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# Energy efficiency in rail vehicles: analysis of contemporary technologies in reducing energy consumption

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*The article focuses on the problem of energy intensity in rail vehicles and analyzes current technologies aimed at reducing it. The author discusses innovations and strategies aimed at increasing energy efficiency in rail transportation. He also outlines the challenges of reducing energy consumption in this sector and future development prospects. The main focus of the article is on the problem of energy demand in rail vehicles, with a special emphasis on railroads. The author analyzes the current challenges of high energy consumption in rail transportation and presents various technologies that have been introduced to minimize this consumption. The article includes descriptions of technological innovations such as advanced energy management systems, efficient braking systems that recover energy, and the use of low aerodynamic drag materials. The author also discusses strategies to improve the energy efficiency of rail vehicles, including both existing ones and those planned for market introduction. One of the key points of the article is also a presentation of the challenges of reducing energy consumption in the rail sector. These include the need to adapt existing infrastructure, the financial aspects of introducing new technologies, and acceptance by consumers and operators, among others.*



## 1. Introduction

Energy efficiency and the pursuit of sustainability are now key challenges for the rail transportation industry. The increase in global interest in environmental protection, along with the rapid growth in demand for rail transportation services, is forcing the search for innovative solutions to reduce energy consumption and carbon emissions in the sector. One of the key aspects needed to achieve these ambitious goals is effective energy management and efficient energy recovery in rail vehicles.

Traditionally, the energy generated during the braking process in rail vehicles was lost, being converted into heat emitted by disc brakes [48]. However, as technology develops, today's rail vehicles are becoming more sophisticated and equipped with systems to recover this energy [20]. These systems allow braking energy to be converted into electricity, which is then used to power other on-board equipment, provide heating or cooling for railcars and accomplish other purposes, significantly increasing the energy efficiency of rail vehicles.

## 2. Energy recovery in trains

In the context of the drive for efficient energy recovery during braking, extensive analysis and comparison of various methods and technologies have been carried out [21, 36, 46, 49]. The results of these studies show the potential benefits, both in terms of economic and technical aspects, of practical implementation of these solutions. The pursuit of efficient braking energy recovery in rail vehicles appears to be an important and promising initiative that can help improve the efficiency of the rail industry while benefiting the environment and society at large.

One solution that contributes to improving energy efficiency and reducing operating costs of rail vehicles is the use of energy storage systems. This type of systems allows excess regenerated energy to be temporarily stored during braking and then used to help

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accelerate the vehicle [3, 7, 17, 19, 45, 58]. This avoids wasting valuable energy, which in traditional solutions is lost as heat in on-board resistors [22]. This approach translates into increased vehicle energy efficiency and reduced vehicle operating costs. Optimal energy management during braking and acceleration processes contributes to minimizing energy losses, benefiting both economic efficiency and environmental concerns [16, 25, 30]. In the face of today's climate change challenges, such innovative technology makes a significant contribution to reducing energy consumption and greenhouse gas emissions.

An interesting project that implements the concept of energy storage in rail vehicles is an initiative by ARES. The American company ARES has developed an innovative energy storage system using electric rail cars, heavy concrete blocks and regenerative braking technology (Fig. 1). The solution captures and stores energy by moving heavy blocks to the top of hills during periods of excess electricity, such as that generated by wind farms, or during off-peak periods. When energy is needed, the railcars are slowed down, and as they return downhill, kinetic energy is converted into electricity through regenerative braking. The system incorporates two technologies: a traction drive system, which is designed for gentler hills, and Ridgeline cable car drive technology, which can handle much steeper slopes.

Fig. 1. ARES energy storage shuttle train [5]

One of the key strengths of the ARES system is that it requires no water, dams or reservoirs, making it quick to deploy and easy to remove at the end of its useful life. The system also boasts efficiencies of up to 78% in both charging and discharging, while maintaining a competitive cost compared to traditional water pumps. Importantly, the ARES project has the potential to scale from small capacities such as 20 MW for ancillary services to an impressive 3 GW, which can be used as part of regional energy storage centers with a capacity of 16–24 GWh [5]. As a result, the project supports efficient energy management and accelerates the achievement of sustainability and environmental goals. The drive for efficient energy recovery in rail transportation focuses on analyzing and comparing different methods, demonstrating the potential benefits both economically and technically. The introduction of energy storage systems to collect and use regenerated energy during braking is a key solution. Such a strategy translates into increased energy efficiency of rail vehicles, reduced operating costs and minimized energy losses. Optimal energy management during braking and acceleration processes contributes to the goals of economic efficiency, as well as environmental concerns in the face of the challenges of climate change.

### 3. Optimization of timetables

Another of the ways to save energy is to optimize scheduling and synchronize acceleration and deceleration processes [10, 32, 33, 42, 47, 52, 56, 60, 61].

The article [21] highlights the importance of energy efficiency in railroad systems. An integrated model, using a genetic algorithm, was proposed to optimize both the schedule and speed profile of trains. Experiments on the Chinese subway system in Beijing have shown that greater train spacing translates into lower energy savings, but the integrated approach can reduce net energy consumption by about 20%. An automatic train control system [26] is used to execute the schedule with a variable sequence of passenger demand, leading to significant energy savings. An integrated approach to optimizing the schedule and speed profile of trains can reduce net energy consumption by about 11% compared to a conventional schedule. In addition, during off-peak hours, the approach with dynamic scheduling and adaptive timing reduces net energy consumption by about 7% compared to the static approach and fixed timing. Wang et al. in their paper [51] focused on modifying the traditional problem of scheduling periodic railroad events, taking into account both train acceleration and deceleration processes and passenger-related aspects. Results based on a real case show that the proposed approach can significantly increase the effective use of regenerative energy, achieving an increase of more than 150%. Data obtained in the article [50] after applying the optimization method show an increase in regenerative energy use of almost 290% and a reduction in 15-minute power peaks of 8.5%, suggesting that the optimized schedule outperforms the original schedule in terms of efficient energy use and reduction in power peaks, especially in the case of delays. The example of the optimization diagram is presented in Fig. 2.

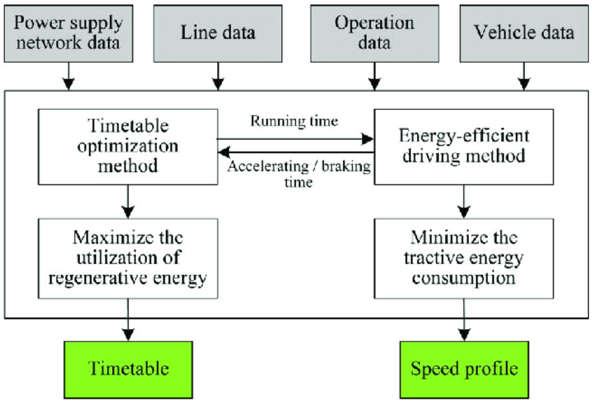


Fig. 2. Optimization of timetables [55]

The article [13] focuses on the process of detecting and utilizing energy losses in electric rail vehicles. The assumption was made that efficient energy management in rail transportation is crucial, and the tendency to recover braking energy is becoming a cost-effective solution. The authors conducted a study in which seven series of measurements were made using scheduled Railjet trains between Hegyeshalom and Győr railroad stations in Hungary. The analysis showed that regenerative braking energy makes a significant contribution to total energy consumption, reaching up to 20–30%.

In summary, energy conservation in rail transportation includes a variety of strategies, such as optimizing schedules and synchronizing acceleration and braking processes. In the context of energy efficiency of railroad systems, the use of integrated models, genetic algorithms and automatic train control can lead to significant savings. Experiments on China's Beijing subway suggest that the integrated approach can reduce net energy consumption by about 20%, and the automatic train control system can yield significant energy savings, especially under conditions of fluctuating passenger demand. In addition, modifications to the traditional problems of scheduling railroad events, taking into account acceleration, braking processes and passenger-related aspects, can contribute to more efficient use of regenerative energy. It is also worth noting that the detection and utilization of energy losses, especially through regenerative braking energy, can be an important element of efficient energy management in rail transportation, as confirmed by an analysis of Railjet trains in Hungary.

## 4. Energy management in rail vehicles

Efficient energy management is the key to savings in the rail sector. Energy management systems allow the monitoring and optimization of a vehicle's energy consumption. For example, intelligent energy management systems can determine which devices on board a vehicle consume the most energy and adjust their operation to save money [6, 18, 23, 28, 39, 40, 54]. The paper [53] proposes an innovative two-step approach to simultaneously optimize train operation, schedule and energy management strategies for energy storage devices (OESDs) on urban rail lines. Based on tests under actual traffic conditions on the Yizhuang subway line in Beijing, it was noted that the optimal solution reduced net energy consumption by about 1.04%, 2.09% and a significant 23.77% compared to other operating scenarios.

Another key component of energy management is real-time monitoring of energy consumption. With advanced telemetry systems and sensors, operators can track a vehicle's energy consumption and adjust its operation based on current conditions. This allows for better use of energy resources and cost reduction.

The article [57] presents an effective methodology for reducing propulsion energy consumption in rail vehicles. The kinetic energy of rail vehicles is obtained from propulsion energy, which makes the conversion of this energy crucial for achieving economic and environmental benefits. Dynamic simulations were carried out for different types of shock absorbers to study the effect of the damping coefficient (DC) on the test targets, so that optimal DC combinations could be identified. The study showed that an optimized vehicle model can reduce energy consumption while driving by about 4%.

There are many practical examples that illustrate successes in the field of energy management and energy recovery in rail vehicles. One of them is the Kinetic Energy Recovery System (KERS) [37, 38], which is used in some trains around the world. The proposed KERS system by the authors [37] is based on a supercapacitor as an energy store, which is connected to a brushless machine by means of a suitable power converter. The first part of the article describes the system, presents its analysis and discusses the mathematical model used for simulation. All KERS components were carefully considered in terms of actual performance and power or energy limitations. The results of the analysis showed that the proposed KERS system can achieve energy savings of 20%, with a slight increase in vehicle weight of only 2%. In addition, the commercial costs associated with this system can be offset within 5 years through improved fuel economy, resulting in an equivalent reduction in $CO_2$ emissions.

One possible solution is the application of supercapacitors. Some trains utilize supercapacitors [24, 27, 41, 58, 59] to capture and store energy during braking. This stored energy can later be used to assist in acceleration or power onboard systems. To achieve better efficiency and reduce losses during braking, a locomotive with an energy storage system – a supercapacitor – is proposed [34, 35].

In the context of electric trains, regeneration technology is employed, enabling the transformation and transfer of braking energy back to the traction network. This innovative technology, discussed in scientific literature [1, 4, 8, 9, 29, 41], allows for the effective recovery of energy that would otherwise be lost during braking. The regeneration process facilitates the recovery and reuse of energy, contributing to increased energy efficiency of electric trains and the reduction of energy consumption in rail transport.

The article [15] introduces a modified power system based on existing AC-powered railway lines, with the potential to enhance the efficiency and environmental sustainability of railway systems. This system expands the current railway infrastructure with intelligent solutions based on energy storage. It incorporates power devices with energy storage modules, which are seamlessly integrated on both sides of the neutral zones in traction substations and on sectional poles. The authors assume that the proposed system has the potential to improve efficiency and sustainability in the energy performance of the railway network.

Effective energy management in the railway sector plays a crucial role in resource conservation. Energy management systems enable the monitoring and optimization of energy consumption by vehicles, and intelligent approaches, such as two-stage optimization in urban railway lines, can lead to significant reductions in energy consumption. Real-time monitoring of energy consumption through advanced telemetry systems allows operators to adapt vehicle operation to current conditions efficiently, contributing to better resource utilization. Additionally, innovative approaches like energy recovery systems, supercapacitors, and regeneration technology illustrate the potential for increased energy efficiency and cost reduction in railway transportation.

## 5. The use of fuel cells

A crucial stride in alleviating the impact of rail transport involves the deployment of hybrid locomotives, particularly suitable for shunting and operating trains on non-electrified tracks [11].

Some trains utilize fuel cells as an alternative source of energy, allowing for a reduction in harmful emissions and increased energy efficiency [4, 12, 31, 43, 44]. Fuel cells generate electrical energy on board by using hydrogen or hydrogen-rich hydrocarbon fuels. The electrical energy is then stored in batteries or delivered directly to the high-voltage traction system of the rail vehicle.

From an operational perspective, rail vehicles powered by fuel cells have the potential to replace diesel-powered vehicles on a one-to-one basis, maintaining comparable range and operating time but with a more efficient and less noisy propulsion system [2]. One of the key advantages of this solution is the minimal need for additional infrastructure, as the on-site refueling station is the only required element compared to diesel-powered rail vehicles. Fuel cell technology offers a long-term, zero-emission alternative, enabling fast refueling (comparable to diesel refueling), characterized by flexibility, integration with renewable energy sources, and low-noise operation. Fuel cells are attributed with the potential to provide a consistent, environmentally friendly, and efficient solution for rail vehicles. Compared to passenger cars and utility vehicles with average operating periods of 8,000 hours or 25,000 hours, fuel cell stacks and their peripheral components in rail vehicles should achieve operating periods of 30,000 to 40,000 hours [42].

In article [14], a evaluation of a hybrid fuel cell propulsion system was conducted in various railway scenarios. Numerical tests were performed on four vehicles considering different routes. The implemented model took into account parameters such as track height, train speed, and vehicle characteristics, calculating power demand. For each route, a hybrid propulsion system was applied, comprising fuel cells and an energy storage system, either a battery or a supercapacitor. Each element was individually modeled and validated, and the entire system was verified based on experimental data available in the literature. A comparative analysis of simulation results was carried out, where hydrogen consumption ranged from 5 kg/cycle to 160 kg/cycle depending on energy consumption on the track, with varying fuel cell efficiency from 50% to 47% due to different fuel cell power supply speeds.

The article analyzes the use of a hybrid fuel cell propulsion system in rail transport. Fuel cells, powered by hydrogen or hydrocarbon-rich fuels, show the potential to replace diesel engines, offering comparable range and operating time. The advantages include emission reduction, energy efficiency, and minimal infrastructure requirements. The numerical model and comparative analysis of simulations confirm the system's efficiency, considering different parameters and railway routes. Fuel cells are considered an ecological and efficient solution for rail vehicles, with the prospect of a long-term emission-free alternative.

## 6. Summary

Currently, the pursuit of sustainable development and efficient energy utilization poses key challenges for the railway transport sector. The increased environmental awareness, coupled with the dynamic growth in demand for railway transport services, requires innovative solutions to reduce carbon dioxide emissions and energy consumption. Focusing on efficient energy management and effective recovery in rail vehicles becomes a crucial aspect of achieving these ambitious goals.

Traditionally, energy generated during braking in railway vehicles was lost in the form of heat emitted by disc brakes. However, technological advancements have introduced systems enabling the recovery of this energy. Modern railway vehicles, equipped with advanced systems, allow the transformation of braking energy into electricity. This energy can then be used to power other onboard devices, heat or cool the wagons, significantly enhancing the energy efficiency of these vehicles. Analyzing various methods of energy recovery during braking, the presented research illustrates potential economic and technical benefits. The use of energy storage systems allows the accumulation of excess regenerated energy during braking and its utilization to assist in the acceleration process. This approach eliminates the waste of valuable energy, traditionally dissipated in onboard resistors, resulting in increased energy efficiency and reduced operating costs. Moreover, effective energy management in rail vehicles involves monitoring and optimizing energy consumption. Advanced telemetry systems and sensors enable operators to track energy consumption and adjust the vehicle's operation to current conditions, allowing for better utilization of energy resources.

Fuel cells have the potential to replace diesel engines, offering comparable range and operating time, with a more efficient and less noisy propulsion system. The minimal need for additional infrastructure, such as refueling stations, makes fuel cell technology an attractive, long-term, zero-emission alternative. The conclusions drawn from the analysis presented in the article guide the development of the railway transport sector toward a sustainable, efficient, and more environmentally friendly future solution. Optimizing processes and utilizing innovative energy recovery technologies are crucial for further progress in the railway industry, both economically and environmentally.

## Nomenclature

| | |
|---|---|
| $CO_2$ | carbon dioxide |
| DC | damping coefficient |
| KERS | kinetic energy recovery system |
| OESDs | energy storage devices |

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