

Energy Efficiency Strategies in Railway Transportation: Technologies, Modeling, and Operational Approaches A Review

Aravindh Balan

Project Manager, Freelance Post Doctoral Scholar inline hydraulics GmbH, Germany
draravindhbalan@gmail.com

Abstract: *The enhancement of the energy efficiency of railway transport has turned into an urgent task due to the rising mobility demand and the rising concerns regarding the environment. Even though the railways are already more energy-efficient than most other modes of transport, additional energy consumption and emissions cuts are necessary to meet sustainability goals. The paper will introduce in-depth review of the energy-efficient techniques in the railroad system, including both technological, infrastructural, modelling and operational techniques. Major technologies, including regenerative braking, onboard and infrastructure-based energy storage systems and other alternative propulsion technologies, including fuel cell-battery hybrid systems, are addressed. The paper also discusses advanced modeling and simulation frameworks that are needed to study the dynamics of trains and traction power supply and the energy flows. In addition, operational strategies to decrease energy consumption such as speed profile optimization, coasting control, time-based energy optimization and traffic control in terms of headway control are discussed. This review offers a comprehensive picture of how coherent technological and operational strategies could deliver a great deal of energy efficiency to the railway transportation systems.*

Keywords: Energy Efficiency, Railway Transportation, Regenerative Braking, OpenTrack, Electrical Traction

I. INTRODUCTION

The rising environmental concerns in the world and the rising demand for rail services have made energy efficiency and sustainability become the topics of concern in the railway transportation industry. Though the current state of rail transport can already be regarded as a form of further energy savings, among the most energy-efficient forms of transportation, a decrease in carbon emissions is necessary to achieve long-term sustainability objectives [1]. Therefore, the design and execution of energy management strategies with high energy efficiency have become a subject of much concern over the past few years.

One of the most important technological improvements that has led to better energy efficiency is the usage of regenerative braking systems. Mechanical braking parts in traditional rail converted the braking energy into heat. However, modern rail vehicles are becoming increasingly fitted with mechanisms through braking energy into electrical power, which can subsequently be reused to operate onboard auxiliary loads, heating and cooling systems or fed back into the traction power network [2]. Such technologies significantly decrease the total energy demand and are an important part of energy-efficient railways[3].

Technological solutions are not the only factor that can impact the railway energy performance; the operational and planning strategies have a strong influence as well. Capacity of railway, which is the number of movements that the infrastructure can handle within a given time under certain operational conditions [4], is not only dependent on physical infrastructure but also on operational practices, scheduling ways and traffic interactions. The International Union of Railways (UIC) underlines that these factors are decisive in the occurrence of capacity since the values of theoretical



capacities are hardly achieved in reality [5]. Effective time schedule planning and traffic control may, therefore, help not only to increase capacity utilization but also to decrease energy use.

In order to overcome these problems, operations research modelling and optimization techniques are extensively used in the analysis of the railway systems. Scheduling theory offers a paradigm for resolving the issues concerning the train schedules, capacity allocation, and passenger transportation planning, in which the quality of services and energy efficiency should be addressed collectively [6]. This paper is an overview of energy efficiency measures in railway transportation, which includes regenerative energy technologies, energy-conscious modelling methods, and techniques of optimization of operations. The review aims to highlight significant trends and challenges, and future trends on how more sustainable railway operations can be attained by synthesizing recent studies.

A. Structured of the Paper

The paper is organized as follows: Section II reviews the energy-efficient technologies in railway systems. Section III includes modelling and simulation systems of energy-efficient railway analysis. Section IV explains the strategies for operational energy efficiency in railway transport, and Section V presents the literature on the research. Lastly, the paper has its conclusion, followed by the identification of future research directions, in Section VI.

II. ENERGY-EFFICIENT TECHNOLOGIES IN RAILWAY SYSTEMS

Train travel has long been seen as a form of green transport with major competitive benefits in terms of environmental sustainability and energy efficiency. According to a recent estimate by the International Union of Railways, usual rail emissions per passenger kilometer on wing/wake "well-to-wheels" account for around one-sixth of all air travel[7]. Meanwhile, by adding renewable energy sources to the electrical grids, electrified passenger lines may significantly reduce emissions.

Table I provides a few instances of onboard ESS implementations. It is evident that the majority of them rely on supercapacitors. High-power Li-ion and NiMH batteries are better options when a high degree of independence is needed[8]. Technical issues caused ALSTOM to cancel the concept for Flywheels were used in onboard ESSs on the Citadis tram in Rotterdam. This method received less attention because of certain cost and safety concerns.

Table 1: Onboard Energy Storage System (ESS) Technologies and Their Railway Applications

Technology	Provider, Commercial Product	Applications
Supercapacitor	Bombardier, MITRAC Energy Saver	Light rail, 750 V, Mannheim, (Germany), 2003
Supercapacitor	Siemens, Sitras MES	The (Austrian) tram in Innsbruck
Supercapacitor	CAF, ACR system	Tram in Granada, Saragossa, and Seville, (Spain)
Supercapacitor	Alstom, STEEM	Paris (France) tram, 2009
Li-ion	Kinki Shayro, LFX-300, streetcar	(North Carolina, USA), Charlotte, 2010
Ni-MH	Alstom – Saft	Nice (France) Tram, 2007
Flywheel	Alstom & CCM, Citadis	Rotterdam (Rotterdam) tram, 2004
Hybrid Supercapacitor + Ni-MH	Siemens, Sitras HES	Lisbon, (Portugal), light rail, 750 V DC, 2008

A. Rolling Stock–Level Energy Efficiency Technologies

As explained below, the electrical and mechanical sub-modules make up the traction mechanical subsystem's ROS module. Given the available line voltage information, the pantograph electrical values are then determined by the interaction with the electric sub-module, such as absorbed power and current, after motion equations are applied using train characteristics and track data to apply the motion resistance of the train.

The ETN module actually transmits the train operating conditions back to the ROS electric sub-module and then to the mechanical sub-module to handle instances of insufficient or excessive voltage at the pantograph (e.g. lowering traction



power and converting to mechanical or electric dissipative braking from regenerative braking)[9]. Train movement is used to manage traffic and avoid collisions with an exceptionally quick simulation time (often between 0.1 and 1 s, although there are no restrictions on how quickly it may be reduced). It connects to a signalling and traffic management system module that is streamlined.

B. Infrastructure-Level Energy Optimization Technologies

Figure 1 illustrates how the train traction system's smart electrical architecture is built on energy storage.

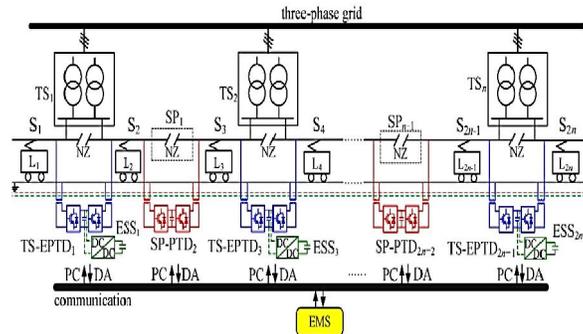


Figure 1: The Smart Electrical Infrastructure Based on Energy Storage for The Railway Traction System

How the current AC-fed train infrastructure with NZs is shown by the red dashed line. For analytical reasons, it is assumed that every locomotive on the same power supply segment has the same electrical locomotive load. There are n TSs in the current system, and trains L_k ($k = 1, 2, \dots, 2n$) are supplied by TS_m ($m = 1, 2, \dots, n$) in the power supply sections S_k . The NZ provides electrical insulation between two adjacent power supply portions[10].

The green dashed line indicates how the recommended energy-storage-based smart electrical infrastructure is laid out. The upgraded EMS is made up of additional PTDs and EPTDs that are linked in parallel to each of New Zealand's two sides. The PTDs and ESS found in the TSs' NZs are referred to by the abbreviation TS-EPTD. In the other NZs of the SPs, the PTDs are referred to by the acronym SP-PTD. Installing TS-EPTDs completes the improved system and removes the requirement to install EESs in SP-PTDs by connecting all power supply sections to ESSs. The EMS uses both active and reactive bidirectional communication technology to specify the power supplied by PTDs and EPTDs. The altered system is capable of both distributed and centralized control.

The systems' energy-management performance may be greatly improved by the centralized architecture's ability to carry out a global optimization to achieve each component's cooperative actions[11][12]. The railway systems' redundancy and dependability may be further improved via distributed control. With the use of bidirectional communication equipment, DA of voltage and current on each power supply segment may be completed by each EPTD and PTD, and the data may be sent to the EMS[13]. The EMS uses voltage and current data to do a worldwide optimization. To have PC over the EPTDs and PTDs, it also makes use of bidirectional communication devices. It should be mentioned that the recommended method is compatible with railway systems that use autotransformers (AT).

C. Alternative Propulsion and Renewable Energy Integration Technologies

As seen in Figure 2, the complete system may be broadly separated into three subsystems.

In both cases, the energy sources are an essential component of the system, supplying the stationary system with heat and electricity in the V2G model [14] or the electrically powered auxiliary and onboard traction systems in passenger train mode[15]. Considering the relatively simple integration, the predictably declining cost of the polymer electrolyte membrane (PEMFC) fuel cell, and the unpredictable regional passenger train duty cycles.



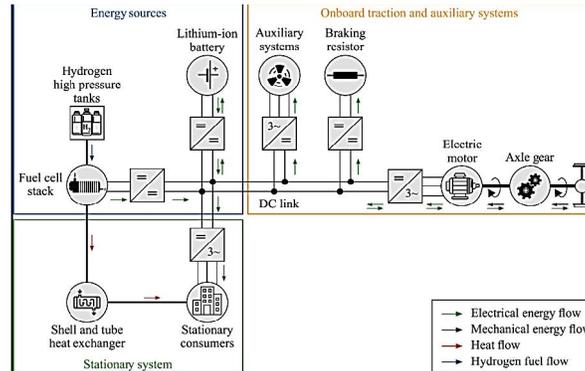


Figure 2 Simplified Schematic Illustration of the Vehicle's Propulsion System and All of the Grid-Connected Components

Powertrain hybridization is necessary to address the delayed dynamic response of fuel system energy when an energy storage system (ESS) is to mitigate fast power fluctuations and avoid fuel cell degradation due to starving problems [14]. Because of its commercial availability, rapid technological advancement, and demonstrated use in the railway industry, a lithium-ion batteries are regarded as an ESS. The following explains how the technology functions in both V2G and passenger train modes.

Passenger Train Mode

In passenger train mode, a fuel cell stack acts as the main mover and a lithium-ion battery module as the ESS. The necessary power for the onboard traction and auxiliary systems is supplied via a 750 V DC connection[16]. The fuel cell stack is connected to the DC connection using a unidirectional DC/DC converter, which adjusts the stack's voltage to the DC link in order to guard against damage to the fuel cell system. In this mode, cooling fluids such as inbuilt cooling components and water-ethylene mixture like fans and cooling radiators are used to reduce the heat output of a fuel cell system.

Vehicle-to-Grid Mode

In V2G mode, auxiliary systems and onboard traction are turned off, but energy sources stay operational. The unidirectional DC/AC inverter that is stationary, which is now connected to the DC connection, changes the voltage (to 480 V or 220 V), and gives stationary users access to alternating three-phase energy. An FCHEMU makes it possible to use a cogeneration system in V2G mode. The heat from the fuel cell system is now collected and utilised to warm buildings or tap water in addition to producing electricity[17]. This is done by warming the water in the external circuit using cooling liquid that is sent to the heat exchanger's shell and tubes.

III. MODELING AND SIMULATION FRAMEWORKS FOR ENERGY-EFFICIENT RAILWAY SYSTEMS

Open Track is a simulation program that models trains and tracks, while Open Power Net is a program that models the power infrastructure[18]. Three modules: schedule, infrastructure, and rolling stock—that the user must enter are displayed in Figure 3, which displays the primary OpenTrack modules. By combining discrete signal information with differential equations that depict the train's motions, the simulation is carried out constantly. The OpenPowerNet simulator was created as an addition to OpenTrack. [19]. The two simulators operate together during the simulation; OpenPowerNet models the electrical network's voltages in relation to the course current consumption and location, while OpenTrack models the driving dynamics and course operation control.



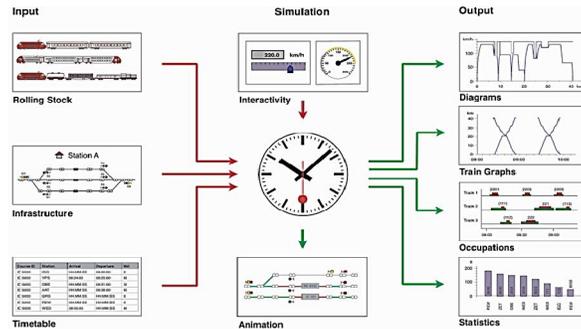


Figure 3: Architecture of a Railway Operations Simulation Framework

The user inputs data before the simulation runs in the model that is displayed, which includes trains, tracks, schedules, and power systems[20]. Wagons and locomotives make up trains, and the user must input data on weight, length, load, adhesive values, and tractive/braking effort. The track is modeled by constructing stations, vertices, routes, signals, and track segments. Track segments' maximum speed, curvature, gradient, and length may all be set by the user. Busbars with line feeders, such as those with contact wires, messenger wires, and rails, are used to link rectifier substations to the power system.

A. Longitudinal Train Dynamics and Traction Energy Modeling

A brief grasp of the extensive nature of the energy problem in train systems may be obtained by referring to several significant projects, such TRAINER and Rail Energy. Table II shows the train energy modeling in TDEAS from LTD's perspective. Train dynamics simulations are used to first extract pertinent forces, velocities, and displacements. These are then utilized to compute different energy components in the train systems[21].

Table 2: Energy Components in TDEAS

Energy Component	Source	Recoverable
Tractive energy	Traction motors	No
Regenerative braking	Dynamic braking	Yes
Gravitational	Track gradient	Partially
Air brake losses	Mechanical braking	No

The eight types of energy are produced by air brakes, train kinetic energy, propulsion resistance, gravitational potential energy, curve resistance, and draft gears of energy components that TDEAS takes into account, locomotive energy consumption (tractive energy), and energy associated with dynamic brakes (DB) (regenerated or converted to heat). Equation (1) is used to determine the first six components.

$$E = \int \sum_{i=1}^{i=n} F_i \Delta s_i dt, \quad (1)$$

The following formula represents the displacement of the iThe vehicle at the current time step: Δs_i , where n is the total number of vehicles (with wagons and locomotives), F_i is the equivalent force acting on the ia vehicle, and E is the related energy component[22]. Equation (2) is used to compute the kinetic energy:

$$E = \sum_{i=1}^{i=n} \frac{m_i V_i^2}{2}, \quad (2)$$

where V_i represents the iThe vehicle's velocity and m_i represents the vehicle's mass.

B. Electrical Traction Power Supply and Power Flow Modeling

A particular linked traction transformer is used to pair power supply arms for various working directions. For two single-phase transformers in addition to the traction transformer. They form a V/v connection TPSS by connecting their primary windings to the grid and their secondary windings to the arms, respectively. The same power supply arm's up-and down-going catenaries are cables that are linked to the substation port.



Assuming the grid is symmetrical, each phase's secondary transformer short-circuit impedance is the same, as determined by Equation (3):

$$Z_S = \frac{U_{2N}^2}{S_k} \quad (3)$$

where U_{2N} is the transformer secondary side's rated voltage and S_k is the grid's short-circuit capacity[23]. The traction network has a parallel MTL skeleton and consists of transverse parallel elements and longitudinal series elements. Figure 4 illustrates the division of this network into N pieces. The dimension of each section's voltage vector $U_i (i = 1, 2, \dots, N)$, current source vector $I_i (i = 1, 2, \dots, N)$, admittance matrix $Y_i (i = 1, 2, \dots, N)$, and impedance matrix $Z_i (i = 1, 2, \dots, N - 1)$ For m parallel conductors is m .

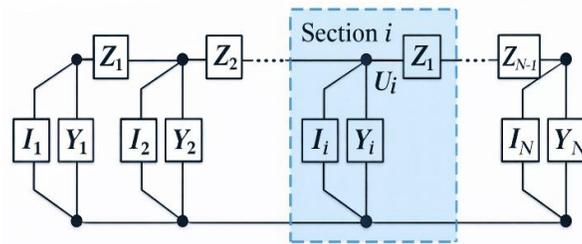


Figure 4: Structure of Traction Network

IV. OPERATIONAL ENERGY EFFICIENCY STRATEGIES IN RAILWAY TRANSPORTATION

To increase the timetable's resilience, the scheduled operating duration is often longer than the minimum operation time. In certain places, coast regime can be employed to conserve energy and maintain train punctuality. On the basis of the optimum regimes, a quick optimization technique is suggested. This approach consists of two steps: first, calculation of the min-time speed profile; second, the supplement time is allocated, and excessive braking is reduced by using the coast regime 3.

A. Min-time Speed Profile Calculation

The speed profile of the four operation regimes is known as the "min-time speed profile" (FP, PP, PB, and FB) while adhering to speed regulations, traction/braking characteristics, and route conditions." If acceleration is required, the forward speed profile is computed in the FP domain, and the reverse speed profile is determined in the FB regime when deceleration is necessary[24]. The forward and backward computation speed profiles, as well as the maximum speed u_{max} , are connected to generate the min-time speed profile.

B. Coast Region Division

The operation resistance and speed constraints are used to determine the associated control regime sequences from the min-time speed profile. FB and PB are referred to as braking (B), while FP and PP are referred to as traction (T). Furthermore, the trip often begins with traction and ends with brakes. Based on the min-time speed profile, a limited number of traction-braking (TB) pairs may be discovered. For example, Fig 3(b) displays two pairs of TB. Using the coast regime during traction portions would result in a drop in train speed in each TB pair.

Energy-Optimal Train Operation and Driving Control

This strategy's initial stage establishes the bounds of workable solutions, taking into account the time and location restrictions of a specified timeline. For the simulations in this stage, just the mechanical portion of the model is employed to lessen the amount of computing required. The objective function J In this step, the equation is given. (4):

$$J_1 = \begin{cases} J_t + J_s & \text{if } J_t \neq 0 \vee J_s \neq 0, \\ J_0 & \text{else} \end{cases} \quad (4)$$

In order to consideration for the intended departure and arrival times t_0, t_f , and the associated locations s_0, s_f . the



penalty terms J_t and J_s represent the time and position limitations of the schedule. Penalty phrases are selected as Equation (5) to (6)

$$J_s = \begin{cases} (s_{dr} - (s_f - s_0))^2 & \text{if } |s_{dr} - (s_f - s_0)| > \Delta s, \\ 0 & \text{else,} \end{cases} \quad (5)$$

and

$$J_t = \begin{cases} (t_{dr} - (t_f - t_0))^2 & \text{if } |t_{dr} - (t_f - t_0)| > \Delta t, \\ 0 & \text{else.} \end{cases} \quad (6)$$

As a result, the optimization technique would remain the same, but the size of the optimization issue would increase. However, just the scenario with a single coasting point is shown in order to provide a more straightforward visual depiction of this strategy[25]. A one-dimensional optimization problem with a given grid of b_v -values ($b_v \in \{b_{v,min}, b_{v,max}\}$) can be solved as an alternative to a grid-based method. Here, for instance, bisection methods can be used to identify the appropriate parameter p_{va} . The solutions that minimize the cost function J_l If the initial optimization phase ultimately led to Equation (7):

$$[p_v^l, b_c^l] = \arg \{ \min_{p_v, b_c} \{ J_l(p_v, b_c) \} \} \quad (7)$$

Timetable-Based Energy Optimization

The extent of the passenger service and transportation organization needs for urban rail transportation is reflected in the time component of the train schedule. The temporal components of the program should remain consistent when it is optimised for energy efficiency. They thoroughly identified the optimization variables and defined the adjustment ranges for each element's variables based on the provided schedule, taking the timetable structure's stability into account. Figure 5 shows an example of an optimization diagram.

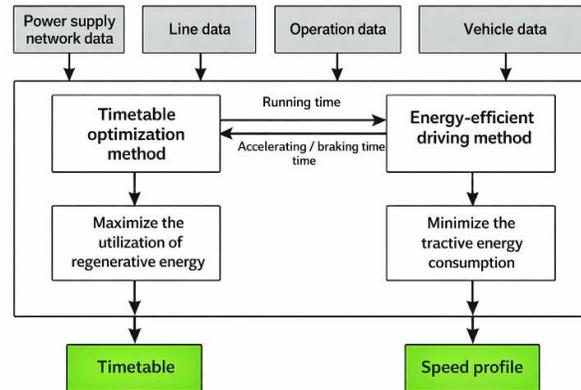


Figure 5: Optimization of Timetables

A sensible arrangement of space-time positional linkages between several trains was found using the schedule, which can significantly lower train operations' energy usage [26]. They discovered that section running times and departure timings may be used to identify the space-time position during train operation based on the train timetable's features. Then, under the required range limits, the energy-efficient schedule changes and optimization may be fine-tuned for these variables, given that doing so does not impact the macro-level stability of the train timetable[27]. Therefore, there are two approaches to design optimization solutions for the EEATT problem: modifying the segment running lengths and departure time by choosing a speed profile in order to use regenerative braking energy.



Traffic Management and Headway Optimization

The technique of creating and preserving a desired distance between a vehicle that is following and the one that is ahead of or leading it is known as "headway control." When trains leave the origin of a rail transportation system, their headways are equal. Due to various disruptions that occur while it is operating, it will typically lose the equalization. The short buffer period often disrupts transit operations, particularly on high-speed, high-density lines. Each driver's individual driving experience, the signalling system's reaction time, dwell time at stations, and unanticipated collisions at the intersection area are among the elements that cause disruptions [28]. The unpredictability of headways is the consequence of various elements working together. Inconsistent headways deter people from utilizing the transportation system.

In high-frequency railway traffic, if a train is delayed due to a point failure, the subsequent trains will have to halt, creating a line. This sudden stop is regarded as an unnecessary stop. Train delays and higher energy use will result from the needless halt. Slowing down and maintaining a suitable pace can help the next train avoid an unneeded halt. It accelerates until it is observed that the collision has been resolved. Based on their expertise, drivers on other subsequent trains employ a similar strategy. This indicates that manual control over the healing process is in place. The headway between subsequent trains would be significantly disrupted if the driver is inexperienced in resolving such issues.

Literature Review

The literature reveals some ways of enhancing the energy efficiency of railways by identifying modeling, optimization, renewable integration, smart energy management, and operational strategies, as shown in Table III.

Muhammad Armghan Shabir et al. (2025) Research looks at how mathematical models and optimization techniques may be applied to improve energy efficiency in a variety of engineering systems, such as industrial, mechanical, electrical, and thermal processes. The work has a strong emphasis on developing mathematical representations at the system level that accurately reflect energy flows, operational restrictions, and performance goals. The efficiency of many optimization strategies, including as heuristic-based methods, dynamic optimization, and linear and nonlinear programming, in lowering energy losses while preserving system dependability and functional stability is investigated[29].

Alshoufi, Al-Nagar and Fischer et al. (2024) consider how renewable energy sources such as solar, wind, biofuel, and kinetic energy recovery may be incorporated into railway infrastructure. Rail microgrid management through the use of intelligent multi-agent systems shows notable improvements in system dependability, energy efficiency, and operating cost reduction. Up to 30% less energy might be used if these energy measures are strategically implemented[30].

Bugarín and Aroso (2024) studied the current approaches that enable energy efficiency to be improved, and confirmed that the prepared studies concentrate more on LRT and Metro systems, as well as existing infrastructures, such as Urban Rail Transit, which are marked by high traffic and energy consumption. But when it comes to analyzing the features and layout of traditional railway infrastructure from an energy efficiency perspective, they discovered that not as much has been done in comparison to methods to increase energy efficiency[31].

Kljaić et al. (2023) focus on improving Railway transport systems' environmental sustainability, safety, and intelligence by reviewing state-of-the-art technologies that have the potential to influence their future. As a framework for the construction of future railway systems, it highlights important facets of the relationship between energy, transportation, and information/communication systems. Next, we explore the field of new propulsion technologies, which are essential to maintaining transportation's sustainability. These include cutting-edge approaches like hydrogen fuel cells, alternative fuel-based systems, and energy storage devices designed to capture kinetic energy and ease power transfer[32].

Qi et al. (2022) review of earlier research on vibration energy collection and associated technology. The study begins by outlining the fundamentals of vibration energy acquisition in a railroad environment, such is the possibility of vibration energy harvesting, train speed, train energy flow, and vibration frequency. Four general categories may be used to classify the techniques for scavenging vibration energy produced by passing trains: electromagnetic harvesters, piezoelectric harvesters, triboelectric harvesters, and hydraulic harvesters[33].

Bin et al. (2021) examine the neutral section's properties to maximize high-speed train operating curves. It can facilitate the smooth passage of trains through the neutral area. The suggested approach is workable and realistic. We establish



unique double-speed restrictions and stability requirements by constructing a mathematical model of a train's real coasting distance in the neutral section. The location of the neutral section is then modeled to develop a train ESP optimization model, operating circumstances, and vehicle performance[34].

Table 3: Overview of the recent research in the area of energy efficiency and sustainable energy management in the railway systems

Authors	Focus Area	Key Findings	Approaches	Objectives	Limitations
Muhammad Armghan Shabir et al., (2025)	Energy efficiency in multi-domain engineering systems	Mathematical modeling; linear & nonlinear optimization; dynamic and heuristic methods	Limited domain-specific railway validation; high computational complexity	Minimize energy losses while ensuring system reliability	Real-time optimization; AI-integrated adaptive models
Al-Nagar & Fischer et al., (2024)	Renewable energy integration in railway systems	Rail microgrids; multi-agent energy management; energy storage systems	Renewable intermittency; infrastructure integration challenges	Reduce railway energy consumption and operational cost	Large-scale deployment; AI-based predictive energy control
Bugarin & Aroso et a., (2024)	Energy efficiency in rail infrastructure design	Comparative analysis of existing methodologies	Limited focus on conventional railways; design-stage neglect	Identify gaps in energy-efficient railway design	Energy-oriented design frameworks for conventional railways
Kljaić et al., (2023)	Future intelligent and sustainable railway systems	System-of-systems framework; alternative propulsion technologies	Technology readiness level; high investment costs	Enhance sustainability, safety, and intelligence	Hybrid propulsion systems; integrated energy-ICT platforms
Qi et al., (2022)	Vibration energy harvesting in railways	Electromagnetic, piezoelectric, triboelectric, hydraulic harvesters	Low power density; environmental dependency	Utilize track-induced vibrations for energy recovery	Hybrid harvesters; power management optimization
Bin et al., (2021)	Energy-efficient train operation in neutral sections	Mathematical modeling; ESP optimization; simulation-based analysis	Case-specific constraints; limited operational scenarios	Smooth and stable high-speed train operation	Adaptive control strategies; real-time operational optimization

VI. CONCLUSION AND FUTURE WORK

The sustainable development of modern railway transportation systems has become a necessity based on energy efficiency. The current paper has examined a broad spectrum of energy-saving solutions by analyzing technological solutions, modelling and simulation models, and operational optimization schemes in railway systems. Systems for energy storage and regenerative braking, both in rolling stock and the infrastructure, as well as the concept of Technologies that aid in lowering energy use and improving energy reuse, include hybrid propulsion. The use of modelling and simulation tools can offer a good understanding of train behaviour and traction power supply behaviour as well as energy interaction at the system level, allowing informed decision-making. Energy performance is further enhanced through operational strategies which include optimized speed profiles, coasting regimes, timetable-based energy optimization, and competent traffic and headway management which reduces delays and unneeded braking. The



future direction of work must be based on the combination of real-time energy control with traffic control systems, the use of intelligent and data-driven optimization, and incorporating renewable energy sources into railway power networks to facilitate the more reliable and effective functioning of the rail system.

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