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Energy Efficiency Strategies in Electric Railway Traction Systems: A Systematic Review with Implications for Developing Countries

Strategi Efisiensi Energi dalam Sistem Traksi Kereta Api Listrik: Tinjauan Sistematis dengan Implikasi bagi Negara Berkembang

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ABSTRACT

Electric railway systems are widely recognized as energy-efficient transport modes; however, significant gaps remain between theoretical efficiency and operational performance in developing countries. In Indonesia, regenerative braking simulations indicate recovery potentials of up to 78%, while actual implementation in the Jabodebek LRT achieves only about 15.65%. This study aims to identify context-appropriate energy efficiency strategies and explain the structural factors limiting their transferability from developed to developing railway systems. This research employed a systematic literature review following PRISMA 2020 guidelines. A total of 33 peer-reviewed studies published between 2010 and 2025 were selected from Scopus, IEEE Xplore, ScienceDirect, and Google Scholar using predefined inclusion and exclusion criteria. The selected literature was analyzed through an integrated framework combining vehicle, operational, and infrastructure perspectives. The results indicate that effective energy savings depend on synergistic integration across system levels, a condition rarely achieved in developing contexts due to power quality instability, fragmented operational planning, and limited institutional coordination. While advanced technologies such as regenerative braking and energy storage systems offer high theoretical benefits, their practical effectiveness is constrained by local infrastructure readiness. Conversely, low-cost operational measures such as eco-driving and harmonic mitigation demonstrate higher feasibility and immediate impact. The primary contribution of this review is the conceptualization of the "adaptation gap" as a critical barrier to technology transfer and the proposal of a phased implementation roadmap that prioritizes operational optimization and power quality improvement before large-scale infrastructure investment.The findings provide an evidence-based roadmap for urban rail operators in resource-constrained environments, emphasizing the need for coordinated institutional frameworks to bridge the adaptation gap between technological design and operational reality.

Keywords: traction power quality; operational optimization; institutional coordination; technology transfer barriers; sustainable urban mobility

ABSTRAK

Meskipun Sistem kereta api listrik dikenal sebagai moda transportasi yang hemat energi, namun dalam praktiknya masih terdapat kesenjangan besar antara potensi efisiensi teoretis dan kinerja operasional di negara berkembang. Di Indonesia, simulasi pengereman regeneratif menunjukkan potensi pemulihan energi hingga 78%, sementara implementasi nyata pada LRT Jabodebek hanya mencapai kurang dari 20%. Penelitian ini bertujuan mengidentifikasi strategi efisiensi energi yang sesuai konteks serta menjelaskan faktor struktural yang membatasi transferabilitas teknologi dari negara maju ke negara berkembang. Penelitian ini menggunakan metode systematic literature review mengikuti pedoman PRISMA 2020. Sebanyak 33 artikel bereputasi yang terbit pada periode 2010–2025 dikumpulkan dari basis data Scopus, IEEE Xplore, ScienceDirect, dan Google Scholar melalui kriteria inklusi dan eksklusi yang telah ditetapkan. Literatur yang terpilih dianalisis menggunakan kerangka terintegrasi yang mencakup aspek kendaraan, operasional, dan infrastruktur. Hasil kajian menunjukkan bahwa peningkatan efisiensi energi secara signifikan hanya dapat dicapai melalui integrasi sinergis antar tingkat sistem, kondisi yang jarang terpenuhi di negara berkembang akibat ketidakstabilan kualitas daya, fragmentasi perencanaan operasi, serta keterbatasan koordinasi kelembagaan. Meskipun teknologi lanjut seperti pengereman regeneratif dan sistem penyimpanan energi menawarkan manfaat teoretis yang tinggi, efektivitas praktisnya sering terhambat oleh kesiapan infrastruktur lokal. Sebaliknya, intervensi berbiaya rendah seperti eco-driving dan mitigasi harmonisa menunjukkan tingkat kelayakan yang lebih tinggi serta dampak yang lebih cepat. Kontribusi utama penelitian ini adalah konseptualisasi 'kesenjangan adaptasi' sebagai penghambat kritis transfer teknologi serta pengusulan peta jalan implementasi bertahap yang memprioritaskan optimasi operasional dan perbaikan kualitas daya sebagai fondasi sebelum investasi infrastruktur skala besar."Temuan ini menyediakan peta jalan berbasis bukti bagi operator kereta perkotaan di lingkungan dengan keterbatasan sumber daya, sekaligus menegaskan pentingnya kerangka koordinasi kelembagaan untuk menjembatani kesenjangan adaptasi antara desain teknologi dan realitas operasional.

Kata Kunci: kualitas daya traksi; optimasi operasional; koordinasi kelembagaan; hambatan transfer teknologi; mobilitas perkotaan berkelanjutan

1. INTRODUCTION

Electric rail traction systems are often hailed as the backbone of sustainable transportation in the global energy transition. Compared to fossil-fuel-based modes, these systems offer well-to-wheel efficiency of around 33–35% (Skrúcaný et al., 2018), significantly lower carbon emissions, and superior mass-carrying capacity (Brenna et al., 2020). However, this potential is often hampered in practice, particularly in developing countries, not by technological shortcomings, but by a mismatch between efficiency strategy designs and local operational realities. Power quality instability, a lack of energy storage infrastructure, and tight but uncoordinated operating schedules hinder the implementation of advanced strategies such as regenerative braking or inter-train energy synchronization (Pradipta et al., 2023; Gunatillake & Samaliarachchi, 2022). Recent developments in the literature indicate a shift from a narrowly technical approach to a more holistic system-of-systems framework (Hu et al., 2023). In this context, the “energy efficiency levers” framework (Feng et al., 2013) remains relevant, but needs to be expanded to

considering interdependencies between system levels. Efficiency strategies can no longer be viewed as a stack of separate solutions, but rather as an ecosystem that includes:

1. Vehicle level (e.g. permanent magnet motors, LC filters, and regenerative braking),
2. Operational level (such as eco-driving, headway management, and use of reserve time),
3. Infrastructure level (including ESS, reversible substations, and renewable energy-based microgrids).

While the energy efficiency levers framework effectively classifies technical strategies across vehicle, operational, and infrastructure levels, it does not explicitly address the institutional and contextual constraints that shape real-world implementation. Conversely, the railway energy ecosystem approach emphasizes systemic interactions among technology, operations, policy, and local conditions but lacks detailed categorization of engineering interventions. Integrating these two frameworks enables a more comprehensive analytical lens, particularly for developing countries, where energy efficiency outcomes are strongly influenced by power quality instability, fragmented operational planning, and limited inter-agency coordination. This synergy allows technical measures to be evaluated alongside institutional readiness, thereby providing a more realistic assessment of strategy transferability and implementation feasibility.

In developed countries like Japan or the Netherlands, the integration of these three levels has resulted in energy savings of up to 20-30% (Brenna et al., 2020). However, in Indonesia or Sri Lanka, similar results are difficult to replicate. For example, Khodaparastan & Mohamed's (2018) simulations showed the potential for energy recovery of up to 78% through regenerative braking, but implementation in the Greater Jakarta LRT only achieved 15.65% (Rizky Fajar & Dalimi, 2023). This gap, which we call the "adaptation gap," is not a reflection of technological failure, but rather a result of systemic fragmentation: a lack of ESS, network voltage fluctuations (Pradipta et al., 2023), and limited institutional capacity (Fatoni & Handoko, 2024). Unfortunately, previous systematic reviews (Feng et al., 2013; Brenna et al., 2020; Hu et al., 2023) tend to overlook these contextual challenges, implicitly assuming that strategies successful in Amsterdam or Tokyo can be directly transferred to Jakarta or Colombo. However, empirical studies in Sri Lanka demonstrate that energy efficiency in developing countries requires an approach that takes into account budget constraints, power quality uncertainty, and dense but inflexible operating patterns (Gunatillake & Samaliarachchi, 2022).

This article fills this gap through a systematic review of 33 studies (2010–2025) that not only categorize efficiency strategies but also test their transferability to developing country contexts. Our main contributions are:

1. Expanding the energy efficiency levers framework with contextual and institutional dimensions;
2. Identify structural barriers that hinder integration between system levels;
3. Provides realistic step-by-step recommendations for urban commuter systems with Indonesia as an illustrative case study, not as a geographical limitation.

Thus, this study not only updates the academic discourse, but also offers an implementation roadmap for operators and policy makers operating within resource constraints.

2. RESEARCH METHODE

This study employed a Systematic Literature Review (SLR) approach, adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines, to ensure transparency, reproducibility, and rigor in collecting, selecting, and compiling scientific literature (Page et al., 2021). This approach was chosen because it comprehensively describes energy efficiency strategies in electric train traction systems and helps identify research gaps and policy implications, particularly in developing countries.

2.1 Literature Search Strategy

Literature search was conducted on four major databases, namely Scopus, IEEE Xplore, ScienceDirect, and Google Scholar, with publication coverage from January 2010 to May 2025. To broaden the scope and avoid bias in selection, the search string was expanded through expert consultation with subject matter experts (SMEs) in railway electrification to ensure comprehensive coverage of domain-specific terminology and concepts related to energy efficiency, traction systems, and supporting infrastructure such as: ("energy efficiency" OR "energy saving" OR "energy recovery" OR "eco-driving" OR "coasting") AND ("electric train*" OR "railway traction" OR "metro" OR "LRT" OR "commuter rail" OR "urban rail transit") AND ("regenerative braking" OR "energy storage" OR "ESS" OR "reversible substation" OR "power quality" OR "harmonic*" OR "traction loss"). This search string was designed to capture three main dimensions of energy efficiency strategies, namely vehicle, operational, and infrastructure, according to the conceptual framework suggested by Feng et al. (2013) and Hu et al. (2023). Additionally, backward and forward citation tracking was applied to primary articles such as Brenna et al. (2020); Feng et al. (2013); and Hu et al. (2023) to identify potentially overlooked relevant articles. Google Scholar was used only as a supplementary tool for snowballing, not as a primary source, to maintain academic credibility.

2.2 Inclusion and Exclusion Criteria

Inclusion criteria:

- Articles in the form of quality scientific journals or conference proceedings (indexed in Scopus/WoS/IEEE);
- Focus on energy efficiency strategies in electric train traction systems (not diesel or non-electric hybrid);
- Present quantitative data, simulations, case studies, or in-depth conceptual analysis;
- Published between 2010 and 2025;
- Available in full-text version.

Exclusion criteria:

- Editorials, abstracts without complete content, or technical reports without peer-review;
- Study of non-electric traction systems (such as diesel or hydraulic);
- Articles that do not present specific analysis related to energy efficiency (e.g., focusing only on safety or comfort);
- Duplicate search results between databases.

2.3 Selection and Deduplication Process

The selection process follows four stages of PRISMA 2020:

- ➢ Identification: The initial search yielded 115 records from all four databases (Scopus: 32, IEEE Xplore: 25, ScienceDirect: 21, Google Scholar: 37).
- ➢ Deduplication: A total of 28 records were identified as duplicates using Zotero's reference manager and manual checking, leaving 87 unique records.
- ➢ Screening: Based on the title and abstract, 44 records were excluded for not meeting the inclusion criteria (e.g., focus on road vehicles, or not relevant to electric traction), leaving 44 records for full assessment.

Eligibility: After reading the full text, 11 records were excluded because: (a) they did not present an adequate energy efficiency analysis, (b) they were descriptive in nature without data, or (c) they were reviews without a new synthesis. Finally, 33 studies met all criteria and were included in the qualitative synthesis. This selection flow is summarized in the PRISMA Diagram (**Figure 1**).

2.4 Quality Assessment and Dual Screening

The screening and quality assessment process was conducted independently by two authors. Initial discrepancies were resolved through discussion until full consensus was reached. The methodological quality of the 33 studies was assessed using the Mixed Methods Appraisal Tool (MMAT) version 2018 (Hong et al., 2018), adjusted for study type:

1. Simulation/modeling studies (e.g., Fu et al., 2023; Peng et al., 2024): assessed based on model validation, transparency of assumptions, and parameter relevance.
2. Empirical case studies (e.g., Rizky Fajar & Dalimi, 2023; Gunatillake & Samaliarachchi, 2022): assessed based on data representativeness and measurement accuracy.
3. Systematic/conceptual reviews (e.g. Feng et al., 2013; Hu et al., 2023): assessed based on the transparency of the search strategy and the depth of the synthesis.

The assessment results show:

22 high-quality studies (≥80% of criteria met), 8 studies of medium quality (50–79%), 3 studies were conceptual/descriptive (<50%), but were included due to their thematic relevance to the analytical framework.

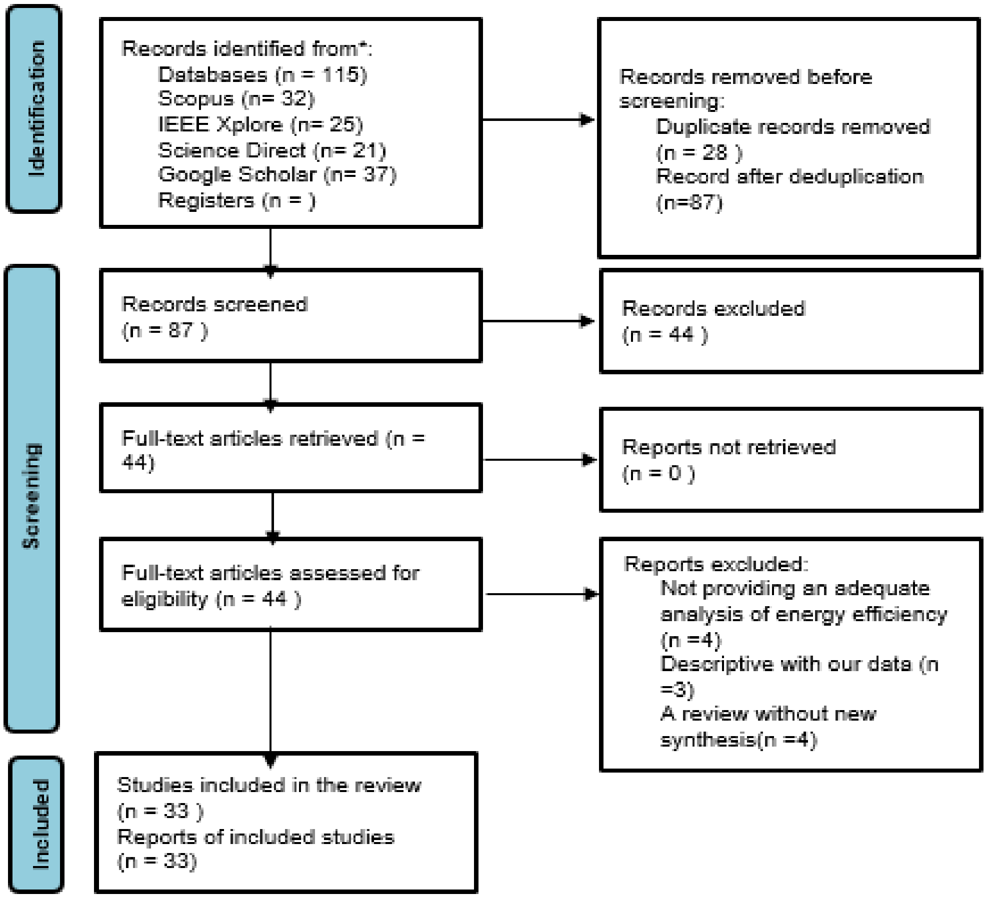

Figure 1. Study selection flowchart based on the 2020 PRISMA guidelines

2.5 Thematic Analysis Framework

Different from previous ad hoc categorization approaches, the thematic synthesis in this study is built on two complementary conceptual frameworks:

1. "Energy Efficiency Levers" (Feng et al., 2013), which groups strategies into three levels, namely vehicles, operations, and infrastructure.
2. "Railway Energy Ecosystem" (Hu et al., 2023), which emphasizes the relationship between technology, operations, policies, and local conditions.

These two frameworks allow for a more in-depth comparative, contextual, and systemic analysis, rather than just a summary of each study.

3. RESULTS AND DISCUSSION

Based on a qualitative synthesis of 33 recent studies (2010–2025), strategies for improving energy efficiency in electric rail traction systems can be divided into three interrelated levels: (1) vehicle level, (2) operational level, and (3) infrastructure level as proposed in the "Energy Efficiency Levers" framework (Feng et al., 2013) and further developed by the "Railway Energy Ecosystem" approach (Hu et al., 2023). This analysis not only categorizes strategies, but examines how interactions between system levels determine their success in practice, context-dependent, and barriers to implementation, especially in developing countries.

3.1 Vehicle-Level Strategies: Intrinsic Efficiency and Energy Recovery

Vehicle-level strategies focus on improving the efficiency of energy conversion and recovering kinetic energy as the vehicle decelerates. Key components include efficient traction motors, nonlinear loss control, and regenerative braking systems.

Research by Kondo et al. (2010) and Nold & Corman (2024) shows that the use of permanent magnet motors (PMSMs) can reduce metal and copper losses by up to 15% compared to conventional induction motors. However, this benefit is only maximized when combined with a highly precise inverter controller, as traction system efficiency varies depending on load, speed, and temperature (Fu et al., 2023). Without a dynamic efficiency model, optimized control can actually increase energy consumption by up to 8% (Nold & Corman, 2024).

Meanwhile, regenerative braking remains the primary strategy. Khodaparastan & Mohamed (2018) reported that in a simulation of a 750 V DC system, up to 78% of acceleration energy could be recovered. However, its success is highly dependent on the availability of synchronous loads and network quality. In systems lacking an Energy Storage System (ESS) or reversible substance, regenerative energy is often wasted as heat in resistors (Iliev et al., 2024). A study by Gunatillake & Samaliarachchi (2022) in Sri Lanka showed that without synchronization between trains, only around 20–30% of the regenerative energy could be used—a figure consistent with the findings of Rizky Fajar & Dalimi (2023) in the Greater Jakarta LRT (15.65%). Furthermore, Tri Rahmawati et al. (2025) found that harmonic distortion due to switching in the inverter can increase power losses by up to 5–7%. Applying an LC filter with the correct parameters (L = 300 μH, C = 300 μF) successfully reduced the THD to below 10%, improving overall stability and efficiency. These parameters (L = 300 μH, C = 300 μF) were derived from the specific case study at PT INKA Madiun (Tri Rahmawati et al., 2025) and may require recalibration for other traction systems with different harmonic profiles and voltage levels. These findings reinforce the point that vehicle efficiency is not just about the components, but also the quality of the power used.

Implications for developing countries: Investments in efficient motors and regenerative braking are insufficient without supporting infrastructure such as ESS, filters, and reversible substances. In Indonesia, where power quality is constantly changing (Pradipta et al., 2023), vehicle-level strategies must be balanced with harmonic distortion management and system protection.

3.2 Operational Level Strategy: Optimizing Travel Dynamics

Operational strategies aim to conserve energy by adjusting speed profiles, schedules, and intertrain cooperation. This approach can save 10 to 30 percent of energy without requiring infrastructure changes (Brenna et al., 2020). Eco-driving and coasting, which involve deceleration without active braking, are considered established strategies.

Peng et al. (2024) developed a train control system that combines natural braking characteristics and reduced power consumption, resulting in energy savings of 12 to 18 percent on urban lines. However, the effectiveness of this method is reduced on intercity lines with long train spacing due to the lack of opportunities for energy synchronization (Wang & Rakha, 2017).

Recent innovations focus on simultaneously optimizing schedule and speed tracking. Scheepmaker & Goverde (2021) and Huang et al. (2021) show that integrating schedule and speed tracking into a single model with two objectives (energy and punctuality) can achieve energy savings of up to 22 percent. Further research by Zhang et al. (2025) and Wu et al. (2025) incorporates carbon emissions as a factor, opening up the possibility of more carbon-efficient train operations.

The most relevant concept for developing countries is intertrain energy cooperation through time management. Urbaniak & Kardas-Cinal (2022) showed that by utilizing the remaining time in the service schedule, trains can cooperate in managing deceleration and warm-up phases, increasing regenerative energy use by up to 35 percent, provided trains are closely spaced and schedules are flexible. Implications for developing countries: Commuter systems like the Greater Jakarta (Jabodetabek) commuter line, which has a 5–10 minute train spacing, are wellsuited to this strategy. However, current schedules are still rigid and not optimized for energy efficiency. Integrating real-time energy cooperation into ATS/ATC systems is a strategic, low-cost approach.

3.3 Infrastructure Level Strategy: Smart Storage Systems and Microgrids

The infrastructure level provides a solid foundation for strategies at the vehicle and operational levels. Without adequate infrastructure, maximum efficiency cannot be achieved. Energy Storage Systems (ESS) are a key solution. According to Szeląg et al. (2025) and Jafari Kaleybar et al. (2023), hybrid ESSs such as batteries and supercapacitors or flywheels can help stabilize voltage, reduce peak loads, and increase regenerative energy utilization by up to 90%. Research by Jackiewicz et al. (2023) also shows that flywheel-based systems can withstand more than 100,000 cycles without significant degradation, making them suitable for intensive daily use. More interesting is the integration of smart microgrids using renewable energy sources.

Ye et al. (2024) developed an energy management method for an electric rail microgrid that combines solar PV, ESS, and traction loads. Using an empirical mode decomposition method, this system can reduce dependence on the main grid by up to 40%. On the other hand, Li et al. (2022) added that PV integration must be accompanied by random schedule optimization due to its unpredictable nature.

However, investing in this infrastructure requires significant funding. Morais et al. (2021) emphasize the need for new business models, such as energy-as-a-service (EAS) or the utilization of used electric vehicle batteries for train stations (Jafari Kaleybar et al., 2023).

Implications for developing countries: While costly, modular ESS systems and small-scale microgrids could be tested in high-frequency rail corridors, such as the Jakarta MRT. Public-private partnerships and government green incentives could reduce financial barriers.

3.4 The Challenge of System Integration in Developing Countries: Why Did 78% Become 15%?

The significant difference between theoretical potential (78%, Khodaparastan & Mohamed, 2018) and actual operational results (15.65%, Rizky Fajar & Dalimi, 2023) indicates systemic barriers to technology transfer. The three main barriers are:

- Lack of vertical integration: Strategies at the vehicle, operational and infrastructure levels are often developed separately.
- In fact, according to Hu et al. (2025), regenerative systems must be designed together with ESS and network control.
- Unstable power quality: Voltage changes in the AC traction network (Pradipta et al., 2023) cause the system protection to operate, stopping the flow of regenerative energy to the network.
- Institutional limitations: The lack of coordination between train operators, PLN, and regulators hampers the development of reversible substances or special tariffs for regenerative energy.

Gunatillake & Samaliarachchi's (2022) study in Sri Lanka provides an important lesson: despite limited budgets, simple predictive models based on operational data can increase efficiency by up to 18% provided there is commitment from the relevant institutions.

3.5 Strategy Comparison Matrix

To clarify comparisons across strategies, Table 1 presents an evidence-based synthesis that maps the energy savings effectiveness, investment requirements, technology maturity (TRL), and contextual dependencies of each approach. This analysis enables decision-makers in developing countries to prioritize interventions that align with their technical, financial, and operational capacities.

Table 1. Strategy Comparison Matrix

No	Strategy	Energy savings	Investment Costs	Technology Maturity (TRL)	Context Dependence	Primary Source
1	Eco-driving	10-20%	Low	TRL 9	Heavy headway, urban route	Brenna et al. (2020) ; Peng et al. (2024)
2	ESS (battery)	20-35%	Tall	TRL 7-8	Network stability, Policy	Szelag et al. (2025); Jackiewicz et al. (2023)
3	LC Filter	3-7%	Low-Medium	TRL 8	Poor power quality	Tri Rahmawati et al (2025).
4	Timetable-optimization	15-25%	Currently	TRL 7	Flexible ATS System	Scheepmaker & Goverde (2021); Zhang et al (2025)
5	Microgrid+PV	25-40%	Very high	TRL 6-7	Sunny climate, Incentive policy	Ye et al (2024); Li et al (2022).

T**able 1** shows that no single strategy is superior across all dimensions. Low-cost strategies such as eco-driving and the application of LC filters offer high ROI and technological maturity (TRL 8–9), making them highly feasible for immediate implementation in developing countries, especially in urban commuter systems with dense headways. In contrast, infrastructure-based solutions such as ESS and PV-based microgrids, while promising energ iny savings of up to 40%, face financial constraints and are highly dependent on grid stability and supportive policies. These findings reinforce the argument that a phased approach, starting with operational optimization and harmonic mitigation before investing in heavy infrastructure, is the most realistic path for developing countries. Furthermore, context-dependent factors (e.g., dense headways for eco-driving, sunny climates for PV) emphasize that technology transfer should be tailored to local characteristics, rather than applied uniformly.

4. RESEARCH GAP AND OPEN RESEARCH QUESTIONS

Based on a combination of topics from 33 recent studies (2010–2025), this review identified three research gaps that remain unaddressed in the current literature. Unlike previous descriptive approaches, these gaps were identified inductively from inconsistencies, contradictions, and methodological limitations in the literature, as recommended by guidelines for high-quality literature reviews.

4.1 The Technology Adaptation Gap: From Developed to Developing Country Contexts

A total of 27 of the 33 studies (82%) were conducted in the context of developed countries (Europe, Japan, Chinese cities) with the assumption:

1. Stable power quality (THD < 5%),
2. ESS infrastructure or reversible substations are available,
3. Compact and flexible train schedule

However, only three studies (Hu et al., 2025; Li et al., 2022; Jafari Kaleybar et al., 2023) explicitly model interactions between levels, such as how the presence of an ESS affects optimal eco-driving constraints or how voltage fluctuations limit the effectiveness of regenerative braking. Without this integration, partial optimization can actually increase total energy consumption due to rebound effects or unexpected trade-offs.

Open research question: How to build a multi-level optimization model that combines vehicle, operation, and infrastructure dynamics in a cohesive framework, especially under uncertainties of power quality and passenger demand.

4.2 The Gap Between Ideal Simulation and Operational Reality

The dramatic difference between theoretical potential and operational reality reflects methodological biases in the literature:

1. Khodaparastan & Mohamed (2018) reported 78% recovery in ideal simulations,
2. Rizky Fajar & Dalimi (2023) only reached 15.65% in the Jabodebek LRT,
3. Gunatillake & Samaliarachchi (2022) found 20–30% in Sri Lanka.

In-depth analysis showed that 21 of the 33 studies used deterministic simulations without considering:

1. Daily passenger load variability,
2. Component degradation (e.g. ESS battery),
3. Network disturbances (voltage drops, harmonics),
4. Limitations of the protection system.

As a result, energy saving claims are often overly optimistic and cannot be replicated in real operations.

Open research questions:

How to develop a long-term operational data-driven simulation model that incorporates technical uncertainty, passenger behavior, and local network conditions to generate robust and implementable recommendations?

Theoretical and Practical Contributions of SLR

1. This review expands the "energy efficiency levers" framework (Feng et al., 2013) by:
2. Introducing contextual dimensions (developed vs developing countries),
3. Identifying the "adaptability gap" as the main barrier to technology transfer,
4. Provides a comparative matrix of evidence-based strategies that synthesizes vehicle, operational, and infrastructure interventions,
5. Propose open research questions that can form the basis of a future research agenda.

In practical terms, this SLR provides an evidence-based roadmap for operators and policymakers in developing countries to:

- Choosing a low-cost strategy with high ROI (e.g. eco-driving + LC filter),
- Designing ESS trials in high-frequency corridors,
- Develop regulations that support energy synchronization between trains.

5. RESEARCH LIMITATIONS

Although this review followed rigorous SLR methodology and met the PRISMA 2020 guidelines, several limitations need to be acknowledged.

1. The search scope is limited to articles in English and Indonesian, so important studies in other languages such as Japanese, German, or French, which are active in railway research may not be covered.
2. Most of the studies analyzed were simulations or based on developed country contexts; only two studies presented empirical data from developing countries (Rizky Fajar & Dalimi, 2023; Gunatillake & Samaliarachchi, 2022), so generalizing the findings to local contexts requires caution. One additional study (Tri Rahmawati et al., 2025) is from an Indonesian national journal that lacks an official DOI and has limited online availability. Nevertheless, this study was retained due to its relevance to the local technical context and its consistency with other empirical findings on power quality in Indonesian traction systems.
3. This review does not include technical reports from train operators or internal policy documents, which may contain valuable operational insights but have not gone through the peer-review process.

6. CONCLUSION

This systematic literature review synthesized 33 studies published between 2010 and 2025 to examine energy efficiency strategies in electric railway traction systems, with particular attention to their applicability in developing countries. By integrating the energy efficiency levers framework with the railway energy ecosystem approach, this study analyzed the interdependence between vehicle, operational, and infrastructure levels, rather than treating these strategies as isolated technical solutions.

The findings demonstrate that optimal energy efficiency can only be achieved through coordinated implementation across all system levels. However, in developing contexts such as Indonesia and Sri Lanka, this integration is constrained by three structural barriers: fragmented strategy deployment, instability of traction power quality, and limited institutional coordination among railway operators, electricity providers, and regulators. These conditions explain the substantial discrepancy between theoretical energy recovery potential (up to 78%) and operational performance (approximately 15–30%), referred to in this study as the adaptation gap.

From a theoretical perspective, this review extends existing energy efficiency frameworks by introducing a contextual dimension that explicitly accounts for developing-country constraints. Practically, the comparative strategy matrix indicates that low-cost interventions particularly eco-driving optimization and harmonic mitigation using LC filters offer high technological readiness and return on investment, making them suitable entry points for immediate implementation. In contrast, capital-intensive solutions such as energy storage systems and renewable-based microgrids require prior operational optimization and institutional readiness to deliver meaningful benefits.

Based on these insights, this study proposes a phased implementation approach, beginning with operational improvements and power quality stabilization, followed by targeted infrastructure investments informed by local performance data. For Indonesian urban rail systems, including PT KAI and LRT Jabodebek, this implies the need to establish formal coordination mechanisms with PLN and regulatory agencies to enable synchronized timetabling, pilot energy storage deployments in high-frequency corridors, and supportive tariff schemes for regenerative energy utilization. . Specifically, we recommend establishing a tripartite coordination forum (PT KAI/LRT Jabodebek-PLN–Ministry of Transportation) to: (1) develop synchronized timetabling protocols for inter-train energy cooperation during peak hours on the Jabodebek LRT corridor; (2) pilot modular ESS deployment in the Jakarta MRT Phase 2 North-South Line using public-private partnership models; and (3) implement feed-in tariffs for regenerative energy returned to the grid, modeled after Japan's successful schemes.

Overall, this review provides an evidence-based roadmap for urban rail operators in resource-constrained environments, emphasizing that sustainable energy efficiency gains depend not only on technological advancement but also on systemic integration and institutional collaboration.

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