate embedded cells directly into the vehicle frame for improved space efficiency and performance, aiming to achieve driving ranges over 800 km and targeted for commercialization by 2025 [35]. Major concern in battery module design is making sure that efficient and reliable cell-to-cell and module-to-module connections, since they are critical for minimizing energy losses, reducing material waste, and maintaining the required performance and safety conditions of the battery pack, with several connection methods commonly used to achieve these goals [35].



Figure 2.11: Interconnection layout for prismatic battery cells [35]



Figure 2.12: Structural arrangement of a pouch cell module [35]

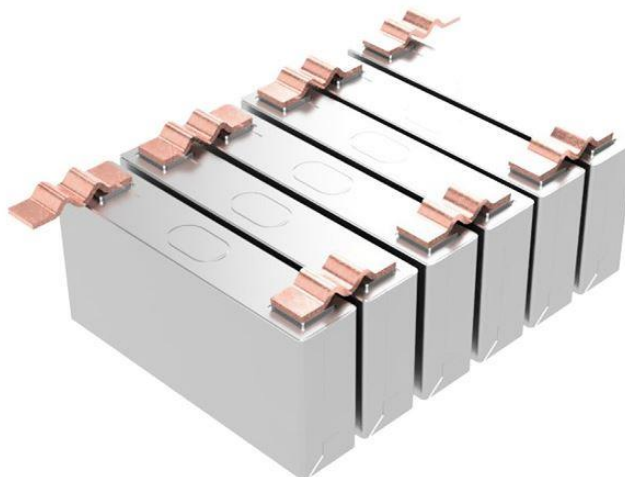


Figure 2.13: Configuration design of a prismatic cell module [35]

In battery module design, reliable cell-to-cell and module-to-module connections are essential, with welding techniques like laser, ultrasonic, and resistance welding providing strong, low-resistance joints; wire bonding used in cylindrical cells offers a lightweight solution that also functions as a fuse, while mechanical fasteners allow for easier disassembly but may loosen over time [35]. Figure 2.11 to figure 2.13 illustrates such kind of different connections in cell level and module levels. As discussed before effective thermal management is equally important, involving insulating foam for cylindrical cells, pressure management for pouch and prismatic cells to handle expansion and contraction, and the use of Thermal Interface Materials (TIMs), such as ceramic-filled polymers, to enhance heat dissipation [35]. These parameters also to be considered when designing battery packs after optimization when those designs are ready to manufacture. However, in this study the battery storage design does not reach up to such level hence deeper analysis will not be discussed.

When it comes to more developed and complicated, battery design methods some studies have optimized the battery design which takes deeper look in to battery modelling part which has to be addressed in the later stages of this research. The simplest start point of this method is shown by figure 2.14, which also can be in cooperated to the battery storage design stage of this research however, deeper analysis has to be continued for the later stages. Gradual process of such deep analysis is shown by figure 2.15.

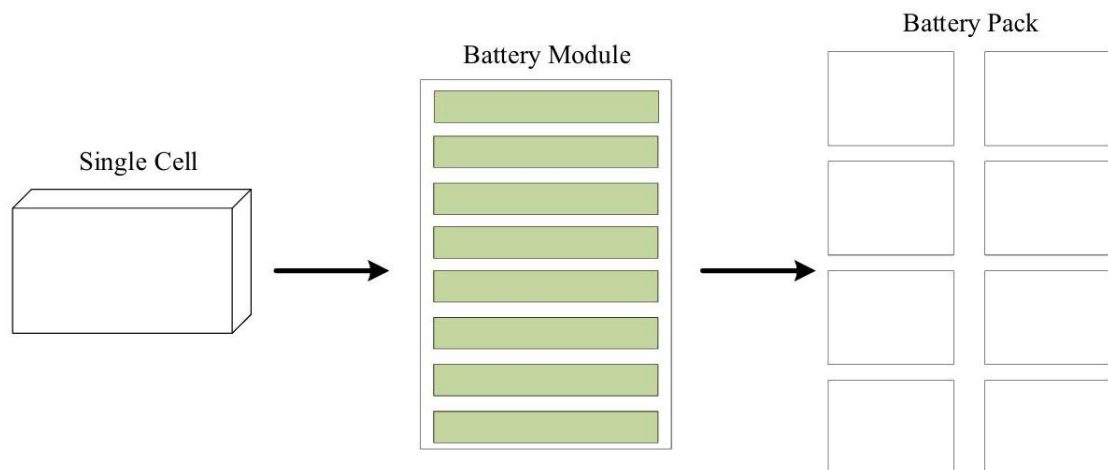


Figure 2.14: Step by step battery pack modeling process [36]

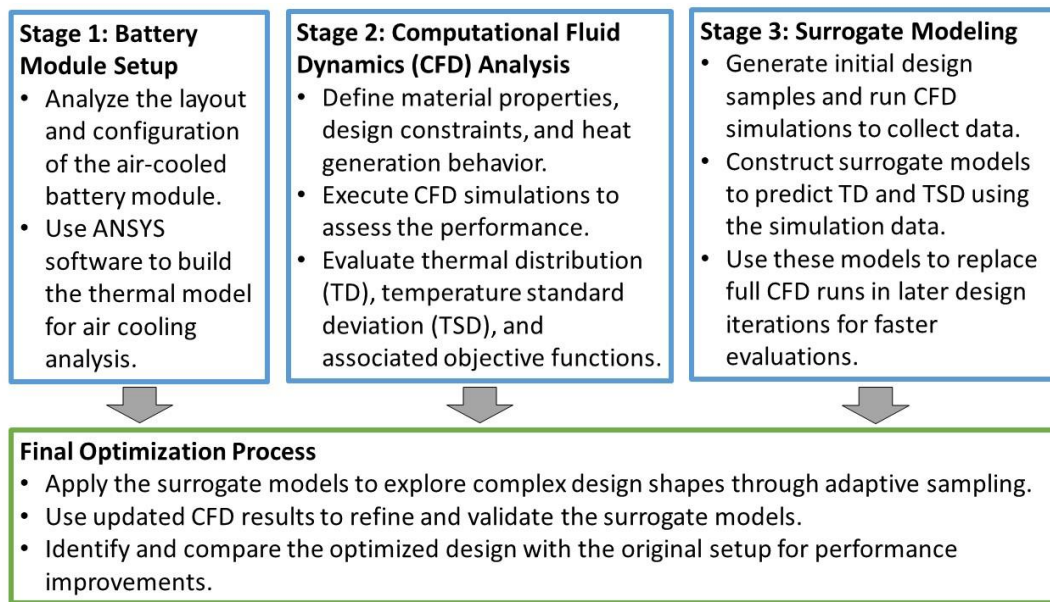


Figure 2.15: Framework for optimizing the design of an air-cooled battery module [36]

According to a study looking at the design, cost, thermal management, and structural aspects of modular EV battery packs, Robust Design Methodology (RDM) was used to identify the key technical requirements needed to implement effective modular battery solutions [37]. By 2018, battery costs had decreased from \$1000/kWh to \$210/kWh, according to this comprehensive study on EV battery pack design further reductions below \$100/kWh are required for market competitiveness, as prismatic cells are more affordable to assemble (\$0.0692/unit) than pouch cells (\$0.125/unit), and modular architectures provide additional cost savings through economies of scale [37]. In the other hand to stay competitive, these modular packs need to meet industry standards because structural and thermal factors are also quite important. EVs can lose up to 85% of their range in cold and hot locations without thermal management, and battery life drops by about two months for every degree Celsius above 30°C [37]. In other hand floor-mounted packs enhance vehicle handling, they increase the risk of impact damage, with cylindrical cells providing the best structural strength and packing density, and larger-format cells (Ex: Volkswagen e-Golf, BMW i3) delivering higher energy capacity without enlarging the battery pack footprint [37]. In order to remain competitive, this study concludes that reliable battery packs require effective thermal management and modular design because battery lifespan and performance

are highly sensitive to temperature, structural configurations like T-shaped or floor-mounted layouts influence safety and design trade-offs, while larger cells help lower assembly costs, reduce wiring, and minimize weight while cylindrical cells offer superior packing efficiency and structural strength [37]. This highlights the fact that modular battery architectures not only reduce manufacturing costs but also enhance thermal stability and safety. Future research is required to optimize crash resilience, thermal control, and scalable design to meet changing market demands [37]. Meantime some of the key findings highlighted in this study can be linked with the current research in order to design the battery storage in proper manner for future recommendations.

The battery cells in a battery pack interact with integrated subsystems to ensure that the battery storage works well and is reliable. These subsystems include temperature control parts, mechanical and structural supports, control electronics, and auxiliary systems that help with safe operation, structural strength, and system performance. The integrated designs of these subsystems form the overall structure needed for reliable and efficient battery pack design. This should be considered in the later phases of the study when improving the battery storage system. It is clear from the literature review above, that designing a battery storage system is a crucial and complicated process that is strongly related to the most recent developments and uses. Artificial intelligence (AI) integration has become a crucial component in maximizing battery performance, especially in domains like battery management and thermal regulation. However, it is crucial to address the basic design principles first in order to develop a preliminary recommendation for a battery storage system. In order to further improve system performance, this fundamental strategy, which is based on the current research findings can subsequently be improved through more complex analysis.

2.5.2 Battery Chemistries

A comprehensive review of existing research on various battery chemistries and their applications was conducted. Based on this, a summary table (Table 2.4) has been compiled, presenting a comparative overview of different battery types, their key performance parameters, and suitable application areas.

Table 2.4: Integrated summary of battery chemistry technologies [9][21][26]
[32][38][39][40][41][42][43]

Battery Type	Energy Density (Wh/kg)	Cycle Life	Charge/Dis-charge Power Capability	Cost (\$/kWh)	Key Advantages	Key Disadvantages	Application Insights
Lithium Iron Phosphate (LFP)	100–160	4000–8000	2C to 10C, stable to 350–500°C	240	High safety, long life, low cost, thermal stability	Lower energy density than NMC	Grid storage, heavy-haul rail, industrial use
Nickel Manganese Cobalt (NMC)	150–260	2000–4000	High power (Needs thermal control)	575	High energy density, reliable performance	Costly, thermal risk, environmental impact (cobalt, nickel)	EVs, portable electronics; EMS can extend life
Lithium Titanate (LTO)	70–100	20,000 +	6C to 10C discharge	750	Ultra-fast charge, long cycle life, very safe	Very low energy density, expensive	High-frequency rail, e-buses, regenerative systems
Lithium Cobalt Oxide (LCO)	200+	500–1000	High power	High	Very high energy density	Poor safety, expensive	Consumer electronics
Lithium Manganate (LMO)	100–150	700–1000	Moderate C-rate	Low	Low cost, moderate energy density	Poor high-temp performance	Backup power, low-cost EVs
Solid-State (Future Tech)	300–500	>5000	Research level	To be Find	High safety, high capacity, compact	Still in development	Aerospace, high-performance EVs, advanced rail systems
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
Super Capacitor	2.5–5	Vey High	Ultra-fast (700–2000 W/kg)	High	Exceptional lifespan, high efficiency, power density	Very low energy density	Rail regenerative braking, high power peak shaving

Flywheel	5 MWh (max)	High	>3 MW output	High	Compact, low maintenance, fast output	Frictional/mechanical losses	Grid energy buffering, industrial and rail systems
Na-Zn Liquid Metal Battery	Theory Based (High)	High	High-temp ($\geq 557^\circ\text{C}$)	Low	Abundant materials, promising energy potential	High operating temperature required	Large-scale stationary grid storage

Further comparison with regarding different battery chemistries based on specific energy and specific power is shown in figure 2.16 below.

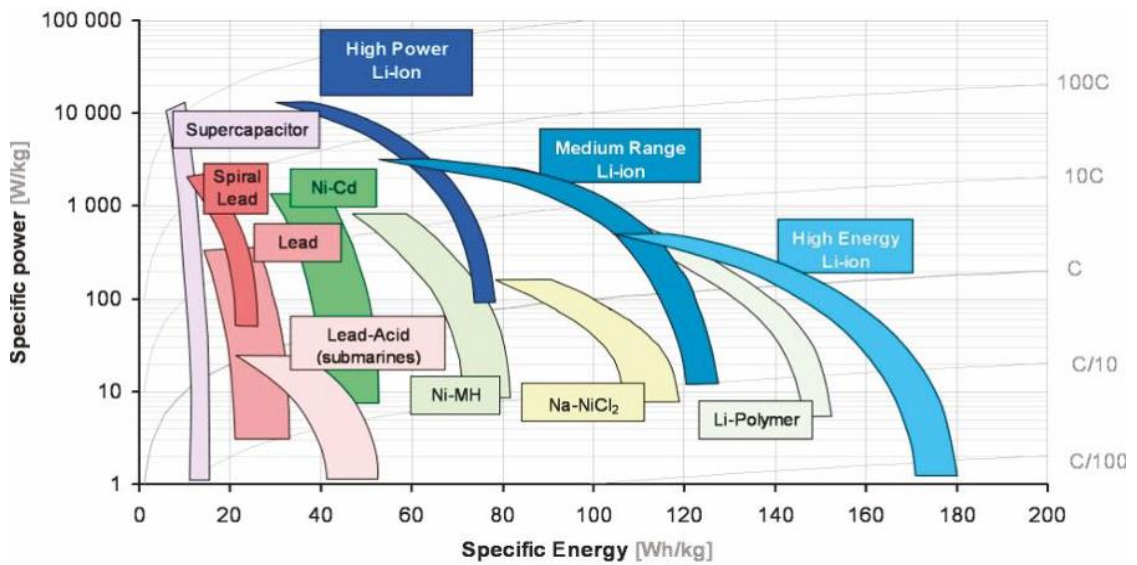


Figure 2.16: Battery chemistry comparison [23]

However hybrid battery-super capacitor systems enhance overall energy storage performance by improving reliability, extending battery lifespan, and lowering costs, as super capacitors boost efficiency by handling high power demands and minimizing the need for oversized battery banks, while probabilistic optimization methods enable more accurate and economically efficient system design [31].

When it comes to battery chemistries at the molecular level, some studies offer a clear and detailed understanding of lithium battery chemistries within individual battery cells. The combination of materials used in each component defines the chemistry of lithium-ion batteries. The electrolyte usually consists of a liquid organic solvent containing lithium salts like LiPF_6 , but research is increasingly focused on solid-state

electrolytes for improved safety and energy density [40]. Although newer materials like silicon and LTO (also known as lithium titanate) are being investigated for improved performance, graphite is typically used for the anode; the cathodes are usually composed of compounds such as lithium cobalt oxide (LCO), lithium manganese oxide (LMO), NMC, and LFP [40]. Figure 2.17 shows the behaviour and structural components of a lithium battery cell during charging and discharging.

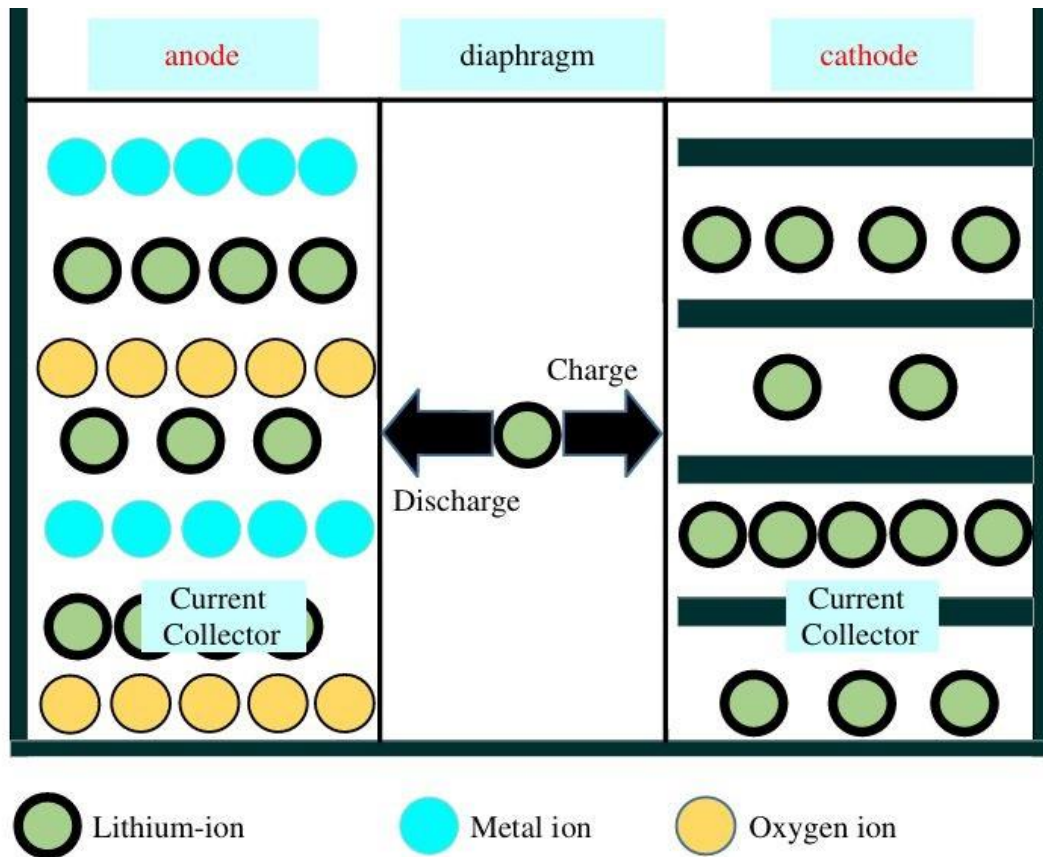


Figure 2.17: Conceptual layout showing the structural components of a Lithium-Ion battery cell [40]

Due to the high energy density and extended cycle life, lithium-ion batteries are generally considered to be the best option for rail applications. Furthermore, the dominance of lithium-based chemistries in a variety of industries is being reinforced by the quick developments in battery technology. 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. The quick development of lithium-ion battery technologies is depicted in Figure 2.18.

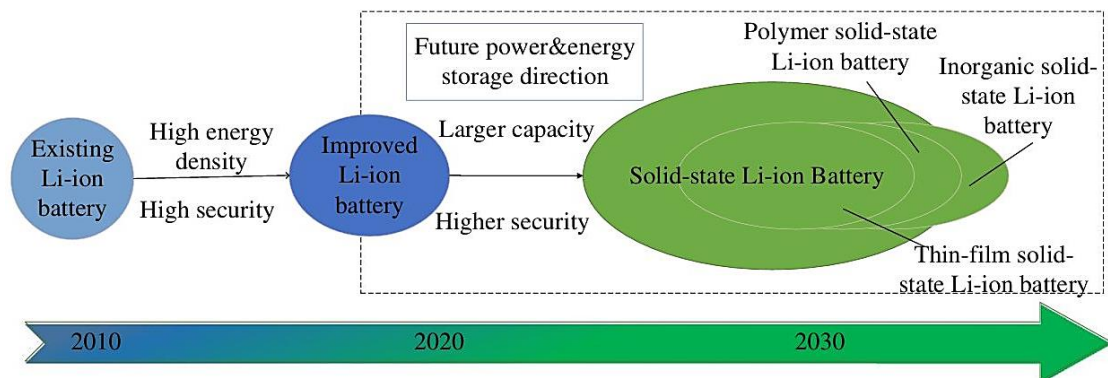


Figure 2.18: Emerging trends and innovation directions in Lithium-Ion battery systems [9]

Lithium-ion batteries because of their high energy density, efficiency, and long lifespan currently dominate the market for electric vehicles. However, newer technologies like solid-state batteries have the potential to improve safety and energy capacity, and alternative chemistries like lithium-sulphur and lithium-air show promise but are still constrained by commercialization issues [43]. Furthermore, temperature, charge-discharge cycles, and depth of discharge have a significant impact on battery lifespan and performance, necessitating the use of advanced thermal management systems [43]. While typical electric vehicle batteries now have a lifespan of 8 to 15 years with approximately 2,000 to 5,000 charge cycles and an annual degradation rate of 1% – 3%, advances in battery technology have significantly improved energy density from 150 Wh/kg – 250 Wh/kg in conventional lithium-ion batteries to 300 Wh/kg – 400 Wh/kg with silicon anodes and up to 400 Wh/kg – 500 Wh/kg in solid-state batteries [43]. Additionally, charging capabilities vary widely, ranging from 1.2 kW – 3 kW for Level 1 home charging, 7 kW – 22 kW for Level 2 public AC chargers, with advancements in electrode materials, such as silicon anodes and lithium-metal cathodes, can increase energy density by 30% to 50%, allowing and up to 350 kW with DC fast charging systems with efficient cooling systems [43].

Fast charging in lithium-ion batteries is primarily limited by material characteristics, charge transfer rates, and electrode microstructure [44]. However, by employing engineering techniques such as particle size reduction, electrolyte additive addition, surface coatings, and improved thermal management, the charging speed and overall performance can be significantly increased, paving the way for the creation of long-lasting, high-capacity batteries that are optimized for rapid electric charging [44].

The Norfolk Southern NS 999 hybrid locomotive project evaluated both lead-carbon and lithium-ion (Li-NMC) battery systems, ultimately finding that while lithium-ion batteries delivered superior performance, their high cost currently limits practical implementation [45].

High energy density, extended cycle life, and effective performance of lithium-ion batteries have made them the preferred option for modern applications like electric cars and portable electronics and; further improvements in electrolyte design and materials have given them an advantage over previous technologies [33]. However, continued research into alternatives like solid-state, lithium-metal, and sodium-ion batteries has been spurred by safety concerns about thermal runaway and environmental issues, especially the use of toxic materials like cobalt [33]. While recycling techniques continue to advance to lessen their ecological impact, these new technologies seek to improve safety, sustainability, and application-specific performance [46].

Over the past three decades, Lithium-Ion Batteries (LIBs) have undergone remarkable advancements, with costs dropping by 98% and energy storage capacity increasing up to fourfold, driven by improvements in battery chemistries [47]. Figure 2.19 illustrates the growth EV demand over years and figure 2.20 shows how the growth of lithium based researches have developed over years.

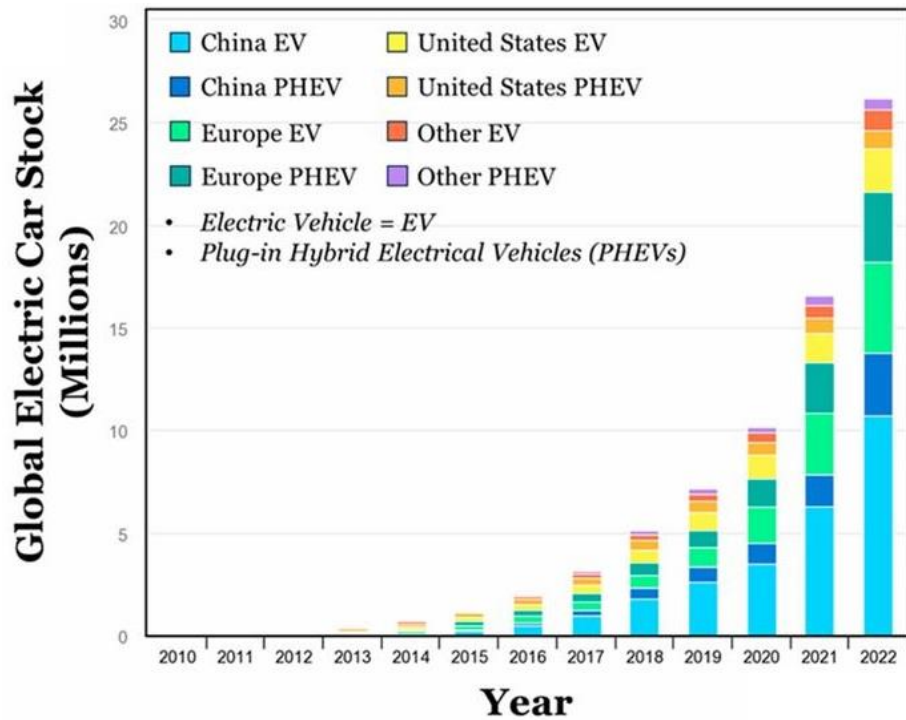


Figure 2.19: Visualization of the global increase in Electric Vehicle (EV) and Plug-in Hybrid Electric Vehicle (PHEV) [47]

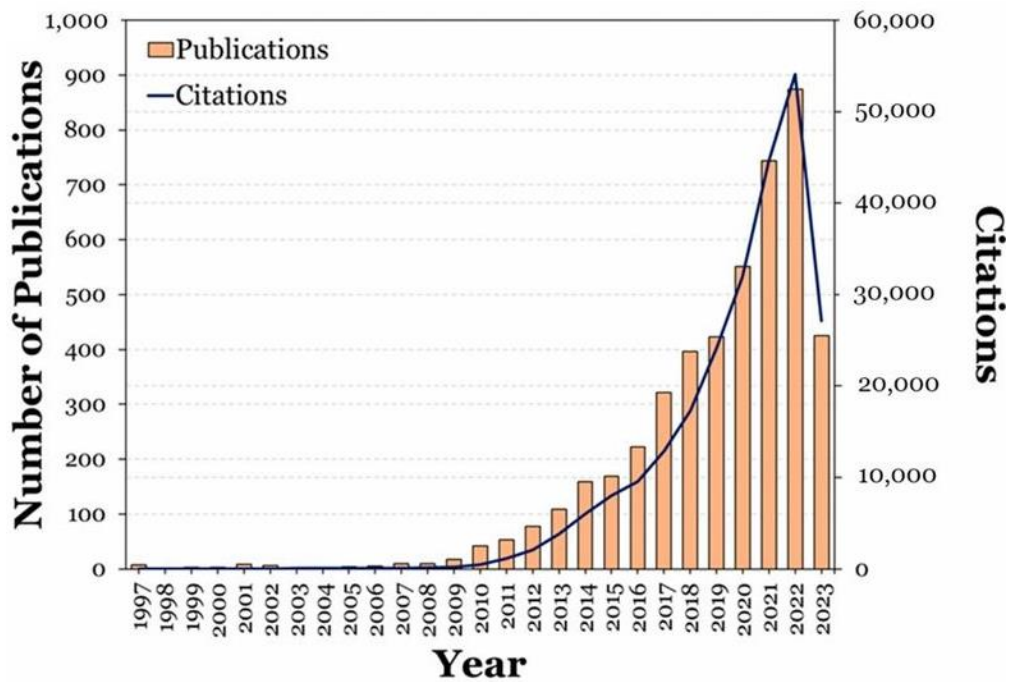


Figure 2.20: Trend analysis showing the growth in academic publications and citations related to Lithium-Ion batteries (LIBs) [47]

Electric vehicles primarily rely on LFP batteries for their safety, long cycle life, and affordability, while Ternary Lithium batteries such as NMC and Nickel-Cobalt-Aluminum (NCA) are preferred for applications requiring higher energy density and superior performance in low-temperature conditions [48].

However, the best choice for energy storage in rail applications that use regenerative braking among the battery types examined LFP. It provides the best overall balance of thermal stability, longevity, affordability, and safety; all of which are essential for railway systems based on the levels of energy harnessed during regenerative braking and the dissipation of stored energy. Its superior dependability and reduced environmental impact make it the most viable and sustainable option for rail-based BESSs, even though its energy density is marginally lower than that of some of the other battery chemistries.

2.6. Safety in Battery Storage Systems

Considering the high energy requirements, challenging operating conditions, and constant vibration and thermal fluctuations experienced during rail operations, safety of the battery storage system is a major factor in hybrid locomotive applications [29]. Batteries have higher possibility to failures like thermal runaway, vibration damage, or impact-related problems; hence, it is crucial that battery packs to be designed to withstand changing environmental conditions [26]. Epoxy-based polymeric adhesives are frequently used to link cells to the battery base structure in order to mitigate the above-mentioned risks and reduce high shock and vibration effects [26]. This creates a battery pack with lightweight and long-lasting, with good damping capabilities [26].

The risk of thermal runaway, short circuits, overcharging, and mechanical damage increases as battery systems especially lithium-ion chemistries are progressively linked with hybrid diesel-electric locomotives to improve fuel efficiency and lower emissions [47]. Advanced BMS, thermal control technologies, sturdy packaging, and rigorous adherence to charging protocols are all necessary to ensure safety [47]. Further improving the thermal and operational safety of ESS in locomotive applications is the goal of newer technologies like solid-state batteries and better cell

designs [40]. The American Public Transportation Association's (APTA) Recommended Practice for Transit Bus Fire/Thermal Incident Investigation has been adopted as a standard guideline for evaluating fire safety in existing passenger rail equipment [49]. In large-scale applications, thermal runaway may be caused by battery pack deformation, which highlights the importance of strong packaging design to prevent fire spread between cells [49]. Thermal runaway is a major safety concern in battery storage systems, particularly in lithium-ion batteries, where rising temperatures accelerate internal exothermic reactions among the electrolyte, anode, and cathode, creating a self-sustaining cycle of heat and pressure that can result in rupture or explosion [49]. Figure 2.21 elaborates the ways of performing fire risk assessment according to APTA.

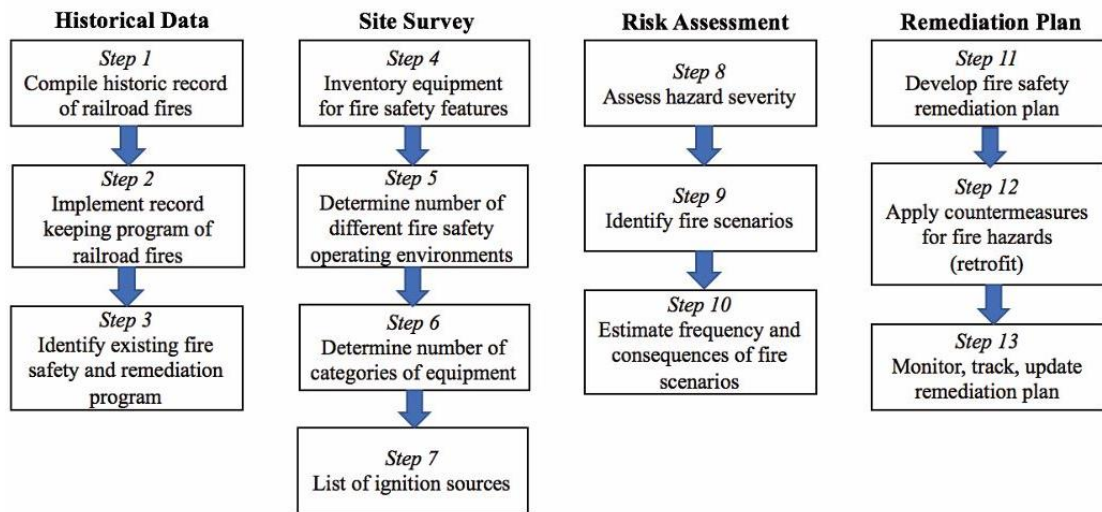


Figure 2.21: Summary of fire risk assessment [49]

Lithium-ion battery trains like the Zero-Emission Boost Locomotive (ZEBL) carry a high fire risk due to thermal runaway, which can lead to explosions and simulation based analysis found that intense heat can weaken steel structures [49]. To reduce this danger, fire protection methods like fire-resistant coatings, gypsum boards, insulation, and concrete encasement are recommended [49]. Maintaining accurate battery temperature through effective cooling systems is a critical safety requirement, improper thermal management can lead to serious hazards [50]. Table 2.5 illustrates comparison between different thermal management systems.

Table 2.5: Comparative analysis of various Thermal Management Systems (TMSs)
[49][50]

Thermal Management Method	Advantages	Disadvantages
Air Cooling System	- Simple design- High reliability- Cost-effective	- Limited cooling efficiency- Uneven temperature distribution
Liquid Cooling System	- Superior thermal regulation- Performs better in hot, humid conditions	- Risk of leakage- Complex system layout- Higher cost than air cooling
Phase Change Material (PCM)	- Operates without power- High thermal storage capacity	- Low thermal conductivity- Volume fluctuations during phase change
Heat Pipe Cooling System	- Excellent thermal conductivity- Minimal maintenance	- Lower overall efficiency compared to other systems
Thermoelectric Cooling System	- Low energy use- Environmentally friendly (green technology)	- Inefficient for high heat loads

Battery design must prioritize safety by preventing failures like thermal runaway, overcharging, and mechanical damage by giving modules and packs strong structural features that protect them from impacts, vibrations, penetration, and environmental intrusions like dust and water [34]. Integrated thermal management systems keep cell temperatures at the right level, BMS stop overcharging, over discharging, and imbalance, and electronic controls protect against voltage and current spikes [34]. Maintaining safety specifically in LIBs requires accurate control of charge-discharge cycles and effective thermal management, recent studies suggesting that solid-state electrolytes may offer enhanced thermal stability and reduce the risk of thermal runaway by replacing conventional liquid electrolytes [33]. Cylindrical cells are usually insulated with expanding foam, while pouch and prismatic cells need controlled stack pressure to deal with expansion and contraction during use [33]. Using thermal interface materials (TIMs), such as ceramic-filled polymers, helps heat escape to keep temperatures safe and stable [51]. Accordingly, when designing safe battery storage, special attention must be given to battery cooling to prevent thermal runaway.

A detailed study of Li-ion pouch cells showed that their mechanical and electrical failure behaviour changes depending on the direction of the impact and the speed of

the loading where the asymmetrical nature of the separator has a big effect on strain and force responses where higher impact rates make the cells stiffer but lower the displacement at failure, which makes them fail sooner [52]. The electrolyte movement also causes changes in the force-displacement profile, which shows how important it is to think about direction-dependent failure mechanisms when designing electric vehicle battery systems for safety [52]. This suggests that special attention should be given to stress concentration and potential loading conditions when positioning the battery storage, in order to enhance the overall safety of the system. Figure 2.22 presents a graphical representation of the results obtained from the above study.

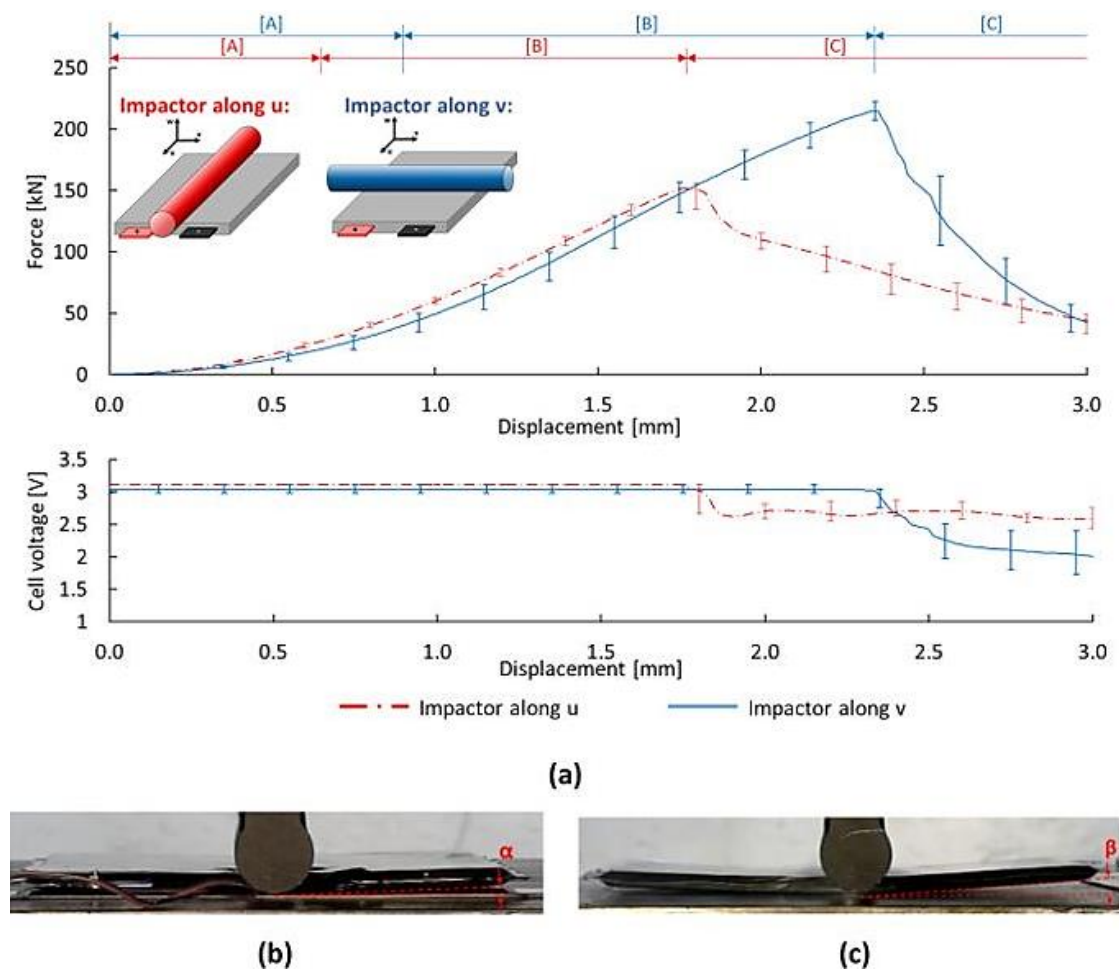


Figure 2.22: (a) Low-speed indentation tests employing a 30 mm diameter indenter on cylindrical cells in a 0% state of charge (SOC); deformation shape seen just before the cell electrically fails when the impactor is applied (b) In the U-direction at 1.8 mm displacement and (c) In the V-direction at 2.35 mm displacement [52]

LFP batteries offer superior safety and high-temperature performance by remaining stable up to 700°C – 800°C and not releasing oxygen during overheating, which greatly reduces fire and explosion risk, whereas NMC batteries begin to decompose at around 250–300°C, releasing oxygen and increasing the likelihood of thermal runaway [48]. Which ensures the safety of LIBs are higher when compared with other battery chemistries. The design of the battery pack has a big effect on both safety and how well the car works. For example, T-shaped packs like those in the GM Chevrolet Volt are safer because they are housed within the vehicle frame, but they take up less space in the passenger cabin [37]. Floor-mounted packs, like those in the Tesla Model S and Audi e-Tron, improve handling and cabin space by lowering the center of gravity, but they are more likely to be damaged by bottom impacts, in other hand cylindrical cells are the strongest structurally, while pouch cells are more likely to fail mechanically [37]. Accordingly, these factors must be considered during battery pack design to ensure safety while maintaining other key parameters such as adequate spacing and optimal balance. The risks associated with different types of battery cells are outlined in Table 2.6.

Table 2.6: Structural safety and crashworthiness of battery cell types [37]

Cell Type	Delamination Risk	Overall Safety Rating	Structural Safety Features
Small Cylindrical	Low	High	Built-in safety (PTC, protective casing)
Large Cylindrical	Low	High	Built-in safety (PTC, protective casing)
Prismatic	Moderate	Medium	Adequate casing, but weaker at edges and corners
Pouch	High	Low	No external casing, easily punctured, minimal structural support

Around 40% of car accidents involve frontal impacts, and train collisions are also common [53]. In these cases, limited cab protection often leads to severe driver injuries where train safety standards like “ECE R94”, “EN15227”, and “APTA PR-CS-S-016-

99” focus on structural integrity and post-collision survival space, but they don't offer much protection for individual passengers, especially standing passengers who are at high risk because there are no restraints or designated crash zones [53]. This shows how important it is to put battery packs in structurally protected areas that meet these safety standards to avoid more hazards during collisions [53]. To make battery-powered locomotives safer, especially during crashes where traditional cabs don't protect passengers well and there is a high risk of injury, it is important to make design changes like adding inflatable tubular restraint systems to lessen impact forces, adding more padding in areas that are likely to be hit, and changing the layout of the interior so that it can absorb crash energy without making it harder for the operator to move around [54]. When putting battery packs in locomotives, it's important to think about the type of truck design; where non-equalized trucks are more likely to lift wheels and derail because the load is not evenly distributed; additionally equalized trucks offer better load balance, which makes the train more stable and reduces the damage to the battery systems during crashes or derailments [50]. So, when deciding where to put the battery pack, it's important to make sure that the structure is strong, especially in crash zones, without throwing off the system's balance, especially the center of gravity [50]. This must be in line with the right safety standards. The current research study's recommendations for battery storage should consider these things.

2.7. Research Gap

Numerous projects have been carried out around the world on the design and use of hybrid and battery-powered trains, some of which are already in use. Integrating regenerative braking systems, which enable the recovery and reuse of kinetic energy that would otherwise dissipate as heat during braking, is one of the key areas of focus within this research. In many electrified railway networks, energy recovery is usually done via overhead catenary systems or third-rail infrastructure, which allow excess braking energy to either be returned to the grid or redirected to other trains operating within the same power section, which was discussed before. Such systems usually employ wayside energy storage units (WESUs) that are intended to absorb and redistribute energy throughout the shared electrical network. These centralized

systems view the rail infrastructure as one large, interconnected unit instead of considering each locomotive as a separate energy hub.

Alternatively, diesel-electric locomotives—who do not need an external source of electricity have a special challenge and opportunity for energy recovery. The possibility of dynamic brake energy harvesting has been demonstrated in several experimental and commercial applications in different countries even in diesel-electric systems. However, these implementations are mostly found in areas with large rail networks and considerable elevation changes. These conditions are ideal for regenerative braking due to the frequent need for deceleration on downhill grades and over long distances, which allows for higher energy capture and better storage efficiency. These systems often involve either onboard battery storage units integrated within the locomotive or strategically placed wayside storage modules.

Although these developments have made it possible to achieve considerable energy recovery in large and busy rail systems, there is still a lack of research focused on localized railway operations, particularly within Sri Lanka. Sri Lanka's railway network, especially the suburban and coastal corridors, has mostly flat topographies and shorter inter-station distances. These operational features pose a problem for the application of traditional regenerative braking systems, which are designed for use in long-distance travel with elevation changes.

The studies that have been done and project works completed so far tend to focus on maximizing energy recovery efficiency under either continuous or steep braking scenarios. Continuous and steep braking scenarios are not common in the Sri Lankan context Railways low- altitude routes. Thus, there is a gap on the sharp short distance and low gradient braking dynamic energy recovery design considerations and the existing literature concerning diesel-electric operated locomotive systems, which are not in the Sri Lankan context.

The other identified gap in research and rest energy system is the absence of defined system in relation to recovery and storage of dynamic brake energy in short distance and low altitude railway networks such as Sri Lanka. This gap also pertains to the

confinement of the energy capture and storage systems under more localised conditions as well as the compact low energy rail environment and its associated safety features. It is important to fill this gap in order to make operational improvements that will keep energy-efficient rail systems running in areas where there aren't many opportunities for electrification or good terrain for crossing.

An extra level of difficulty comes in designing the onboard energy storage systems for the locomotives used in Sri Lanka. The concerns of onsite safety issues become more acute with regard to thermal management as well as crash. It is very important to take care of battery pack mounting to ensure proper protection from derailment and collision impact. Comprehensive protection against hazards such as thermal runaway should be incorporated so that effective temperature regulation systems are in place. Moreover, the conceived design whether equalized or non-equalized of the locomotive's underframe and truck system would fundamentally affect the safety and structural strength of onboard energy storage units as well as braking and post-accident events. However, this won't be discussed in deeper within this research.

2.8. Review Summary

The review is mostly about how regenerative braking systems and hybrid locomotives are being developed for diesel-electric railway networks, which are short and have less changes in terrain. However existing systems usually employ centralized energy recovery techniques, like WESUs hooked up to national or regional power grids. Most of these approaches are designed to service long-distance travel with varying terrain. In contrast, Sri Lanka's railways are characterized by short-distance, low-elevation travel. There is a considerable design gap in developing energy recovery systems for such diesel-electric locomotives running in Sri Lankan context.

To fill this void, the study's Methodology section will outline the approach to be used in obtaining real-world data quantifying dynamic braking and associated energy loss on SLR considering S14 DEMU. This encompasses data cleansing procedures that will ultimately enable the estimation of recoverable energy. A corresponding system design will be created that is based on the operational profile of chosen locomotives, and key

results will be documented to justify the major design choices after the analysis.

The straightforward computations associated with determining the potential value of energy recovery will be complemented with the engineering of a battery-based energy storage solution as outlined in the Design and Development section. This will include basic design considerations on battery safety, installation trauma locations on the locomotive, crash resilience, battery configuration and capacity, and thermal management safety. In addition, the structural and performance integrity of the proposed storage system will be validated based on past research learnings.

The financial feasibility of the implemented conventional operations versus the proposed system will be addressed with a cost comparison in the Results and Discussion section. In addition to this, the section will aim at accentuating the sustainable benefits that come with the intervention which include decreased fuel consumption, emission reduction, and overall energy efficiency boost. Finally, more technological advancements and system scalability will be investigated.

The Conclusion will discuss the findings of the research with particular emphasis on the contribution made towards bridging the addressed research gap. Moreover, it will recount the practical problems and the scope of limitations that were faced throughout the study. Most importantly, it will explain how the proposed system aids in achieving broader sustainability goals for railway operations in Sri Lanka and why further research is needed, including the use of renewable energy and intelligent control systems for optimizing battery charge and discharge cycles.

Finally, the References section will list all cited scholarly works, technical reports, and other relevant data sources used in the research so that the inquiry will remain verifiable and academically sound.

This study seeks to address the local issue of diesel-electric railway systems in Sri Lanka by integrating internationally-regarded practices of regenerative braking. The aim is to offer a practical, safe, and sustainable solution for dynamic brake energy harvesting at a localized scale.

CHAPTER 3

METHODOLOGY

3.1. Data Collection on Dynamic Braking and Energy Wastage

In metro and electrified rail tracks the power that can be harnessed through regenerative braking lies around 40% of its total energy [55]. Various research articles have employed different approaches to quantify recoverable energy. A commonly used method has several key steps. First, the basic resistance and simulation calculation models are constructed under braking conditions; Second, the engineering calculation method for regenerative braking energy is established using the energy conversion and balance relationship, based on a thorough analysis of the object's braking characteristics; Lastly, a real-world example is used to illustrate the application of this calculation method, confirming its practical effectiveness [55].

In this case, initial data collection was conducted using an onboard data logger installed in the S14 DEMU. The route and DEMU were selected for their convenience and accessibility, specifically targeting on the upcountry line. Travel data were collected at 1-second intervals for journeys lasting approximately 10 hours each, over a period of up to 30 days. Data were gathered from three DEMUs; S14-973, S14-979, and S14-985 over five days, covering the journey from Colombo to Badulla and the return trip from Badulla to Colombo. However, the on-board data logger failed to provide the necessary information on the energy dissipated during dynamic braking applications.

Since the power output data was not available from the on-board data logger, an alternative method was needed to quantify the energy dissipated during dynamic braking. Several methods were considered, with the most promising being the use of an on-board clip-on unit to measure real-time power output. However, practical and economic constraints made this approach unfeasible. Instead, data from the logger and theoretical data were used to establish a relationship and develop a model to generate a new dataset for calculating the power dissipated during dynamic braking.

Data logger provided the data extracted from the DEMU's main generator, including voltage, current, temperature, power requirement, and power output for each component of the generator circuit. It notably illustrates the excitation current produced by the main generator to power the separately excited traction motors during dynamic applications. Additionally, it includes DEMU running speed, brake system parameters such as brake pressure, and mechanical brake application data. This comprehensive dataset provides a holistic view of the main generator's behaviour and its components, offering practical insights during the journey. The electrical power circuit of the DEMU is depicted in figure 3.1.

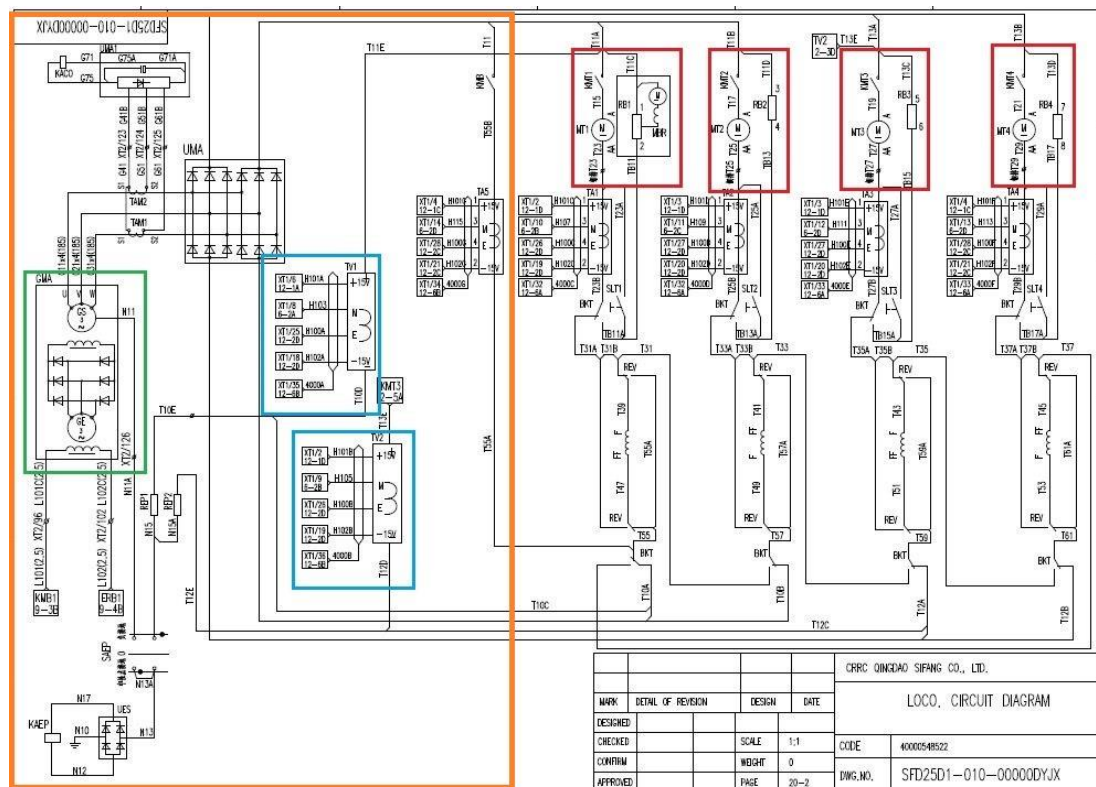


Figure 3.1: Main electrical power circuit of the DEMU [56]

In the electrical power circuit of the DEMU, the red boxes highlight the four traction motors connected to the resistor grids, while the blue boxes represent the auxiliary generator and the starting motor, which can also function as an auxiliary generator when required. The green box indicates the main generator that supplies power to the traction motors. Additionally, the orange box captures the main generator circuit and its components, which are monitored by the on-board data logger, providing detailed

information about the system's performance.

The S14 DEMU's traction motor is a separately excited DC electric motor, requiring separate excitation to function as a generator during dynamic braking. This excitation current (I_e) is recorded by the on-board data logger. Figure 3.2 illustrates the behaviour of I_e and the total power of the DEMU during the journey, with the blue graph representing power from the main generator and the orange graph depicting the excitation current. Since the data logger is connected only to the main generator and the auxiliary generators, it does not provide detailed information about the traction motors, aside from the variation in excitation current.

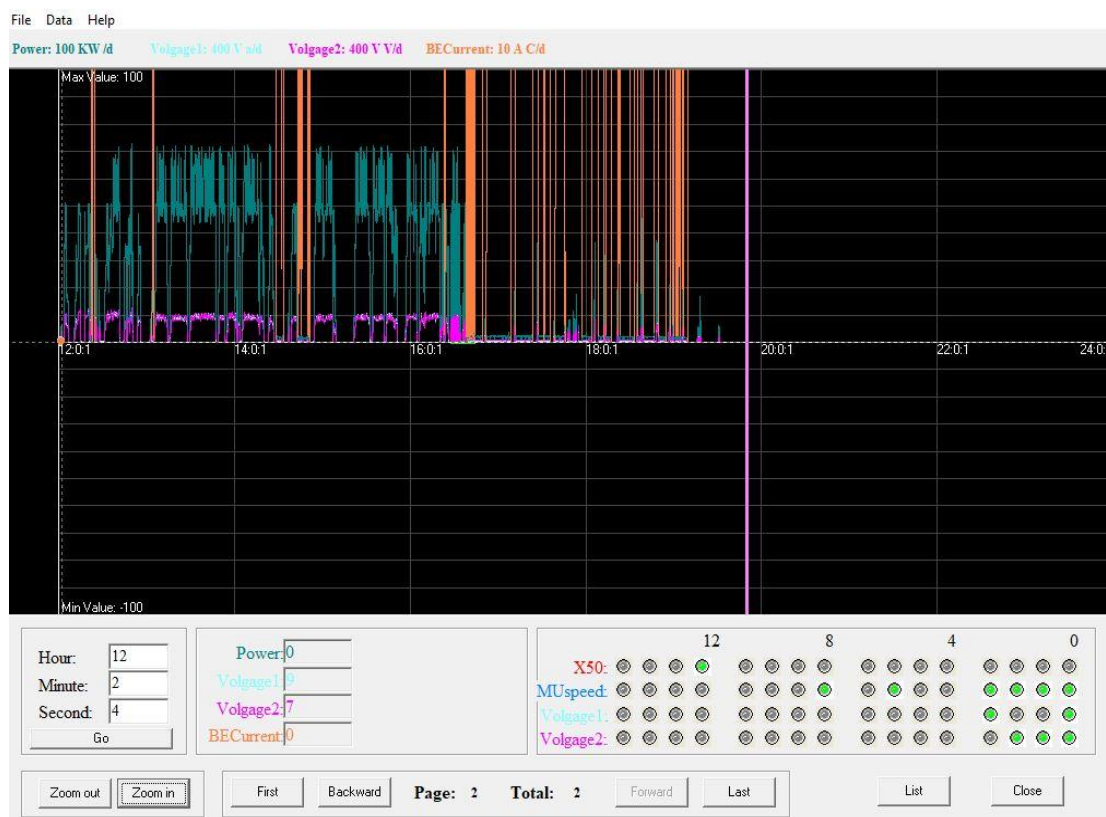


Figure 3.2: Graphical representation of data collected from the on-board data logger

3.2 Data Preparation and Refining

When dynamic braking is applied, the circuit area highlighted in red (consider one of the four traction motors marked in red) in figure 3.1 is isolated. During this process, the engine enters into an idling state, and the main generator produces a small current to excite the traction motors, activating the dynamic braking function. Simultaneously,

the traction motors act as generators, using the excitation current and kinetic energy to oppose the DEMU's movement. The current flows (back EMF – Electro Motive Force) through the resistor grid, dissipating as heat. Increasing the resistance results in more energy being wasted as heat, which opposes the movement of the drive wheels and facilitates regenerative braking. Figure 3.3 presents a simplified version of the isolated circuit depicted in red in Figure 3.1.

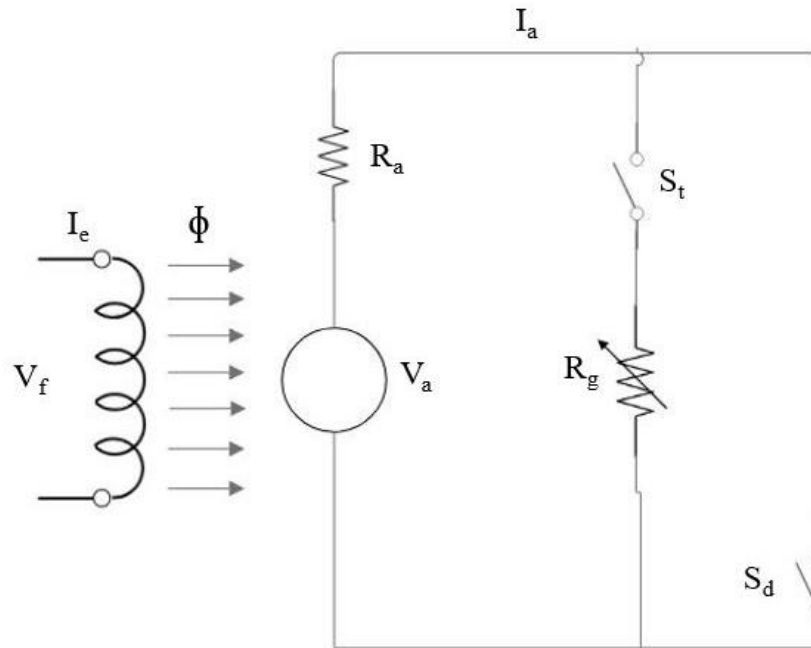


Figure 3.3: Simplified circuit of the traction motor / resistor grid during dynamic braking

In figure 3.3, V_f represents the excitation voltage from the main generator, I_e represents the excitation current, V_a represents the traction motor armature voltage, R_a represents the internal resistance of the traction motor armature, I_a represents the armature current and the current that flows through the resistor grid, R_g represents the resistance of the resistor grid, and V_g represents the voltage across the resistor grid. Additionally, the data logger provides I_e (excitation current) in one-second intervals during dynamic braking. The values for R_a and R_g are available from the manufacturer's maintenance manual [57][58][59]. Furthermore, during dynamic braking, the S_t switch remains closed while the S_d switch is open, allowing power to be generated through back EMF. In contrast, under normal operating conditions, the

S_t switch is open and the S_d switch is closed, enabling the motors to generate traction power.

Figure 3.4 illustrates the behaviour of a separately excited DC motor operating as a generator. The data show that as the field current (used as the excitation current) increases, the voltage difference at the armature also rises [60]. However, there is a point at which the voltage becomes constant despite further increases in the field current, indicating the saturation state [61]. Additionally, figure 3.5 demonstrates that when the rotational speed of the armature increases, the voltage gap also increases, even if the field current remains constant [60].

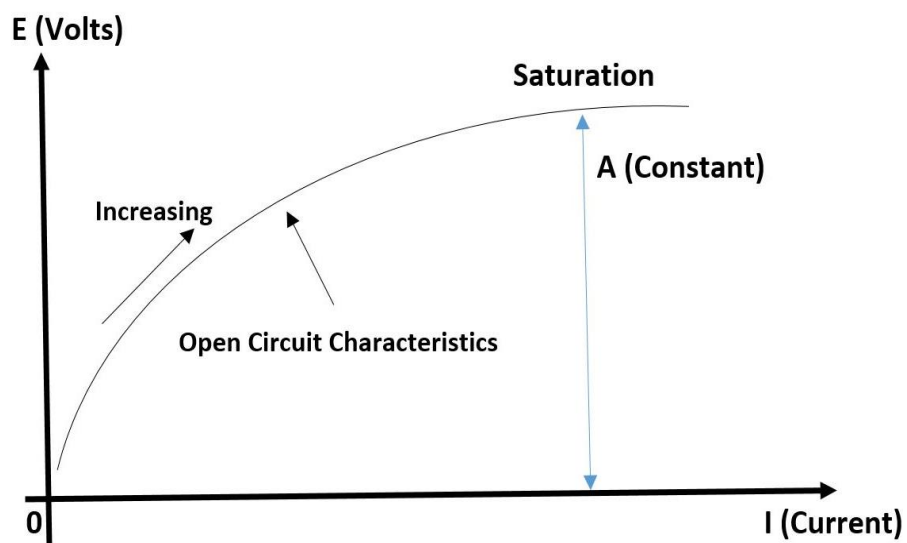


Figure 3.4: Variation of armature voltage with excitation current (field current) in a separately excited DC motor [60]

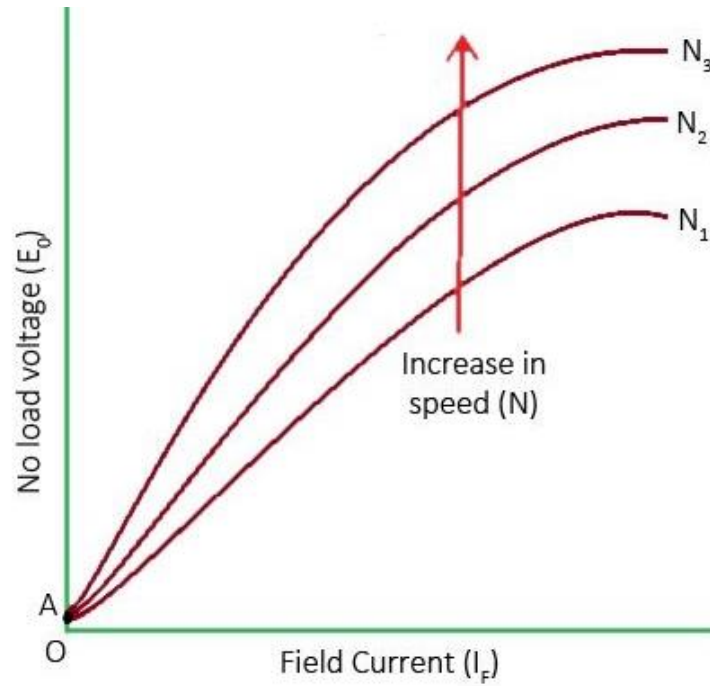


Figure 3.5: Variation of armature Voltage with the speed (armature rotation) [61]

To understand the amount of regenerative energy that can be captured during dynamic braking, data on voltage and field current behaviour were obtained from a previous study conducted by the DEMU manufacturer [59]. This research aimed to analyse the quality and power of dynamic braking. Figure 3.6 illustrates the behaviour of separately excited DC motors equipped in a DEMU under the discussion [59]. The curve obtained during the trip from Colombo to Badulla is referred to as the rising curve, while the curve from the return journey, Badulla to Colombo, is shown as the declining curve in figure 3.6.

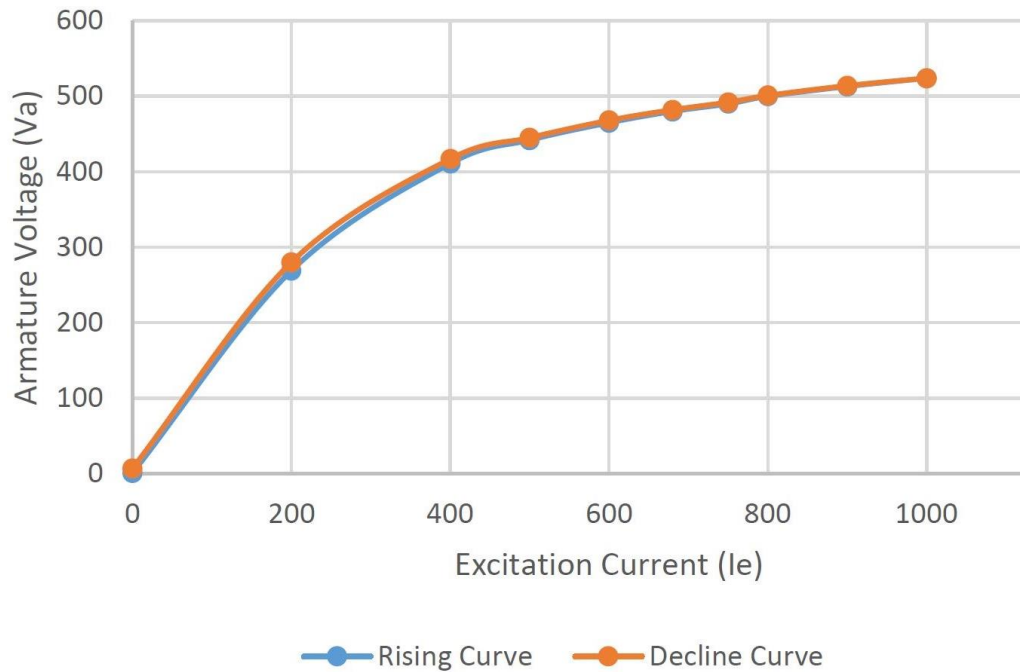


Figure 3.6: Variation of armature voltage (V_a) with excitation current (I_e) of the traction motor (characteristic curve of traction motor) [59]

The research was conducted by analysing the DEMU's performance at speeds below 25 km/h. The manufacturer-provided characteristic curve was utilized to calculate the dynamic brake energy, which is a key element of this study. This curve (Figure 3.6) was developed based on the practical conditions of a moving train in passenger service. During the data collection stage, the same scenario was replicated, ensuring that speeds and other conditions remained consistent across both cases. Only current and voltage readings were used to create the curve equation; no information about regenerative braking power was taken into account. Consequently, this curve was used to analyze and quantify the available data starting at the point at which the parameters required to assess regenerative power generation became available.

The variation in excitation current during the journey was used to identify the periods when dynamic braking was applied. A relationship based on this data needs to be developed to calculate the dynamic braking power generation. Additional data, obtained by consulting the manufacturer's operation manual, is required to achieve this.

To obtain the V_a values at the time of dynamic braking using the I_e values collected

from the data logger during the DEMU run, the characteristic curve shown in Figure 3.6 must be mathematically illustrated. To develop an equation for the existing research data and for the curve shown in Figure 3.6, MATLAB's plot and curve fitting function were employed [62]. The corrected and refined curve obtained from this tool is shown in Figure 3.7. Additionally, an equation for this curve was generated after refining and matching it with the existing curve.

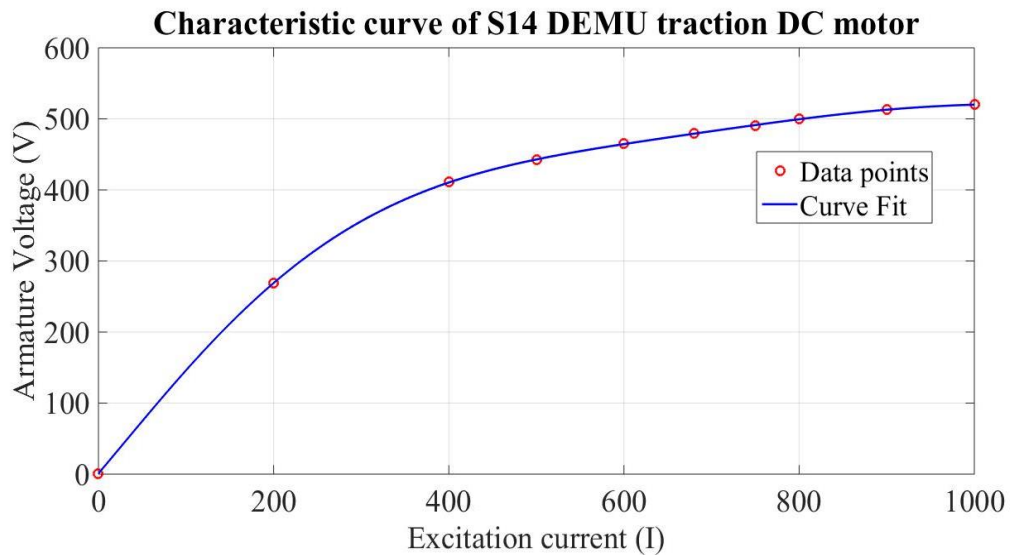


Figure 3.7: Refined curve created by using MATLAB plot and curve fitting functions

The most suitable curve that fits the data illustrated in figure 3.7 was derived from a polynomial function. The equation of the characteristic curve is as follows:

$$f(x) = a_0 + a_1 \cdot \cos(x \cdot w) + b_1 \cdot \sin(x \cdot w) + a_2 \cdot \cos(2 \cdot x \cdot w) + b_2 \cdot \sin(2 \cdot x \cdot w) \dots \quad (1)$$

The coefficients in the equation, with 95% confidence bounds, are:

$$a_0 = 34.55 \quad (-148.9, 218)$$

$$a_1 = -175.7 \quad (-281, -70.3)$$

$$b_1 = 584 \quad (301.3, 866.8)$$

$$a_2 = 142.1 \quad (64.35, 219.8)$$

$$b_2 = 51.97 \quad (-4.815, 108.8)$$

$$w = 0.002361 \quad (0.001929, 0.002793)$$

According to the MATLAB curve fitting function, the goodness-of-fit parameters for the refined curve (Figure 3.7) are as follows:

SSE (Sum of Squares due to Error)	=	6.801
R-square (Coefficient of Determination)	=	1
Adjusted R-square	=	0.9999
RMSE (Root Mean Squared Error)	=	1.304

These results indicate that the curve fits very well with the practical data, as it closely aligns with the given characteristic curve and exhibits minimal error as per MATLAB's definitions [62]. Using this curve, the V_a values for the periods during which dynamic brakes are applied can be extracted.

The relationship between the parameters shown in Figure 3.3 can be explained using basic principles, primarily Ohm's Law. This fundamental principle is used to quantify the energy values, and the relationship is developed as follows:

By applying Ohm's Law to the circuit shown in Figure 3.3, we derive the following equations:

$$V_g = V_a - I_a R_a \quad \dots (2)$$

$$I_a R_g = V_a - I_a R_a \quad \dots (3)$$

$$I_a (R_g + R_a) = V_a \quad \dots (4)$$

$$I_a = \frac{V_a}{(R_g + R_a)} \quad \dots (5)$$

In this relationship, the values of R_g and R_a are obtained from the manufacturer's maintenance manual and the user manual. Specifically, R_a is 0.017Ω , as given directly in the user manual, where the resistivity change due to temperature is neglected [57]. For R_g , the maximum value at a hot state is 1.4648Ω , and at 20°C , it is 1.2860Ω [59]. Therefore, the average resistance during the time of dynamic braking is considered to be 1.3754Ω , based on the manufacturer's details and the provided data [58].

The power dissipated during dynamic braking (P_d) can be determined using the

following formula:

$$P_d = V_g I_a \quad \dots (6)$$

Given that the DEMU has four traction motors, each with its own resistor grid, the total power generation for a single engine must be multiplied by four. According to the manufacturer, the power dissipated in each circuit is equal, as the operating conditions for the DEMU remain consistent across all circuits [58]. Since the DEMU consists of two identical engines, the total power generation during dynamic braking is eight times P_d (Considering two engines and four traction motors installed in each engine). Both engines are controlled as a single unit, and their outputs are nearly identical during the dynamic braking process, as stated by the manufacturer [57][58][59]. Additionally, the assumptions mentioned above were applied to derive these results.

3.3 Energy Quantification and Results Obtained

Based on the data collected from the data logger, as well as refined and available data, a dataset was prepared to analyse the dynamic braking power output. The power dissipated by the DEMU was measured at one-second intervals over approximately 10-hour journeys, resulting in 36,000 data sets per journey. This data collection process was repeated for 30 days, encompassing 30 journeys with three DEMUs. However, for the final assessment, only 10 days were considered (specifically, five round trips between Colombo and Badulla). Using this raw data, an average quantified result was derived through the methods discussed previously. Additionally, the periods of dynamic braking application, their durations, and the corresponding quantified data values were identified and refined from these data sets.

3.3.1 Quantified data

The parameters associated with the traction motor and resistor grid of a DEMU traveling from Colombo Fort Station to Badulla Station (departing at 8:30 AM and arriving at 7:30 PM) and returning from Badulla Station to Colombo Fort Station (departing at 5:45 AM and arriving at 4:30 PM on the same day) is shown by Table

3.1 (Illustration purposes only. Full table is included in appendix):

In Table 3.1, the following notations are used for the coefficients in Equation (1). $P1 = a_0$, $P2 = a_1 \cdot \cos(x \cdot w)$, $P3 = b_1 \cdot \sin(x \cdot w)$, $P4 = a_2 \cdot \cos(2 \cdot x \cdot w)$, and $P5 = b_2 \cdot \sin(2 \cdot x \cdot w)$. Here, x represents I_e , and w is a constant value of 0.002361, as shown in Equation (1). Using MATLAB's plot and curve fitting functions, the values for P1 to P5 are obtained.

Table 3.1 – Part of quantified data

Ie (A)	P1	P2	P3	P4	P5	Va (V)	Rg (Ω)	Ra (Ω)	Ia (A)	P (W)
31	34.55	-175.23	42.71	140.58	7.58	50.19	1.38	0.017	36.04	1808.87
79	34.55	-172.65	108.30	132.33	18.94	121.46	1.38	0.017	87.23	10595.26
149	34.55	-164.94	201.23	108.36	33.62	212.82	1.38	0.017	152.85	32528.73
176	34.55	-160.75	235.75	95.79	38.39	243.73	1.38	0.017	175.04	42662.08
190	34.55	-158.32	253.28	88.64	40.62	258.78	1.38	0.017	185.85	48092.7
207	34.55	-155.13	274.19	79.45	43.09	276.15	1.38	0.017	198.33	54767.32
227	34.55	-151.06	298.22	67.99	45.64	295.33	1.38	0.017	212.10	62641.28
210	34.55	-154.54	277.84	77.78	43.49	279.11	1.38	0.017	200.45	55949.28
68	34.55	-173.44	93.36	134.84	16.40	105.71	1.38	0.017	75.92	8024.919
29	34.55	-175.29	39.96	140.77	7.10	47.08	1.38	0.017	33.81	1591.911
28	34.55	-175.32	38.58	140.86	6.85	45.52	1.38	0.017	32.70	1488.376
28	34.55	-175.32	38.58	140.86	6.85	45.52	1.38	0.017	32.70	1488.376
28	34.55	-175.32	38.58	140.86	6.85	45.52	1.38	0.017	32.70	1488.376

Additionally, the energy dissipated during each dynamic braking application, along with the corresponding time and energy for each phase, was extracted from the quantified data (See appendix for raw data). This analysis helps to identify the dynamic braking patterns and determine where dynamic braking was applied, considering the time and geographical location of the train route. A sample of the data collected using this method is presented in Table 3.2 and Table 3.3.

Table 3.2: Set of quantified data during dynamic braking application from Badulla to Colombo (including time of application and power dissipated)

Energy Dissipation Time Period	Time Between Energy Dissipation	E (J)	T (s)	E (kWh)	Total Energy Dissipated (kWh)	P (kW)
Start 5.45 AM - End 4.30 PM						
9.18.5 - 9.24.35	6Min 30ec	41133339.6	390	11.4259277	91.40742133	105.4701
9.33.27 - 9.47.5	8Min 52 Sec	71762174.77	818	19.9339374	159.4714995	87.72882
9.48.34 - 9.55.48	1Min 29 Sec	37918843.88	434	10.5330122	84.26409751	87.370608
10.2.1 - 10.2.13	6Min 13 Sec	323127.4796	12	0.08975763	0.718061066	26.92729
10.2.33 - 10.9.41	20 Sec	41349659.7	428	11.4860166	91.88813267	96.611354
10.11.15 - 10.18.22	1Min 34Sec	45584286.31	421	12.6623018	101.298414	108.27621
10.20.9 - 10.29.9	1Min 47Sec	57944543.47	540	16.0957065	128.7656522	107.30471
10.32.41 - 10.45.1	3Min 32 Sec	75777097.06	740	21.0491936	168.393549	102.40148
10.56.21 - 10.59.38	11Min 20 Sec	14423350.35	197	4.00648621	32.05188967	73.214976
11.10.59 - 11.13.30	11Min 21Sec	18308240.91	151	5.08562248	40.6849798	121.24663
11.17.11 - 11.20.10	3Min 41Sec	14120942.12	179	3.92248392	31.37987138	78.887945
11.20.48 - 11.30.40	38Sec	64253529.66	592	17.8482027	142.7856215	108.53637
11.33.44 - 11.40.11	3Min 4Sec	44825130.13	387	12.451425	99.61140029	115.82721
11.41.54 - 11.46.19	1Min 43Sec	31436055	265	8.7322375	69.8579	118.62662
11.48.15 - 12.5.9	1Min 56Sec	109581425.5	1014	30.4392849	243.5142789	108.06847
12.7.41 - 12.12.47	2Min 32Sec	42079985.27	306	11.6888848	93.51107838	137.51629
12.13.22 - 12.18.45	35Sec	36170817.93	323	10.0474494	80.3795954	111.98396
12.20.35 - 12.28.3	1Min 50Sec	48884911.42	448	13.5791421	108.6331365	109.11811
12.50.2 - 12.51.56	21Min 59Sec	6787567.695	114	1.88543547	15.08348377	59.540068
12.55.54 - 12.57.22	3Min 58Sec	6412237.22	88	1.78117701	14.24941604	72.866332
12.58.1 - 12.58.56	39Sec	3795183.098	55	1.05421753	8.433740218	69.003329
13.3.45 - 13.9.24	4Min 49Sec	28774502.89	339	7.99291747	63.94333976	84.880539
13.10.6 - 13.11.46	42Sec	4595450.715	100	1.27651409	10.2121127	45.954507
13.10.6 - 13.11.46	1Min 40Sec	1739313.791	40	0.48314272	3.865141758	43.482845
13.24.59 - 13.25.48	13Min 13Sec	3620430.105	49	1.00567503	8.045400233	73.886329
13.26.13 - 13.26.45	25Sec	1572108.016	32	0.43669667	3.493573369	49.128376
13.27.34 - 13.28.36	49Sec	3357961.85	62	0.93276718	7.462137444	54.160675
13.32.14 - 13.33.41	3Min 38Sec	5584137.744	87	1.55114937	12.40919499	64.185491
13.34.9 - 13.34.49	28Sec	2783542.79	40	0.77320633	6.185650644	69.58857
14.31.43 - 14.55.3	56Min 54Sec	152662066.4	1400	42.4061296	339.2490364	109.04433
14.56.56 - 14.58.15	53Sec	7106132.12	79	1.97392559	15.79140471	89.951039
15.6.57 - 15.14.17	8Min 42 Sec	45157103.89	440	12.54364	100.3491198	102.62978

Table 3.3: Set of quantified data during dynamic braking application from Colombo to Badulla (including time of application and power dissipated)

Energy Dissipation Time	Time Between Energy Dissipation	E (J)	T (S)	E (kWh)	Total Energy Dissipation (kWh)	P (kW)
Start 8.30 AM - End 19.30 PM						
12.22.20 - 12.23.19	3Hr 52Min 20Sec	4915632	60	1.365453333	10.92362667	81.9272
14.28.4 - 14.33.18	2Hr 4Min 45Sec	29369059	314	8.158071875	65.264575	93.53203424
14.43.3 - 14.51.37	9Min 45Sec	38723444	514	10.75651233	86.05209867	75.33744047
16.38.25 - 16.49.27	1Hr 46Min 48Sec	74072965	662	20.57582361	164.6065888	111.8926963
16.52.0 - 17.8.36	2Min 33Sec	101515482	996	28.19874489	225.5899591	101.9231743
17.11.36 - 17.23.47	3 Min	72840188	731	20.23338559	161.8670848	99.64458022
18.21.50 - 18.33.5	58Min 3Sec	63211602	675	17.55877844	140.4702275	93.64681836
18.35.31 - 18.37.38	2Min 26Sec	11186057	127	3.107238028	24.85790422	88.07918819
18.39.21 - 18.46.20	1Min 43 Sec	43139942	419	11.98331716	95.86653724	102.9592882
18.49.47 - 18.54.48	3Min 27Sec	28226801	301	7.840778125	62.726225	93.77674834
18.57.40 - 18.59.4	2Min 52 Sec	7685149.8	84	2.13476382	17.07811056	91.48987801
19.0.3 - 19.9.24	59Sec	40542864	561	11.26190673	90.09525387	72.26892021

In the table 3.2 and table 3.3 the symbols represent -

- E(J) – Total energy dissipated during the selected time period by a single traction motor
- T(s) – Selected time period in seconds
- E (kWh) - Total energy dissipated during the selected time period in kilo Watt hours by a single traction motor
- Total Energy Dissipation (kWh) – Total power dissipation considering the DEMU (Considering all traction motors in both engines)
- P (kW) – Average power dissipation during the selected time period

By summarizing the data collected from three DEMUs over a period of five days for 10 journeys, a quantified dataset (Energy and Power dissipation during dynamic

braking application) was dissipated to provide a clear understanding of the potential of harvesting dynamic energy. This dataset also offers insights into the average dynamic brake applications considering the geographical influences and drivers' driving patterns. The summarized data is presented in table 3.4 below.

Table 3.4 – Quantified data as a summary

Train No	Day 1 (kWh)		Day 2 (kWh)		Day 3 (kWh)		Day 4 (kWh)		Day 5 (kWh)		Average (kWh)	
	COL to BDL	BDL to COL	COL to BDL	BDL to COL	COL to BDL	BDL to COL	COL to BDL	BDL to COL	COL to BDL	BDL to COL	COL to BDL	BDL to COL
973	1145.40	2397.69	1121.85	2427.63	1141.24	2410.34	1162.34	2394.87	1140.23	2394.56	1142.21	2405.02
979	1110.59	2405.78	1152.43	2384.25	1171.24	2390.25	1129.37	2336.56	1165.29	2397.56	1145.78	2382.88
985	1178.99	2401.32	1132.12	2399.11	1134.56	2384.57	1140.55	2387.76	1164.26	2410.33	1150.10	2396.62
Avg.	1144.99	2401.60	1135.47	2403.67	1149.01	2395.05	1144.08	2373.07	1156.59	2400.82		

The analysis indicates that the dynamic energy potential during the route from Colombo to Badulla ranges between 1.1 and 1.2 MWh, while the return journey from Badulla to Colombo dissipates between 2.3 and 2.4 MWh. Considering the variation between the minimum and maximum values of the quantified data, the trip from Colombo to Badulla showed a gap of 53.67 kWh, which corresponds to 4.83% of the minimum recorded value. On the other hand, for the return trip from Badulla to Colombo, the gap between the minimum and maximum values was 73.8 kWh, equivalent to 3.16% of the minimum recorded value. This variation could potentially be reduced further by extending the dataset. However, given that the percentage differences are relatively small, the dataset used for this study covering 10 days of data from 3 locomotives over 5 round trips were considered sufficient for data quantification. During these trips, the power dissipation is approximately 100 kW in specific time intervals and maximum value lies below 150 kW value. To effectively utilize this significant amount of energy, an energy recovery method is necessary to prevent it from being wasted. Currently, this energy is dissipated as heat during the journey. Prior to this research, the extent of this energy wastage had neither been quantified nor calculated, leaving the total waste incurred during the process unassessed.

3.3.2 Evaluation of Quantitative Data Supporting System Development

The results of this study show beyond a doubt that the energy released during dynamic braking may be collected and used for a useful purpose. The following is the total amount of power that auxiliary functions will use during the service journey [57][58]:

- The auxiliary generator gives 25 kW to train lights, fans, and buffet items.
- Two air-conditioned compartments, each with 10 kW of power
- Two driver cabins and guard cabins, each with 5 kW of power

For a 10-hour trip, this combined auxiliary system will use about 0.55 MWh of energy, at 55 kW of energy consumption rate ($25 \text{ kW} + 2 \cdot 10 \text{ kW} + 2 \cdot 5 \text{ kW} = 55 \text{ kW}$). The energy created during dynamic braking is more than enough to meet this need, which means it can be used to power up these auxiliary needs.

Table 3.4 shows that the amount of energy dissipated during one cycle of dynamic braking is about 3.5 kWh. To effectively capture this energy, a system that can handle about 150 kW of power at once is needed. Further, the solution needs to be able to store between 1.1 MWh and 2.5 MWh of energy, which is the overall average energy loss stated in Table 3.4. This amount of capacity makes sure that there is enough energy to meet extra energy needs that can be met with the recovered energy. The quantified data can be used to design an energy capture and utilization system that can redirect the energy from dynamic braking to power auxiliary functions. Furthermore, the excess energy harvested through this system can be utilized to meet other identified energy demands, ensuring that energy wastage is minimalized. Implementing such a system would reduce excess energy usage and prevent energy wastage, thereby enhancing overall energy efficiency.

Topography along the Colombo to Badulla rail line is a major influence on train operating patterns, particularly in relation to speed control and the application and frequency of dynamic braking cycles. Topography influences all aspects of the dynamic braking process, and thus, it has to be considered in the design of battery

energy harvesting from dynamic braking. Steep gradients will require more frequent or longer braking, which increases the chances of capturing energy through regenerative braking. On the other hand, flatter gradients will require fewer braking events, which means there is less potential for energy recovery.

To determine how to apply these geographical factors to the system development, terrain data was obtained from the Way and Works Department of Sri Lanka Railways [11]. This data enabled mapping of elevation and gradient changes along the Colombo–Badulla route. The terrain profile showing elevation and gradient changes is illustrated in Figure 3.8, it assists in describing energy calculations for section specific areas to help determine energy storage requirements, initial battery loading cycles, and score battery charging processes. To create a battery energy harvesting system from dynamic braking, it is important to ensure that the system design not only meets technical feasibility, but that it also addresses the operational context and the route terrain.

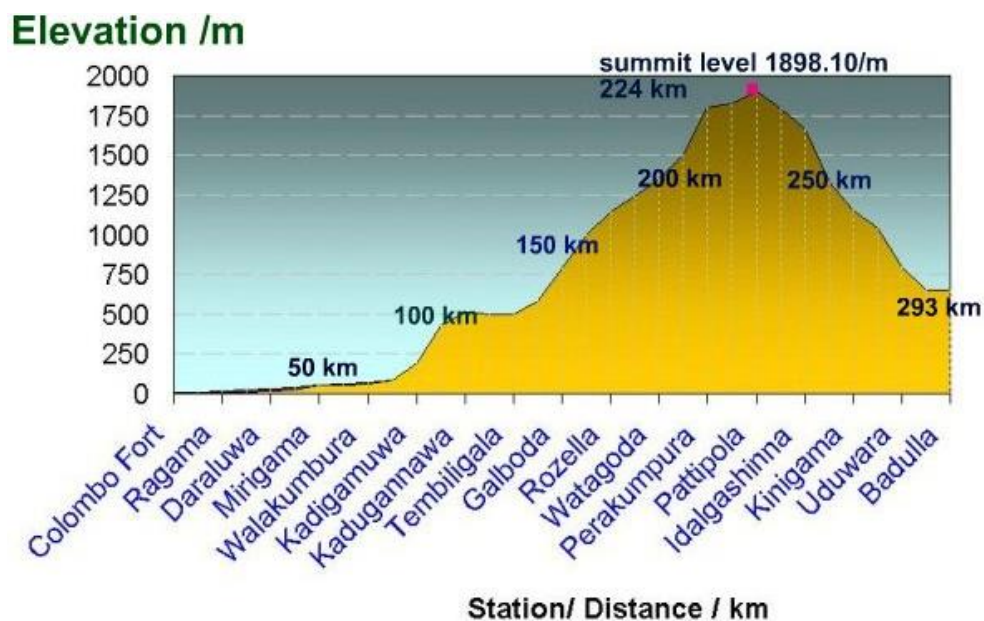


Figure 3.8: Altitude variation along the Badulla Colombo train route [63]

From the braking patterns and total energy dissipation results we presented in Table 3.2 and table 3.3, together with the findings of the literature review, it appears that the

entire dynamic braking energy cannot be practically harvested. Furthermore, one needs to use all harvested energy which could present several technical and operational issues, especially within the current structure of SLR. However, the analysis of auxiliary power requirements indicates that part of the energy that could not be harvested and was lost, could usefully be harvested to satisfy the auxiliary loads as discussed above.

It should be pointed out that there are important operational constraints and restrictions posed on a railway system like Sri Lanka Railways, which prohibit major changes to the system; most importantly, those involving the primary propulsion and power supply systems. Therefore, any proposed result must be designed to supplement the existing system without interfering with reliability or compliance. As such, rather than amending the existing supply of auxiliary power (mainly diesel-driven AC and auxiliary generators), a battery storage system is proposed as a supplementary component that would store a fraction of the dynamic braking energy that would be dissipated as heat, and then deliver that energy as auxiliary power to other subsystems at a later time, and without interfering with the main power supply system.

To ensure the battery system remains effective and usable, and that the BMS is able to properly function, a controlled charging and discharging cycle must occur. The controlled charging and discharging cycle is based on cyclic operation, which will capture energy during high-energy capacities during braking phases and store this energy for future dissipation into auxiliary loads. When charging the battery, the auxiliary loads of the DEMU will still be met by the diesel engine through the existing generator systems. Because of this reason the timing of energy harvesting will be critical: when charging the battery, the most important aspect is the battery should be charged when output from regenerative braking is at its peak. Further, the battery charging should be completed in the shortest time possible. This minimizes the time period when the diesel engine must be operated solely to meet auxiliary power to the DEMU, which increases the overall system and fuel economy in a meaningful manner.

As a result, the information contained in Table 3.2 (Average Energy Harvested During Trip from Badulla to Colombo) and Table 3.3 (Average Energy Harvested During Trip

from Colombo to Badulla) must be examined carefully to determine the periods in the trip that harvesting energy was produced. The altitude profile in Figure 3.8 identifies the brake force needed to manage the track contour, which can be used to relate to energy harvesting periods.

There is a good opportunity for energy recovery on the trip from Badulla to Colombo during the trip from Badulla to Gampola with a maximum opportunity for energy harvesting. This area has a large downhill gradient and is most suitable for dynamic braking and recovering energy. The downhill section is normally completed in about 6.5 hours, which is a concentrated opportunity for recovering energy.

To confirm this observation, two energy dissipation tables with train schedule table on this trip were selected for review. The schedules displayed in table 3.5 was selected to represent a realistic operation, and to understand how the proposed system can be incorporated within the service. This is to demonstrate that the system is designed to be complemented with train operations to allow energy recovery potential without affecting reliability standards or operating practices.

Table 3.5: Train schedule from Badulla to Colombo [11]

Train Station	Reaching Time	Leaving Time	Stop Time
Badulla		5:45	-
Hali Ela	6:00	6:01	1 minute
Uduwara	6:09	6:10	1 minute
Demodara	6:23	6:24	1 minute
Ella	6:39	6:40	1 minute
Kithal Elle	6:45	6:46	1 minute
Heel Oya	6:54	6:55	1 minute
Kinigama	7:04	7:05	1 minute
Bandarawela	7:11	7:14	3 minutes
Diyatalawa	7:28	7:29	1 minute
Haputale	7:41	7:43	2 minutes
Idalgashinna	7:59	8:00	1 minute
Ohiya	8:20	8:21	1 minute
Pattipola	8:36	8:37	1 minute
Ambewela	8:45	8:46	1 minute
Perakumpura	9:05	9:06	1 minute
Nanu Oya	9:16	9:22	6 minutes
Radella	9:30	9:31	1 minute
Great Western	9:39	9:40	1 minute
Watagoda	9:52	9:53	1 minute
Talawakelle	10:08	10:12	4 minutes
Kotagala	10:25	10:26	1 minute
Hatton	10:37	10:39	2 minutes
Nawalapitiya	11:42	11:46	4 minutes
Ulapane	11:58	11:59	1 minute
Gampola	12:18	12:19	1 minute
Kandy	12:38	12:50	12 minutes
Peradeniya	12:58	13:00	2 minutes
Kadugannawa	13:16	13:17	1 minute
Rambukkana	13:56	13:59	3 minutes
Polgahawela	14:10	14:11	1 minute
Veyangoda	14:41	14:42	1 minute
Gampaha	14:53	14:54	1 minute
Ragama	15:04	15:05	1 minute
Colombo Fort	15:27		-

Moreover, when considering the complete round trip, the total estimated auxiliary energy requirement was about 1.1 MWh ($2 \times 0.55 \text{ MWh} = 1.1 \text{ MWh}$). This energy requirement is a significant indicator of the ability to accommodate an energy harvesting system during the operational cycle of the DEMU. To successfully meet this auxiliary demand through regenerative braking, the total energy recovered, in this study, only within the identified energy harvesting section, needs to be greater than or equal to this amount.

In this study, the section between Badulla and Gampola was identified as the optimum section for charging the battery because of the mainly downhill gradients and regular dynamic braking occurring on this incline. As such, it is vital that we quantify the total energy that can be harvested from the section of the journey to determine whether it will sufficiently meet, or supplement, the total auxiliary power requirement.

Table 3.2 outlined the average energy harvested during several segments of the trip, and has been further revised to account for total, cumulatively dissipated energy from Badulla to Gampola. A deeper analysis of cumulative energy dissipation gives a better perspective of the energy recovery potential of this charging phase. Cumulative energy dissipation for the trip segment from Badulla to Gampola is reported as 1768.7 kWh (See annexure for detailed calculation data). This assessment is an important one, for ensuring the feasibility of a battery assisted auxiliary power system as an idealized potential versus practical energy dissipation achieved according to expectations, on normal routes, and under standard route conditions.

According to the train schedule, the journey from Badulla to Gampola takes approximately six and half hours. Following this, an additional three and half hours are required to reach Colombo, completing the one-way trip. The return journey from Colombo to Badulla takes approximately ten hours, bringing the total duration of a full round trip to around twenty hours. Given the energy harvested through regenerative braking during the initial segment from Badulla to Gampola, it is estimated that the recovered energy is sufficient to power the train's auxiliary systems for the remaining 13.5 hours of operation. This effectively utilizes energy that would otherwise be wasted, thereby improving energy efficiency and sustainability.

This proposed energy recovery system also ensures operational reliability. In the event of unforeseen circumstances such as insufficient energy harvesting due to changes in braking patterns, lower-than-expected gradients, or degradation of battery performance, the existing auxiliary power supply, which includes diesel-powered generators, can seamlessly take over. This hybrid arrangement ensures that there is no compromise in service quality or safety, providing a dependable fall-back option in emergencies or low-charge situations.

The knowledge gathered in this, and earlier study sections serves as the foundation for the system's design. In conclusion, during the energy cycle's charging phase, the battery storage unit mainly uses the Badulla to Gampola segment to capture regenerative braking energy. Any extra energy that cannot be stored due to capacity limitations will be released as heat, just like in conventional dynamic braking systems.

The quantified data indicates that the total amount of recoverable energy in this segment is approximately 1.7 MWh (See Annexure). However, it is conservatively assumed that only a 1.2 MWh can be used to charge the battery storage system due to practical limitations, safety margins, and real-world inefficiencies. Despite this reduction, the energy collected still surpasses the estimated auxiliary power needed for the remaining round trip, which is less than 1.0 MWh.

This outcome shows that the proposed system is technically possible and could significantly improve energy efficiency in short-distance, low-gradient diesel-electric locomotives. The next section will provide a more detailed analysis of these values and how they affect system design, sustainability, and operational cost-efficiency.

CHAPTER 4

FEASIBILITY STUDY ON SYSTEM DESIGN

4.1. Synchronization of Regenerative Energy Dissipation with System Demands and Analytical Considerations for Feasibility Analysis

The information in the preceding sections makes it abundantly evident that the frequency and magnitude of the regenerative braking energy produced by DEMU engines are extremely erratic. Since batteries need a stable and regulated charging environment, this erratic behaviour makes it extremely difficult to directly channel the harvested energy into battery storage systems. Without appropriate regulation, efficiency losses, thermal issues, and deterioration of battery health may occur.

The results of the literature review indicate that maintaining battery performance, extending operational life, and guaranteeing safe operation through efficient charge/discharge cycle management all depend on a well-regulated and optimized charging strategy. The implementation of a specialized charge control mechanism is necessary to overcome the inherent inconsistency of regenerative energy. In order to ensure compatibility with the suggested voltage-current curve and thermal limits of the battery chemistry, this system should close the gap between fluctuating input energy and the battery's ideal charging profile [38]. A small-scale capacitor bank is suggested as an intermediary energy storage solution in order to achieve this. The purpose of this bank would be to temporarily store the instantaneous regenerative energy, which would then be released at a steady and regulated rate appropriate for charging the primary battery pack [31]. By successfully separating the dynamic nature of energy dissipation from the steady-state demands of battery charging, this buffering technique enhances system dependability, energy efficiency, and battery life [31].

Although the exact design, optimization of battery packs and BMS are outside the main scope of this study, a fundamental understanding of how battery chemistry affects overall system performance is necessary for an effective regenerative energy storage strategy. The literature review and earlier research findings highlight several significant factors that affect battery selection, such as chemical composition, safety

features, lifecycle efficiency, thermal behaviour, and economic viability. For the design requirement battery chemistry, safety and energy storage is taken into consideration.

Among the commercially available lithium-ion chemistries, LFP batteries are the most suitable option for rail-based regenerative energy storage systems. Comparative studies that emphasize LFP's intrinsic benefits—such as its exceptionally long cycle life of over 4,000 cycles, high thermal stability with safe operating temperatures up to 60°C, and superior safety profile because it resists thermal runaway and overcharging support this choice [32]. Additionally, because LFP batteries are composed of plentiful and non-toxic materials like iron and phosphate, they are less susceptible to market volatility and geopolitical supply chain risks than cobalt- and nickel-based chemistries like NMC [32]. These facts were explained clearly and in detail based on past research findings in the literature review part of this research.

Economically speaking, LFP batteries are about 30% less expensive per kWh than NMC batteries, which makes them especially appealing for large-scale applications where dependability and affordability are crucial, like railway systems. In locomotive applications, where space and weight are limited, the lower energy density of LFP batteries (usually between 130 and 160 Wh/kg) compared to their NMC counterparts (up to 250 Wh/kg) is not much appealing, yet acceptable, especially when considering the trade-off between cost-effectiveness, durability, and safety as per the major findings made at literature review based on past studies [64]. Hence LFP batteries are the best choice for the main energy storage subsystem in the proposed regenerative braking energy harvesting architecture because they have been thoroughly evaluated for performance, safety, sustainability, and practicality. Their strong features make them a reliable, efficient, and scalable storage platform for an eco-friendly rail transportation system that balances the energy that is produced and used in locomotive braking systems [32]

Auxiliary power demands peak at about 100 kW during engine start-up, according to field observations made on the S14 DEMU. This requirement drops to between 50 and 60 kW once steady operation is attained [57]. The auxiliary energy demand (apart from

battery charging) during the roughly 6.5-hour drive from Badulla to Gampola was assessed as follows using quantitative data gathered from field trips, earlier research findings, and conversations with locomotive experts:

- 1.7 MWh of regenerative energy could be harvested on average over the 6.5-hour trip.
- 70% system efficiency is assumed based on literature review for energy recovery and transfer to battery storage.
- The net energy available for charging batteries is $1.7 \text{ MWh} \times 0.70 = 1.2 \text{ MWh}$.

The estimated auxiliary loads for the 13.5-hour return leg of the journey were:

- The base auxiliary power requirement is 0.75 MWh, or $0.055 \text{ MW} \times 13.5 \text{ hours}$.
- A 20% margin was assumed based on literature review to account for variations in power demand (such as changes in the AC load or engine restarts): $0.75 \text{ MWh} \times 1.20 = 0.9 \text{ MWh}$
- Taking into account a 90% average LFP battery discharge efficiency: $0.9 \text{ MWh} \div 0.90 = 1 \text{ MWh}$ is the required stored energy.

In order to meet the auxiliary power demands during the return leg of the trip with sufficient efficiency and safety margins, a battery pack with a minimum usable capacity of 1 MWh is required. The total amount of regenerative energy captured (1.2 MWh) exceeds this requirement, allowing the system to fully charge the battery during the 6.5-hour braking phase. The existing resistor bank management systems can be used to release any excess energy above the battery's capacity, contingent on operational and safety requirements.

In view of these results, a 1 MWh LFP battery storage system is recommended for integration into the proposed energy harvesting architecture. This system should be developed in collaboration with global battery manufacturers, following safety

standards and contemporary best practices, in order to meet the sustainability goals outlined in this study.

4.2. Design of the Battery Storage System Considering Safety, Performance Parameters, and Available Technological Solutions

In view of these results, a 1 MWh LFP battery storage system is recommended for integration into the proposed energy harvesting architecture. This system should be developed in collaboration with global battery manufacturers, following safety standards and contemporary best practices, in order to meet the sustainability goals outlined in this study.

In hybrid locomotive applications, the proper placement of the battery storage system is a critical engineering and safety consideration. This is particularly true in systems like the S14 DEMUs, which operate under high thermal loads, continuous mechanical vibrations, and occasionally challenging crash environments. Optimal battery placement must address not only space availability and integration with existing subsystems but also safety, thermal management, structural integrity, and dynamic load distribution. Based on insights from Section 2.6, a quantitative and qualitative evaluation of battery placement alternatives was carried out.

4.2.1 Constraints and Risks in Locomotive Engine Compartment vs Safety and Structural Advantages of Passenger Compartments

The Environmental factors, structural integrity, operational safety, and thermal management must all be carefully taken into account when integrating battery storage systems into railway rolling stock. Despite being near the traction and braking systems, the engine compartment of the S14 DEMU is a very inappropriate location for batteries for a number of important reasons.

The S14 DEMU's engine compartment is known for its continuously high temperatures, which are caused by the large diesel engines, auxiliary systems, and inadequate airflow. Internal temperatures can often rise above 50°C during long uphill

trips or dynamic braking, which is significantly higher than the ideal operating range for the majority of lithium-ion battery chemistries. High temperatures can cause lithium-ion batteries to lose capacity and perform worse because they are thermally sensitive. More importantly, prolonged exposure to such temperatures without sufficient thermal regulation raises the risk of thermal runaway, a dangerous situation where the battery goes into an uncontrollably hot state that can cause an explosion or fire. The engine bay is a high-risk location for battery deployment since it lacks the sophisticated cooling infrastructure and thermal isolation needed to ensure the safe operation of a BESS [54].

The engine compartment faces high levels of mechanical vibration and shock in addition to thermal challenges because of its close proximity to the powertrain, bogies, and other dynamically loaded components. Over time, this kind of mechanical stress can weaken battery cell integrity, raising the possibility of internal short circuits and premature system failure [50].

Additionally, compared to passenger compartments, the locomotive's front section usually offers less crashworthiness in terms of crash safety. The results of the literature review, which were previously discussed, indicate that locomotive cabs are more susceptible to damage in the event of a frontal or lateral collision because they frequently lack the energy absorption zones present in passenger compartments. By putting battery systems in such a place, crew safety and emergency response may be at further risk from post-crash hazards brought on by battery rupture or fire.

In contrast, passenger compartments, especially reserved or air-conditioned compartments provide a much more controlled and stable environment for housing battery storage systems. These compartments are constructed with higher structural safety standards, including defined crumple zones, energy absorption structures, and better fire suppression systems [49]. Furthermore, passenger compartments typically experience less constant vibration and heat stress [50]. The temperature inside air-conditioned compartments stays within the optimal range for battery systems, and the battery modules' longer life cycles and increased dependability are guaranteed by the decreased mechanical agitation. Passenger compartments are a better setting for the

safe and effective integration of energy storage because of these benefits.

Nevertheless, there are certain difficulties in integrating battery systems into passenger compartments. Because they are heavy and dense, batteries can have a big impact on the compartment's dynamic stability, axle loads, and center of gravity. Uneven weight distribution from improper battery placement can reduce ride comfort, increase track wear, or even cause instability in curves or at high speeds which can increase the tendency of derailments [50].

A thorough weight distribution analysis is necessary to address the possible effects of battery integration on passenger compartment performance. The load-bearing capacity of different passenger compartment configurations, the additional mass that the battery packs add in relation to normal passenger loads, and the identification of safe and structurally suitable installation locations should all be considered in such an analysis. These areas need to accommodate battery placement without sacrificing operational safety, ride comfort, or vehicle dynamics.

4.2.2 Quantitative Weight Distribution Analysis and System-Level Impact Assessment of Battery Integration

A thorough quantitative analysis of weight distribution was conducted in order to assess the viability of incorporating a large-scale BESS into the current passenger rolling stock. In order to ensure compliance with safety thresholds established for Sri Lanka's railway infrastructure particularly on the upcountry line, which is marked by steep gradients, tight curves, and demanding dynamic loading conditions this assessment sought to ascertain the structural viability of integrating battery modules into the current passenger compartment configuration [11].

Using manufacturer provided specifications for each type of compartment within the S14 DEMU configuration, the analysis started by establishing baseline weight data for the train at maximum passenger occupancy. Two engine compartments and seven passenger compartments make up this arrangement (train formation).

The empty weight (tare weight) of each compartment was taken straight from the technical documentation of Sri Lanka Railways. In accordance with international engineering practice, a standard average body weight of 70 kg per passenger was assumed for passenger load estimations [65]. The fully occupied gross weight of each compartment was determined by adding the total live load for each compartment type to its tare weight, taking into account the manufacturer's recommendations regarding seating and standing capacity. The comparison between the anticipated weights resulting from the addition of battery modules and the current loading conditions was based on this thorough weight profiling. According to operational guidelines published by Sri Lanka Railways, the goal was to ascertain whether the compartments could structurally support the suggested battery systems without going over the safe weight limits per compartment (usually capped at 50 tons) and the total DEMU weight threshold (500 tons) [57][58].

The significance of preserving proper vehicle dynamics, including load balance, center of gravity, and crashworthiness, was also considered in the analysis. One of the main goals was to find structurally sound locations for batteries without sacrificing ride quality, safety, or derailment resistance. To sum up, this analytical method serves as the basis for choosing the best battery integration techniques that guarantee effective and safe energy recovery via dynamic braking systems. The following section provides an overview of the results and how they affect system design.

The selected DEMU formation under study consists of the following configuration:

- 2 × Air-Conditioned Reserved Compartments
- 1 × Second-Class Reserved Compartment
- 1 × Third-Class Reserved Compartment
- 1 × Second-Class Ordinary Compartment
- 1 × Third-Class Ordinary Compartments
- 1 × Third-Class Buffet/Cafeteria Compartment

Each compartment’s structural (tare) weight and passenger capacity were taken from manufacturer-provided data [66][67][68][69]. Passenger weights were calculated based on the standardized average value of 70 kg per person, following common railway engineering practice (See Tables 4.1 to 4.3).

Table 4.1: Compartment tare weights (without passengers) [66][67][68][69]

Compartment Type	Tare Weight (Tons)
Engine Compartment	74.0
Air-Conditioned	37.6
Second Class Reserved	33.4
Third Class Reserved	32.9
Second Class Ordinary	33.4
Third Class Ordinary	32.9
Third Class Buffet	33.7

Table 4.2: Passenger weight calculations [66][67][68][69]

Compartment Type	Seating/Standing Capacity	Total Passengers	Total Passenger Weight (Tons)
Air-Conditioned (Reserved Seating Only)	44 / 0	44	3.1
Second Class Reserved (Reserved Seating Only)	48 / 0	48	3.4
Third Class Reserved (Reserved Seating Only)	72 / 0	72	5.0
Second Class Ordinary	48 / 78	126	8.8
Third Class Ordinary	72 / 84	156	10.9
Third Class Buffet	50 / 92	142	9.9

Table 4.3: Combined gross weight per compartment (including passengers)

Compartment Type	Gross Weight (Tons)
Air-Conditioned (Reserved Seating Only) (×2)	40.7 each → 81.4 total
Second Class Reserved (Reserved Seating Only)	36.8
Third Class Reserved (Reserved Seating Only)	37.9
Second Class Ordinary	42.2
Third Class Ordinary	43.8
Third Class Buffet	43.6
Engine Compartments (×2)	74.00 each → 148.0 total

Total DEMU Weight under Full Load Conditions

$$\text{Total Weight} = \{(2 * 74.0) + (2 * 40.7) + 36.8 + 37.9 + 42.2 + 43.8 + 43.6\} \text{ Tons} = 433.7 \text{ Tons}$$

The maximum permitted gross DEMU weight for safe operation throughout the national rail network, including the difficult gradients and sharp curvature of the upcountry line, is 500 metric tons, in accordance with the technical guidelines supplied by Sri Lanka Railways' Original Equipment Manufacturer (OEM) [57]. In order to guarantee structural integrity, ride safety, and dynamic stability, the OEM also specifies a maximum gross weight limit of 50 metric tons per individual compartment [58].

According to the study's quantitative weight distribution analysis, the DEMU's total gross weight, when all passengers are seated, is roughly 433.7 metric tons. With a residual weight capacity of roughly 66.3 metric tons, this value stays well within the OEM's recommended upper limit. Depending on its design and passenger class, each passenger compartment typically exhibits an available margin between 7 and 13 metric tons. The air-conditioned (AC) compartments, in particular, have an extra weight tolerance of up to 9 metric tons per unit.

Based on the previously discussed safety standards and structural considerations, passenger compartments offer the highest degree of safety for battery integration compared to alternative locations within the rolling stock. A detailed spatial analysis indicates that, excluding designated crash zones, all compartments provide substantial space between the compartment bogies and beneath the passenger seating area. These under-seat and undercarriage regions present viable locations for battery installation, both in terms of structural integrity and thermal management which is a similar approach as chassis-based battery storage in EV industry (See Section 2.6 for more data).

Strategic placement of battery packs along the flat undercarriage beneath the passenger compartments is particularly advantageous. This configuration effectively lowers the DEMU's overall center of gravity, thereby enhancing ride stability, traction, and handling characteristics, especially critical for navigation through the steep gradients

and sharp curves typical of Sri Lanka's upcountry railway lines. Moreover, the structural design of the battery housing can be optimized to contribute to the overall torsional rigidity of the compartment, functioning as a semi-load-bearing component. From a thermal management perspective, integrating battery systems in the undercarriage region also facilitates passive and active cooling. The lower half of the battery enclosure can be exposed to the external environment, promoting natural air cooling. Furthermore, in compartments equipped with air conditioning such as the first-class air-conditioned compartments; there exists the potential to channel conditioned air for supplementary cooling of the battery packs, thereby improving system efficiency and lifespan. Given the generous spatial availability in the undercarriage area, battery modules can be distributed longitudinally across multiple compartments. This not only supports better weight distribution across axles but also minimizes localized structural loading. Consequently, the integration of BESS into the undercarriage of passenger compartments represents a technically feasible solution that adheres to safety and performance criteria, provided that proper engineering controls are implemented to maintain axle load limits and dynamic stability. Based on the insights gained considering space arrangement of different passenger compartments a CAD model was developed to analyse the S14 passenger compartment and allocation of space for battery storage. Figure 4.1 to figure 4.3 shows how this battery storage is going to be placed considering a CAD model.

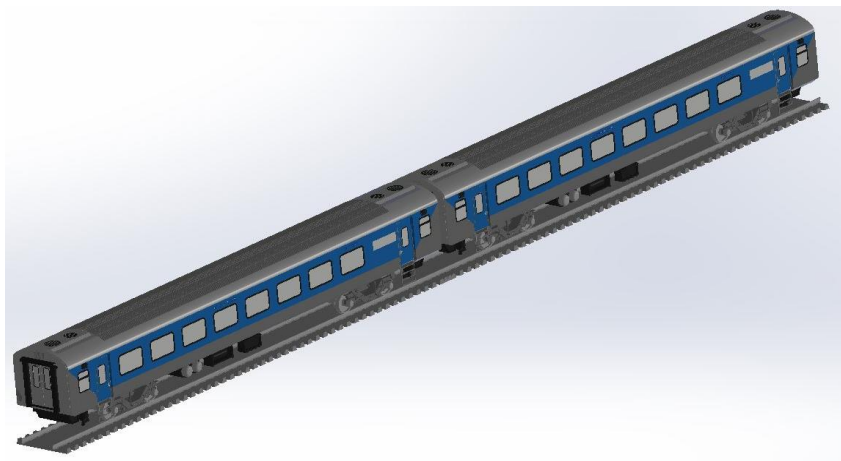


Figure 4.1: 3D CAD model of the passenger compartment of S14 DEMU (without seats)

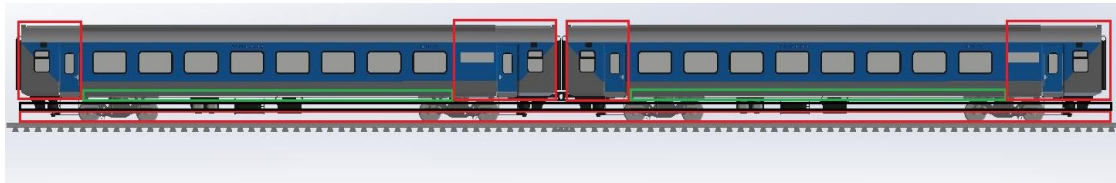


Figure 4.2: Different zones of the passenger compartment based on safety concerns

Figure 4.2 illustrates the classification of crash zones, buffer zones, and safe zones for battery placement, taking into account both safety and the balance of the compartment. The red-marked areas represent high-risk zones. These include the lower section of the undercarriage, which is particularly vulnerable to damage during derailments and collisions, and the two corners of the passenger compartment, which are designed as crash zones to absorb inertial forces and deform in the event of an impact. The buffer zone is shown by the black-shaded area immediately above the lower red zone. Although not as dangerous as the crash zones, debris from collisions or derailments could still affect this area.

The safest spot to install a battery, on the other hand, is indicated by the green-marked area. According to findings in the literature, this zone provides optimal structural balance for the DEMU and is further reinforced by the compartment's underframe and chassis components considered to be the most structurally robust. In addition to its structural advantages, this area benefits from effective ventilation due to its exposure to airflow during DEMU movement. It can also make use of the cooling provided by the compartment's air conditioning system. This location is the most appropriate for battery integration within the DEMU structure because of these features, which taken together address many of the important safety and operational considerations mentioned in the literature (See Section 2.6).

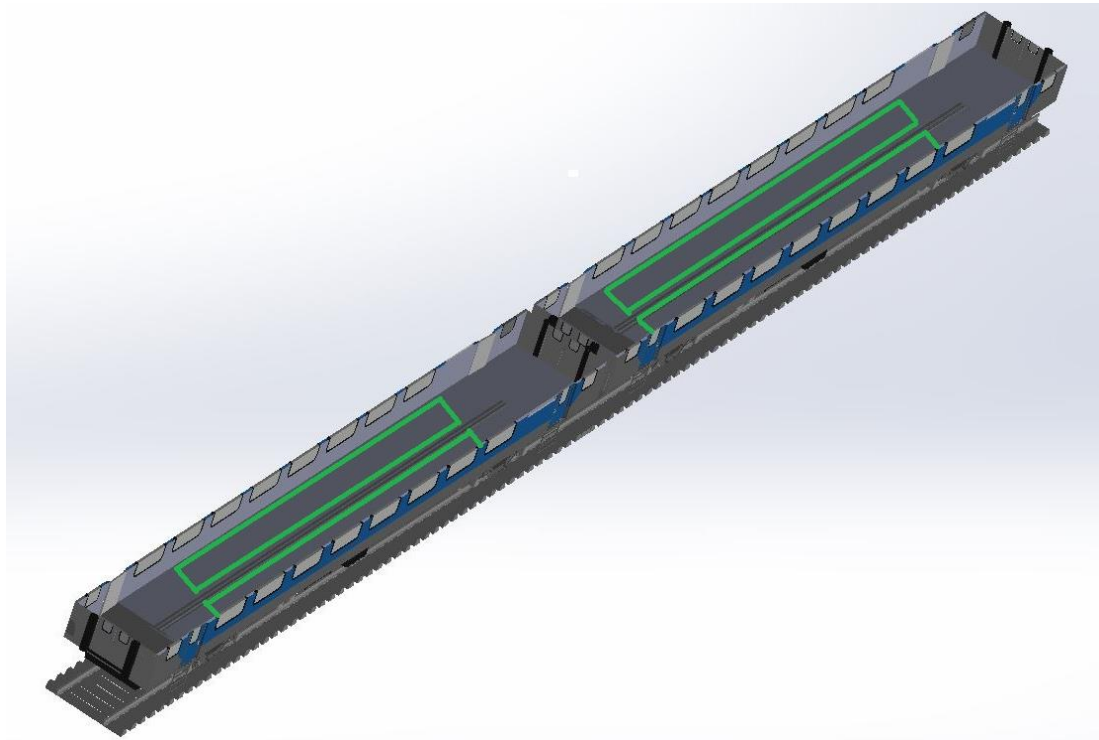


Figure 4.3: Cross section of S14 DEMU passenger compartment without seats and areas where battery storage can be assembled

Figure 4.3 illustrates the most suitable location for installing the battery packs as part of a distributed battery storage system to capture and utilize waste energy. This proposed location offers both safety and convenience in terms of accessibility and system integration. CFD simulations to analyse thermal management and battery system performance, and Finite Element Analysis (FEA) to evaluate structural integrity, can be used to further optimize the placement in subsequent phases of this study. Nonetheless, the chosen site is advised for battery installation within the parameters of this study since it is in line with the results of the literature review and the approaches used in earlier investigations. To satisfy the performance, safety, and integration criteria identified in the preceding sections, several battery manufacturers were contacted with the objective of developing a modular battery storage solution utilizing LFP chemistry [32].

A battery pack with an energy storage capacity of roughly 1 MWh has been determined to be appropriate for integration based on the input and specifications obtained from

multiple suppliers. A continuous discharge rate of up to 100 kW and a maximum charging rate of 150 kW are supported by this system's design. The chosen LFP systems can achieve 5,000 or more charge/discharge cycles under air-cooled conditions, guaranteeing long-term operational reliability, based on data from the literature review and vendor documentation [70].


According to supplier estimates, depending on the final configuration and structural enclosures, the battery pack's total weight will vary from 8 to 15 metric tons [70][71]. By distributing the battery modules along the passenger compartment's undercarriage above the structural frame and on the chassis, the modular design maximizes axle load balance, guarantees adherence to weight-related infrastructure limitations, and ensure overall safety including structural safety [53]. To keep the battery system within ideal operating temperature ranges and guarantee safety and long-term performance, air cooling features will be incorporated. Additionally, the air-conditioned first-class compartments provide the most practical setting for battery integration, according to the previously determined structural and spatial evaluations. Up to 9 metric tonnes of extra weight can be structurally supported by each of these compartments without sacrificing design safety limits. By utilizing the available undercarriage space and the close proximity to pre-existing HVAC systems, the battery system can be split equally between two of these compartments.

Furthermore, the air-conditioned compartments have the best structural protection and are ideally situated in the mid section of the DEMU's formation, reducing exposure to crash zones. This makes them perfect for critical system integration. Since the air conditioner and battery packs share a power source, their close proximity allows for shared thermal exchange interfaces and streamlines auxiliary power management, which is an additional operational advantage.

4.2.3 Development of Battery Storage Model Based Simulation on Key Parameters

To obtain information about a feasible BESS, several battery manufacturers were contacted. Following their advice, a suitable configuration for the battery module was created for the suggested system. The manufacturer gave us a lot of important


information for this development process, such as cell chemistry, nominal voltage, capacity, charge/discharge rates, thermal characteristics, and cycle life performance. Figure 4.4 provides the cell details and figure 4.5 provides cell module details provided by one of the battery manufacturers.



314Ah Battery cell

No.	Item	Parameter
1	Battery type	LFP
2	Nominal voltage/capacity	3.2V/314Ah
3	Nominal charging and discharging rate	0.5C
4	Range of cell voltage	2.5V~3.65V
5	Width	173.7±0.3mm
6	Thickness	71.5±0.5mm
7	Height (total height)	204.8±0.5mm
8	Height (body height)	200.2±0.5mm
9	Distance between poles	123.0±0.3mm
10	Cell weight	5.6±0.3kg

Figure 4.4: Cell chemistry details given by the battery manufacturer [70]



Battery module

No.	Item	Parameter	
1	Configuration	1P16S	
2	Nominal voltage (V)	51.2	
3	Voltage range	Minimum voltage (V)	46.4
		Maximum voltage (V)	56
4	Nominal capacity (Ah)	314	
5	Nominal energy (kWh)	16.0768	
6	Dimension (W*D*H, mm)	420*790*242	
7	Weight (kg)	118kg±1	
8	Ingress protection level	IP20	
9	Cooling type	Air cooling	

Figure 4.5: Battery module details given by the battery manufacturer [70]

As described in Section 2.5.1, cell to cell developed module and module to module develop pack shown by figure 2.14 was used to build up the BESS. The battery pack sizing is as follows,

- Cell Voltage = 3.2 V
- Cell Capacity = 314 Ah
- Cell Energy = 314 X 3.2
= 1004.8Wh
- Battery Module Capacity = 314 Ah
- Battery Module Voltage = 51.2 V
- Amount of cells used for battery module = 51.2 V / 3.2 V
= 16 Cells

Since battery capacity remains the same, all the cells are connected in series connection to build by battery module

As per the field test results the system needs to work under 600A and 1500V (see appendix “Field Test Results”) and to harness 1MWh power, the following requirements should be full filled;

- Module Energy = 51.2 X 314
= 16,076.8 Wh
- By linking 64 battery modules by 32 series connection and 2 parallel connection,
- Total Energy of the battery pack = 16,076.8 X 64
= 1,028,915.2 Wh
= ~ 1 MWh

- Battery Pack Voltage $= 51.2 \text{ V} \times 32$
 $= 1638.4\text{V}$

Accordingly, by developing this kind of a battery module assembly the required output can be obtained. To accurately model how the battery pack would act and work in real-world situations, the Battery Design toolbox (Battery Build App) in MATLAB Simulink was used [72]. This platform made it possible to make a battery model that was specific to the chosen module's needs. The modelling process was done in line with the most critical factors learned from the literature section in this. It is ensured that the battery configuration wouldn't affect the DEMU's structural integrity or balance, especially in crash zones and the center of gravity. The simulation model that came out of this work is a basic tool for predicting performance, analysing system integration and improving the BESS in rail applications in the future. However further simulations can be continued via MATLAB tools or either better simulation platforms like ANSYS. Figure 4.6 and figure 4.7 illustrates the newly developed battery storage system simulated through MATLAB.

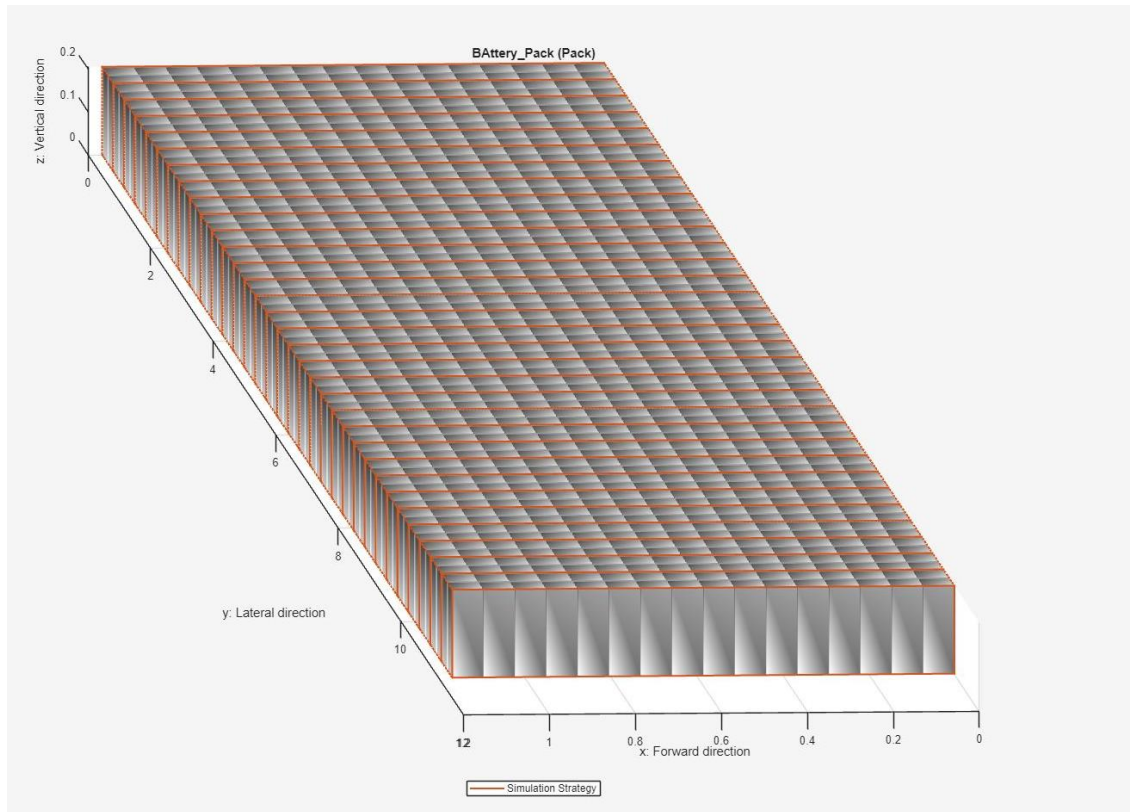


Figure 4.6: Battery pack design developed using MATLAB

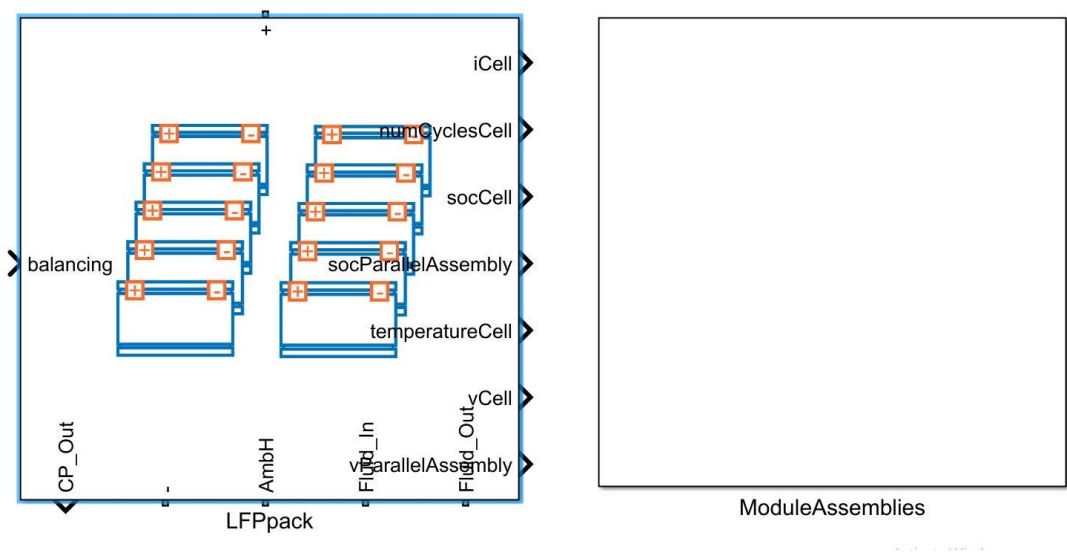


Figure 4.7: Battery pack optimization from MATLAB

To obtain deeper analytical insights, MATLAB was used to further explore the development of the battery cooling system and BMS [72]. But as mentioned earlier,

optimizing the overall design is outside the purview of this study. With the goal of integrating the BESS into the first class compartments(AFC) of a S14 DEMU, a preliminary battery pack design was created using the SOLIDWORKS modelling tool based on the results of MATLAB simulations.

The BESS was split into four distinct battery packs in order to make room for the entire BESS as well as to guarantee even weight distribution. Two of these battery packs were designed to be installed inside a single AFC compartment. A total mass of 4,984.3 kg was added into one AFC compartment since one battery pack is about roughly 2,492.2 kg in mass which is determined by the MATLAB-based design calculations (See Annexure MATLAB battery design).

Each battery pack measures 7,200 mm in length, 850 mm in width, and 250 mm in height. The dimensional layout of the battery pack as it fits inside the AFC compartment is shown in Figure 4.8.

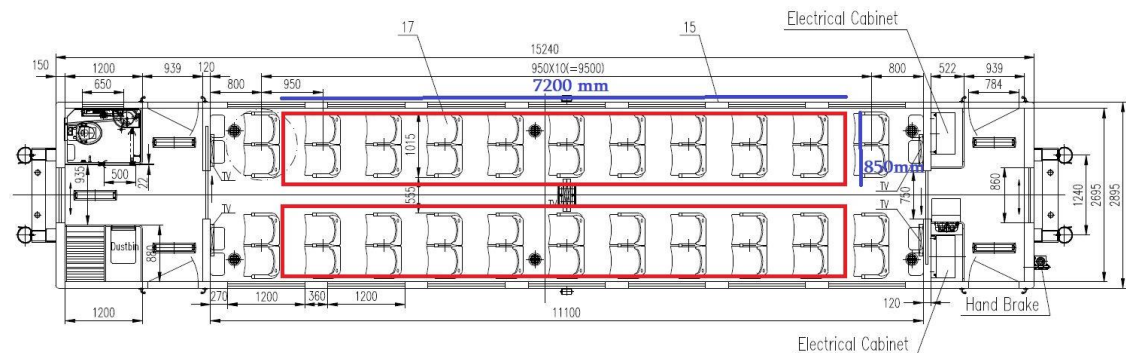


Figure 4.8: Battery module assembly layout within the dimensional layout of S14 AFC compartment

The battery pack was redesigned using SOLIDWORKS and incorporated into a 3D model of the AFC compartment based on the simulation results. This step was taken to support the design suggestions made in this study and to provide a clear visual representation of the spatial arrangement.

The top view of the battery arrangement inside the AFC passenger cabin is shown in

Figure 4.9, providing a clear illustration of the spatial arrangement. The isometric view of the battery pack assembly inside the same compartment of the S14 DEMU is shown in Figure 4.10, which highlights the design's structural fit and physical integration.

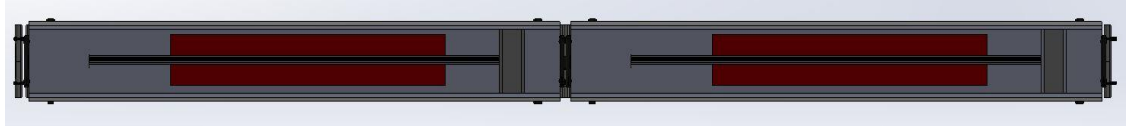


Figure 4.9: Top view of the S14 AFC compartment after installing two battery packs

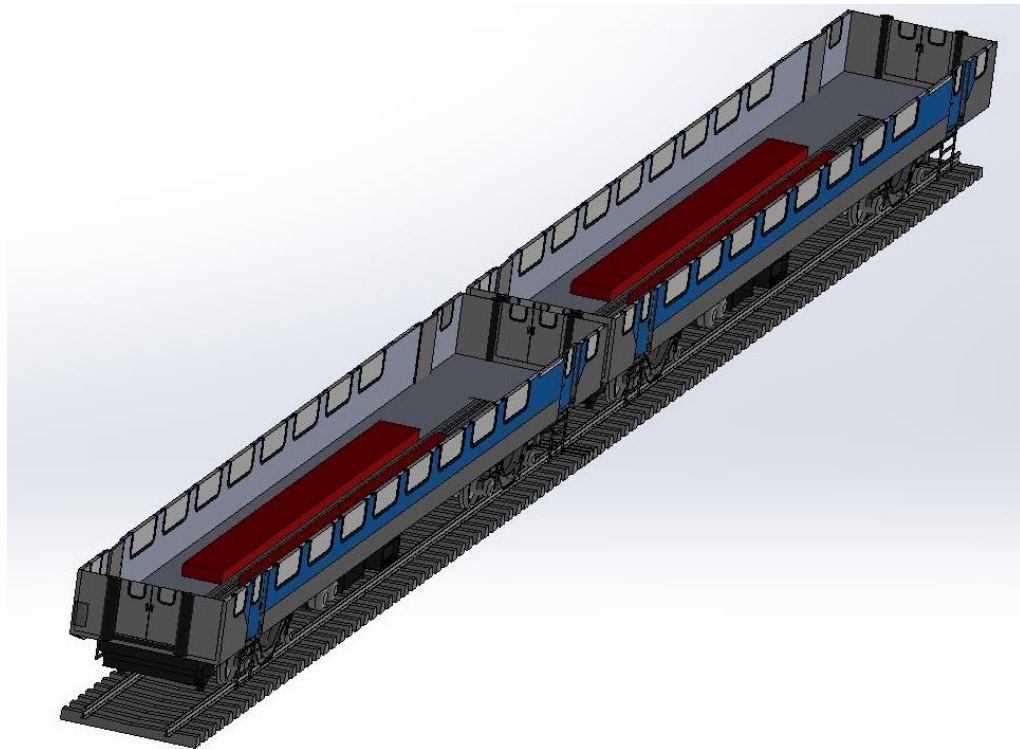


Figure 4.10: Isometric view of the S14 AFC compartment after installing two battery packs

An additional weight of 9,968.6 kg was incorporated into the DEMU on top of its normal gross weight. This increase, approximately 10 tons, represents about 2.3% of the total weight of the unit. Similarly, daily passenger demand varies between 100 and 130 passengers, which corresponds to roughly 2% of the total weight. Therefore, the impact of this additional weight on system mass and fuel consumption is considered negligible. This assumption is adopted in the subsequent cost calculations.

CHAPTER 5

RESULTS AND DISCUSSION

Evaluating the possible financial savings and sustainability benefits linked to the installation of a BESS in locomotive operations is a key goal of this study. A thorough cost comparison between the newly suggested battery-based dynamic brake energy capturing system and the current diesel-powered configuration has been carried out in order to precisely evaluate the proposed system's economic feasibility.

A thorough computation of current fuel consumption trends, energy losses dynamic braking, and associated fuel expenditure are all included in this analysis. The suggested system lessens the need for diesel fuel by introducing dynamic braking energy capturing system that can be utilized for auxiliary energy requirements of the DEMU. A comprehensive view of cost-effectiveness is provided by measuring the long-term operational savings attained through decreased fuel consumption and improved energy efficiency, as well as the capital investment necessary for the purchase, installation, and auxiliary subsystems of battery systems. The analysis also accounts for anticipated maintenance cost savings as a result of hybrid operation's reduced mechanical stress on diesel engines and brake systems.

Additionally, this cost analysis takes into account the sustainability effects of the suggested remedy, such as decreased GHG emissions, decreased particulate emissions, and conformity to more general environmental objectives and sustainable development goals [16]. These substantial but intangible advantages help make railway operations more robust and ecologically conscious. In the end, this comparative analysis supports SLR's decision-making by allowing them to evaluate the long-term environmental benefits of switching to a hybrid battery-powered locomotive system in addition to the financial return on investment.

5.1. Comparative Cost Analysis of the Proposed Battery Storage System Implementation

The financial implications of this research, especially the possibility of long-term cost savings through the installation of a battery-assisted energy storage system, are among its most important findings. A structured quantitative analysis that focuses on two main cost components; the capital investment needed for battery pack integration and current fuel consumption expenses has been carried out in order to assess these financial outcomes in a quantifiable and objective way.

The economic choices related to switching from a traditional diesel-only operation to a hybrid (diesel+battery) configuration are particularly covered in this section. This analysis offers an evidence-based framework for evaluating long-term affordability by calculating the initial cost of purchasing and installing a battery system in addition to the anticipated cost savings from unexpected increase in energy use. The method provides a clear understanding of the financial return on investment over time by comparing the current operational costs with the operating conditions under battery-assisted performance in the future. For SLR looking for financially feasible ways to update rail transport systems while adhering to energy efficiency objectives, this cost analysis will be vital.

The main source of power for the traction and auxiliary systems of the S14 DEMU is its MTU 12V4000R41 diesel engine. In addition to auxiliary generators that provide power to non-traction systems like lighting, fan-driven ventilation, and buffet requirements, this engine powers the main generator that propels the wheels. Several field tests were carried out under various operating conditions in order to determine the fuel consumption specifically related to auxiliary power requirements. However, because of the integrated nature of the power distribution where a single engine simultaneously supplies energy for both propulsion and auxiliary demands, it was difficult to separate the auxiliary fuel usage from the overall engine consumption.

As a result, manufacturer-provided specifications were used as the primary basis for estimating fuel consumption. According to MTU's technical documentation, the

specific fuel consumption of the 12V4000R41 engine at rated power is approximately 205 g/kWh [73]. In addition to the main DEMU engine, the AFC compartments on the S14 DEMUs are powered by independent Deutz F6L 912 diesel engines, which are specifically installed to meet the cooling and ventilation demands of these compartments. According to manufacturer specifications, these engines exhibit a specific fuel consumption of 222 g/kWh under rated operating conditions [74]. The density of Lanka Diesel (Regular Diesel) supplied by CEYPETCO is specified within the range of 820 to 860 kg/m³ at 15°C, based on their official product specifications and this density is determined using standard test methods, namely ASTM D1298 and ASTM D4052. However, for applications in Sri Lanka Railways, an exact density value is not formally provided. Industry experts suggest that the diesel used tends toward the higher end of this range. Therefore, for the purposes of calculations in this study, a density value of 850 kg/m³ has been assumed [75]. For this study, the density of diesel fuel is set at 0.85 kg/L, which is a common value used in analyses of thermodynamic and energy systems. This number is very important for changing mass-based fuel consumption data into volumetric terms, which are better for figuring out costs and planning logistics.

5.1.1 Estimation of Fuel Consumption – Baseline for Auxiliary Systems

To evaluate the economic feasibility of integrating a battery storage system, a foundational step is the accurate estimation of fuel consumption associated with existing auxiliary power requirements. This includes energy consumed by both the main diesel engine for onboard auxiliary systems and the standalone engines used in AFC compartments

- Diesel fuel density: 0.85 kg/l
- Specific Fuel Consumption (SFC) – Main Generators: 205 g/kWh
- Specific Fuel Consumption (SFC) – AFC Engine: 222 g/kWh

- Fuel consumption per kWh for main generator: $(205 \text{ g/kWh}) / (850 \text{ g/l})$
 $= 0.2 \text{ l/kWh}$

Assuming a constant auxiliary load of 35 kW, fuel consumption is:

- $35 \text{ kW} \times (205 / 850) \text{ l/kWh} = 8.4 \text{ l/hr}$
- Fuel Consumption per kWh for AFC Engine: $(222 \text{ g/kWh}) / (850 \text{ g/l})$
 $= 0.3 \text{ l/kWh}$

Assuming a typical operating load of 20 kW, the fuel consumption will be:

- $20 \text{ kW} \times (222 / 850) \text{ l/kWh} = 5.2 \text{ l/hr}$

Total Estimated Diesel Consumption for Auxiliary Loads:

- $8.4 + 5.2 = 13.6 \text{ l/hr}$

5.1.2 LFP Battery System based on Supplier Recommendations

To evaluate the viability of deploying LFP battery solutions, many battery suppliers/manufacturers were contacted in an attempt to replace the diesel-powered auxiliary systems of DEMUs. Finding a solution that could satisfy the particular energy requirements of the auxiliary subsystems while maintaining conformity with the overall DEMU design and safety regulations was the goal. Off-the-shelf modular battery systems were covered in most supplier responses. To meet the particular needs of railway traction applications, these standard modules usually have to be redesigned and modified. Appropriate capacity sizing to meet load needs, integration with current onboard electrical systems, and efficient thermal management were crucial elements that required attention in order to guarantee operating safety and performance stability under a variety of environmental circumstances.

Proposed Battery Solution Overview[70][72]:

- Design life: 10 years
- Cycle life: >6000 cycles (at 80% DoD)
- Battery type: LFP 1P16S
- Weight: ~118 kg
- Dimensions: 420 mm × 790 mm × 242 mm
- Communication protocols: RS485, CAN
- IP rating: IP20
- Operating temperature range: -20°C to 55°C
- Charging Voltage: 56V
- Max charge / discharge current: 628A
- Quoted base price for battery modules: USD 121,428 (see Appendix)
- Estimated additional costs for packaging, cooling, charging system integration as per the supplier recommendations (30–50%) [76]: Considering worse case of 50% price addition
- Total Battery System Cost:
 $121,428 \text{ USD} \times 1.5 = 182,142 \text{ USD}$
- Exchange Rate Assumption: LKR 300 = 1 USD (as on 2nd July 2025)
- Total System Cost in LKR:
 $182,142 \times 300 = 54,642,600.00 \text{ LKR}$

5.1.3 Overall Cost comparison (Current System and Suggested System)

Existing Diesel based Auxiliary Operation

- Fuel consumption per hour: 13.6 l
- Journey duration: 20 hours
- Diesel cost per liter: LKR 289 (as on 2nd July 2025)
- Total cost per journey (current system):

$$13.6 \text{ l} \times 20 \times 289 = 78,608 \text{ LKR}$$

Battery based Auxiliary Operation

- Battery backup duration: 6.5 hours (As proposed, during this time window, the dynamic braking energy is used for charging the batteries therefore the diesel engines are in operation to power up the auxiliary systems of the DEMU)
- Total cost per journey (with battery):

$$13.6 \times 6.5 \times 289 = 25,547.6 \text{ LKR}$$

Diesel Cost Savings Per Journey

- $78,608 \text{ LKR} - 25,547.6 \text{ LKR} = 53,060.4 \text{ LKR}$
- Annual saving (Assuming 300 operating days):
 $53,060.4 \times 300 = 15,918,120 \text{ LKR}$
- Payback period:
 $54,642,600 / 15,918,120 = 3.4 \text{ years}$

Long term Economic Impact

Given that, the battery system has a cycle life exceeding 6000 full cycles, and assuming one cycle per operational day:

- Operational days per year: 300
- Projected cycle life:
 $6000 / 300 = 20$ years

However, conservatively applying the manufacturer-recommended usable lifespan of 10 years:

- Total savings during payback (10-year period):
 $(10 - 3.4) \times 15,918,120 = 105,059,592$ LKR

This demonstrates a net economic gain exceeding LKR 105 million within the conservative 10-year battery life. Additional indirect financial benefits, such as reduced engine runtime, lower maintenance and overhaul frequency, and minimization of auxiliary generator-related downtime, are not quantified here but represent further cost efficiency. Furthermore, at the end of the battery's useful life, repurposing or resale to battery recycling markets may yield residual value, enhancing the overall return on investment.

5.2. Attainable Sustainability Goals through System Implementation

In addition to its economic impact, the proposed BESS's long-term contribution to environmental responsibility and sustainable development has been assessed. The quantification of ecological benefits that go beyond short-term cost savings is a key result of this study. In particular, the solution dramatically lowers the DEMU fleet's overall fuel consumption by lowering dependency on diesel-powered auxiliary systems. The environmental impact of railway operations is subsequently reduced, and ambient air quality is directly improved as a result of the significant decreases in GHG emissions and other dangerous pollutants.

Adoption of cleaner energy sources is facilitated and alignment with national and international climate goals is strengthened by switching to a battery-powered auxiliary system. It supports international frameworks like the Paris Agreement and is in line with the Sustainable Development Goals (SDGs) of the United Nations, specifically:

- SDG 7: Affordable and Clean Energy
- SDG 9: Industry, Innovation, and Infrastructure
- SDG 13: Climate Action

Additionally, as a result of this modification, diesel engines operate for shorter periods of time, which reduces mechanical wear and tear and, consequently, the long-term need for maintenance and spare parts. This indirect sustainability benefit reduces resource usage and related emissions from manufacturing and maintenance logistics.

A long-term emissions reduction study was carried out using projected fuel savings and standardized emission factors in order to analytically evaluate the proposed system's environmental impact. The estimated overall decrease in diesel consumption over a ten-year operational period is computed as follows:

$$\begin{aligned} \text{Total Fuel Saved} &: 13.6 \text{ l/h} \times 13.5 \text{ h/day} \times 300 \text{ days/year} \times 10 \text{ years} \\ &= 550,800 \text{ l} \end{aligned}$$

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 [57]. Accordingly, based on the Environmental Protection Agency's 2020 National Emissions Inventory for U.S. locomotives, it is assumed that U.S. line-haul locomotives classified as Tier 1 exhibit emission levels comparable to those of the S14 DEMU. Based on these results, the emissions were converted using Table 5.1 to calculate the total emissions produced by the diesel combustion of the S14 DEMU.

Table 5.1: Emissions made as per the environmental protection agency's , 2020 national emissions inventory [77]

Pollutant	EPA (g/gal)	Converted (g/l)	Converted (kg/l)
Carbon Dioxide (CO ₂)	10,150	2,681.35	2.68135
Nitrogen Oxides (NO _x)	120.5	31.83	0.03183
Carbon Monoxide (CO)	26.624	7.03	0.00703
Particulate Matter (PM)	2.95076	0.78	0.00078
Sulphur Dioxide (SO ₂)	0.0939	0.0248	0.000025

Based on the findings made on table 5.1, the cumulative emission reductions (with the savings of 550,800 l of diesel over 10 years' time) are summarized by table 5.1:

Table 5.2: Green house gas emission savings over the period of 10 years

Pollutant	Emission Factor (kg/L)	Total Reduction
Carbon Dioxide (CO ₂)	2.68135	1,476,888 kg \approx 1,476.9 metric tons
Nitrogen Oxides (NO _x)	0.03183	17,532 kg \approx 17.53 metric tons
Carbon Monoxide (CO)	0.00703	3,872 kg \approx 3.87 metric tons
Particulate Matter (PM)	0.00078	429.6 kg \approx 0.43 metric tons
Sulphur Dioxide (SO ₂)	0.000025	13.77 kg \approx 0.01 metric tons

Lowering carbon dioxide emissions directly helps to mitigate climate change, while lowering sulphur dioxide, nitrogen oxides, and particulate matter helps to improve public health and ensure that air quality regulations are followed.

In summary, the installation of the battery storage system promotes a strategic transition to low-emission transportation infrastructure while also improving the energy efficiency of railroad operations. The value of the environmental benefits lies in promoting a railway network that is resilient, future-ready, and environmentally conscious, even though they might not be immediately measurable in monetary terms.

CHAPTER 6

CONCLUSION

6.1. Research Summary

This work looks into whether it is possible and useful to use dynamic braking energy from diesel-electric locomotives running on Sri Lanka's railway network, with a focus on the Class S14 DEMU. The research suggests using a BESS to recover and reuse braking energy, which is usually lost as heat through resistor banks, for extra power needs on the upcountry railway line, which has steep inclines, sharp curves, and lots of braking zones. Furthermore, these findings can be readily applied to the S12 and S10 DEMUs, which operate under similar working conditions and share the same technical parameters. Thus, this new contribution to sustainable rail transportation can be effectively integrated within the Sri Lankan context, specifically targeting this class of engines.

To test this possibility, an experimental method was used involving data from on-board data loggers and manufacturer specifications. Because it was difficult to directly measure high-voltage and high-current electrical parameters during operation especially since access to the main traction circuitry was limited an indirect estimation method was used. The results showed that about 3.5 MWh of energy is lost on a full round trip. When locomotive pilot brake on the way down from Badulla to Colombo, the train lose about 2.4 MWh of energy. More importantly, during the most efficient descent phase between Badulla and Gampola, there is about 1.7 MWh of recoverable braking energy. Prior studies confirm that nearly 70% of this energy can be effectively stored through a properly managed dynamic braking and BESS. A detailed system-level design was proposed for integrating a 1 MWh LFP battery storage system into existing rolling stock infrastructure. Structural and weight distribution studies showed that it is technically possible to put the battery modules in the undercarriage space of AFC compartments. This setup not only meets the limits for axle loads and gross compartment weight, but it also makes the compartment more stable by lowering the center of gravity.

There was also a detailed cost-benefit analysis. The proposed battery system, which is expected to cost about Rs. 55 million, is expected to pay for itself in less than four years. The system could save over Rs. 105 million on diesel costs over the course of its expected 10-year life. The system helps long-term environmental sustainability goals by reducing reliance on diesel fuel and cutting down on GHG and other pollutant emissions, in addition to providing financial benefits. Over the course of ten years, the system can prevent burning 550,800 L of diesel fuel, which means it can stop the release of more than 1,470 metric tons of CO₂ and other harmful substances.

6.2 Publications

The Part of this study is published in the IESL Annual Sessions in 2024.

- **H.K.K.K. Madhumal**, J.G.A.S. Jayasekara, N.C. Sapumanage, L.U. Subasinghe, “Quantifying Energy Wastage in Dynamic/Regenerative Braking of Diesel-Electric Multiple Units on Sri Lanka's Upcountry Railway Line: Toward Enhanced Energy Recapture and Utilization”, Annual Sessions of IESL, pp. 583-595, 2024. Online: <https://app.box.com/s/qmk1gcyi8w7z6sf7q1v84n93ysf1ggot>

Another Part of this study is submitted for reviewing to be published in the International Conference on Business Research 2025.

- **H.K.K.K. Madhumal**, J.G.A.S. Jayasekara, N.C. Sapumanage, L.U. Subasinghe “Sustainable System Design for Harvesting Dynamic Brake Energy in Locomotive Engines: Enhancing Economic Savings and Sustainability in Rail Transportation” , International Conference on Business Research (Pending Approval).

6.3 Limitations and Challenges

The DEMU being studied has a separately excited DC traction motor system that is powered by a DC generator that can deliver about 2000V and 1000 A[58]. This gives it an average power output of about 1270 kW[57]. Because of the high voltage and

current levels, it was not possible to directly measure power flow during operation using external instruments. In addition, operational safety rules make it illegal to add third-party measurement circuits to the main traction power loop while it is in use. Because of these limitations, it was not possible to get real-time data on power dissipation and energy use from outside sensors or measuring instruments. Instead, the DEMU's built-in data logging systems were the only ones that were used. These onboard loggers gave us a starting point for figuring out energy use trends, but since we couldn't measure them directly, we had to make a lot of assumptions and interpolate data, which always leaves room for error. Even though we tried our best to make sure the results were accurate by comparing them to manufacturer specifications and previous studies, the fact that there was no permanent energy metering (like a dedicated logger connected to resistor grids or traction motors) made the results less accurate.

The choice of battery and the way the system was put together were also mostly based on general design rules. This study did not go into great detail about engineering analyses, such as detailed charge-discharge behaviour, thermal management, cycle life degradation, and advanced battery modelling. It did, however, look at basic sizing and operational needs. The final design parameters for storage were based on initial field assessments and manufacturer recommendations instead of being fully optimized through simulation or validated data.

Limitations in collecting field data also affected estimates of the effects on the environment. During the up and down trips between Badulla and Colombo, it was not possible to do full emissions testing, like exhaust gas analysis or fuel combustion profiling, even though indicative testing was done to look at operational trends. So, we used standard emission coefficients and fuel savings over the expected operational lifecycle to figure out the environmental benefits, like lower emissions. Lastly, the study had to make a number of simplifying assumptions because real-world operations are complicated and there isn't any perfect monitoring infrastructure. The thesis clearly states these assumptions, which were needed to fill in gaps in the empirical data. However, it is known that adding a permanent and high-resolution energy monitoring

system and looking more closely at battery performance parameters would make future research much more reliable and useful.

6.4 Future Work and Research Directions

This study is the first to look closely at how dynamic braking systems can be used to dissipate energy on Sri Lanka's railway network. As a result, it is a basic study that opens up many paths for more research and technological progress to make locomotive operations more sustainable.

One of the foremost priorities for future work is the comprehensive acquisition of real-time field data while the DEMU is operating under typical service conditions. Although this study relied on the DEMU's built-in data logging system, validation of the current findings and refinement of system parameters require the deployment of an independent, high-resolution remote data logger. This separate system should be added to the existing system in a way that doesn't get in the way. It should be able to measure the voltage and current profiles across the resistor grids, which will give us accurate information about dynamic braking energy losses. This kind of system would make it easier to analyse energy balances and make predictions about fuel savings and emissions reductions more reliable.

At the same time, the need for extra power must also be looked at again by measuring the actual load during field operations. The current values, which are based on the manufacturer's specifications, show the worst-case design conditions and may be higher than what is actually needed. By recording real auxiliary load profiles, especially when the temperature and other conditions change, the battery storage system can be made even better in terms of size and cost. This would make it possible to come up with a cheaper way to store energy without lowering the system's reliability.

Adding terrain profiles and driver behaviour to the energy modelling framework is another important area for future research. This study did not look at these kinds of factors in a quantitative way. However, how you drive, especially how fast you

accelerate, how hard you brake, and how well you control the throttle, has a direct effect on how much energy you can recover through dynamic braking. Adding AI and ML algorithms can make it easier to study these behaviours in a more advanced way. You can make a predictive driving model by comparing GPS-based elevation data with how much you use the throttle and brakes. You can use advanced filtering methods like Kalman Filters or other AI-based optimization methods to find and improve patterns. This makes it possible to create a driver-assist system that encourages energy-efficient train handling and makes the most of regenerative braking.

When thinking about future locomotive designs, it might be possible to look into a hybrid auxiliary power architecture that directly uses the energy from braking to power auxiliary systems. This could mean that the dedicated diesel-powered auxiliary generator units will have to be smaller. But it's a good idea to keep a regular auxiliary system as a backup in case the battery system fails. This is for safety and redundancy.

In addition, Sri Lanka's current railway practices rely heavily on mechanical braking to stop trains, especially at stations. With more testing in the field and improvements to the AI-based driving models, it will be possible to come up with the best braking strategy, which combines dynamic and mechanical braking. This approach not only conserves more energy but also significantly reduces wear and tear on mechanical brake components. Such strategies are particularly beneficial in suburban and flat terrain operations, where frequent stops occur and dynamic braking energy is presently being entirely wasted as heat.

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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-haNy3v0AMRdgR9dVIDOuDEI3OCXQ?usp=drive_link