
ASSESSING THE ECONOMIC IMPACT OF TRACTION VOLTAGE CHOICE FOR SLOVENIAN PUBLIC RAILWAY INFRASTRUCTURE

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Abstract

Driven by the green transition, we are currently witnessing intensified investment in railway infrastructure and efforts to enhance interoperability with the European network. This paper evaluates the economic feasibility of transitioning to alternative traction power supply systems (15 kV or 25 kV). Such a transition aims to bolster energy efficiency, strengthen competitiveness, and improve Slovenia's integration into key European transport corridors.

Key Words

Public railway infrastructure; Slovenian railway network; energy efficiency; traction power supply system; economic analysis.

INTRODUCTION

The electrification of railway lines in Slovenia was carried out in stages. A 3 kV DC system was selected for the traction power supply. The choice was based on the technological state of the art at the time, the specific characteristics of Slovenian railway lines, and the desired autonomy of the Slovenian railway system within the framework of the then common state. The first electrification using the 3 kV DC system was completed in 1955 on the Postojna–Rakek section. An electric locomotive reached Ljubljana from the Primorska direction in November 1962. Two years later, the Ljubljana–Jesenice line was electrified, followed in 1967 by the Ljubljana–Zidani Most section. Electrification toward Maribor proceeded in several stages and was completed in 1974, while the lines to Sevnica and Dobova had already been electrified in 1969. As the network expanded, the demand for new electric locomotives also increased (Orbanić, 2013).

After a period of relatively modest investment in railway infrastructure and operations, we are now witnessing a renewed and intensified investment cycle. The green transition has accelerated investments in railway infrastructure and new electric trains (Brenna et al., 2020; Kljaić et al., 2023; Milewicz et al., 2023; Kuznetso et al., 2024; Szabó & Panker, 2025; Song et al., 2026; Zuo et al., 2026). Investments related to the upgrading and modernization of railway infrastructure are managed by the Infrastructure Directorate within Slovenske železnice. These upgrades are also part of ensuring interoperability (the ability of a system to operate seamlessly with other systems) within the Trans-European rail system. This includes modernization efforts and increased investments in routes and lines forming part of major European transport corridors. In parallel with large-scale upgrades, smaller sections of infrastructure are also being modernized and renewed, and noise mitigation measures are being implemented in critical areas (GOV.SI, 2023)

In this period of intensive renewal and investment, it is appropriate to consider the future traction power supply system. The currently used 3 kV DC system in Slovenia is relatively rare in Europe. Modern technologies offer alternative systems that are, in certain respects, more suitable and cost-effective.

Slovenia must follow the development of European railway transport and accordingly develop its infrastructure. In 2015, the Government of the Republic of Slovenia adopted the Transport Development Strategy for the Republic of Slovenia until 2030. This strategy also envisages the modernization of railway infrastructure. Through these measures, the country aims to increase transport capacity, enable a higher number of train services, and rely on more efficient energy supply systems. The Slovenian railway network forms part of the Baltic–Adriatic Corridor, which also includes the Port of Koper, as well as the Mediterranean Corridor. Following Croatia's accession to the European Union, the Ljubljana–Dobova railway section became part of the Mediterranean Corridor. In order to maintain the competitiveness of the Port of Koper and other logistics operators, Slovenia requires modern and advanced infrastructure to eliminate bottlenecks in

logistics flows and to strengthen connectivity and national competitiveness (Ministrstvo za infrastrukturo, n.d.).

Based on Regulation (EU) No 1315/2013 on Union guidelines for the development of the Trans-European Transport Network, the Republic of Slovenia is committed, in cooperation with other countries along the respective corridors, to establishing two core network corridors:

- the Mediterranean Corridor,
- the Baltic–Adriatic Corridor (Ministrstvo za infrastrukturo, n.d.).

The main objective of this article is to present a comprehensive economic analysis of the transition of the Slovenian railway network from the existing 3 kV DC system to a more modern 25 kV AC system. Using a cost–benefit analysis (CBA) methodology, we estimated total investment costs, expected savings, and broader economic and environmental effects of the transition. The analysis focuses on infrastructure upgrade costs, rolling stock adaptations, implementation costs, administrative expenditures, and risk contingencies. At the same time, we examined both direct and indirect benefits, such as improved energy efficiency, reduced transmission losses, lower maintenance costs, and the elimination of negative effects caused by stray currents. Through risk and sensitivity analyses, we evaluated how changes in key parameters affect the financial sustainability of the project and its long-term economic justification.

ECONOMIC ANALYSIS

The cost of transitioning to a new voltage system can be divided into several specific components.

1. Infrastructure upgrades (Správa železnic, 2024):

- **Traction substations (TS):** replacement and modernization of transformers, converters, and other key components.
- **Overhead contact line system:** adaptation or replacement of the catenary system, including masts, conductors, and insulators.
- **Underground infrastructure:** adaptation of existing ducts and cables to accommodate higher voltage levels. Estimated share: ~40–50% of total costs.

2. Rolling stock adaptation (Ministrstvo za infrastrukturo, 2024):

- **Upgrade or replacement of locomotives and trainsets:** the new system will require rolling stock compatible with higher voltage (25 kV AC).
- **Multi-system trains:** where necessary to ensure interoperability with different voltage systems on neighbouring railway networks. Estimated share: ~25–30% of total costs.

3. Implementation works and logistics (European Union Agency for Railways, 2023):

- **Construction works:** installation of new components and removal of obsolete systems.
- **Operational impact:** costs related to potential disruptions in railway traffic during implementation.
- **Transport and logistics:** costs associated with the supply of materials and equipment.
Estimated share: ~10–15% of total costs.

4. Administrative and engineering costs:

- **Planning and design:** feasibility studies, technical designs, and required documentation.
- **Alignment with European standards:** ensuring interoperability and compliance with European railway standards.
- **Administration:** project management, permitting, and certification costs.
Estimated share: ~5–10% of total costs.

5. Contingency costs and risks (Računsko sodišče Republike Slovenije, 2010):

- **Unforeseen costs:** project delays, increased material prices, or additional technical adjustments.
- **Risk contingency:** financial reserves allocated to cover unexpected circumstances.

METHODOLOGICAL FRAMEWORK OF THE ECONOMIC AND ENERGY ANALYSIS

To ensure methodological clarity, the economic analysis is divided into an investment component and an operational component, with the latter also including the assessment of energy savings. The boundary of the analyzed system is defined as the entire traction power supply system, encompassing the transmission of electricity from the public power grid to the traction substations, distribution via the overhead contact line system, and the return current through the rails.

The calculation of operational savings primarily includes system losses in the supply and distribution segments of the infrastructure. Losses within the traction vehicles themselves and auxiliary onboard systems are not included, as the analysis assumes the use of modern multi-system rolling stock regardless of the selected voltage system; therefore, such differences would not be methodologically comparable.

The valuation of energy savings is based on a comparison of energy transmission efficiency between the 3 kV DC and 25 kV AC systems. The financial effects are calculated with respect to the total annual electricity consumption of the Slovenian electrified railway network. A more detailed quantification of savings is presented in the following section within the operational cost–benefit analysis.

Table 1: Estimated cost per kilometre

Estimated Cost per km	Data from a Real Project – Czech Republic	Labor Cost in Slovenia Compared to the Czech Republic
Infrastructure Upgrade	45 %	40,85 %
Estimated 40–50% of total costs	493.259,67 EUR	538.036,69 EUR
Material costs: ~35–40 % of total costs	383.646,41 EUR	383.646,41 EUR
Labor costs: 10–15 % of total costs	109.613,26 EUR	154.390,28 EUR
Rolling Stock Adaptation	27,50 %	
Estimated: ~25–30 % of total costs	301.436,46 EUR	335.019,23 EUR
Material costs: ~20–27 % of total costs	219.226,52 EUR	219.226,52 EUR
Material costs: 5–8 % of total costs	82.209,94 EUR	115.792,71 EUR
Implementation Works and Logistics	12,50 %	
Estimated 10–15 % of total costs	137.016,57 EUR	159.405,08 EUR
Material costs: ~5–10 % of total costs	82.209,94 EUR	82.209,94 EUR
Labor costs: ~5–7 % of total costs	54.806,63 EUR	77.195,14 EUR
Administrative and Engineering Costs	10 %	
Estimated: ~5–10 % of total costs	109.613,26 EUR	152.151,43 EUR
Material costs: ~0,5–1 % of total costs	5.480,66 EUR	5.480,66 EUR
Labor costs: ~4,5–9 % of total costs	104.132,60 EUR	146.670,76 EUR
Contingency Costs and Risks	5 %	
Estimated: ~5 % of total costs	54.806,63 EUR	66.000,88 EUR
Material costs: ~2,5 % of total costs	27.403,31 EUR	27.403,31 EUR
Labor costs: ~2,5 % of total costs	27.403,31 EUR	38.597,57 EUR
Total Distribution per km	100%	1.250.613,30 EUR
If total costs represent 100 %	1.096.132,60 EUR	
Material costs: ~63–78 %	772.773,48 EUR	
Labor costs: ~22–37 %	323.359,12 EUR	

Cost–benefit comparison

Energy savings due to reduced losses in the traction power supply system:

- In the 3 kV DC system, energy losses amount to 10–15%.
- In the 25 kV AC system, losses amount to only 2–4%.

This means that the efficiency of electricity transmission when transitioning from the 3 kV DC system to the 25 kV AC system is significantly higher (approximately 95–99% efficiency, compared to roughly 85–90% in the DC system).

Monetized annual energy savings

If annual electricity consumption costs are estimated at approximately EUR 47 million, the direct annual energy savings resulting from the transition to a 25 kV AC system are projected to reach 30%, totalling EUR 14.1 million per year.

This projected reduction represents the cumulative efficiency gains of the modernization. The figure accounts for the synergistic effect of two primary factors. First, direct transmission losses are significantly reduced, falling from 10–15% in the existing 3 kV DC infrastructure to just 2–4% in the 25 kV AC system due to higher voltage and lower current requirements. Second, the AC system enables a substantially higher efficiency of regenerative braking. Unlike the DC system, which often dissipates excess energy as heat, the 25 kV AC infrastructure allows for seamless energy recuperation and feedback into the national power grid. Consequently, the combined impact of minimized line losses and enhanced recuperation leads to the total estimated energy saving of 30% relative to current consumption costs. The analysis assumes that conversion losses related to transforming alternating current into direct current are equivalent and therefore do not materially affect the comparative assessment.

Table 2: Indirect (external) economic benefits

Type of Benefit	Type of Benefits	Description	Possible Financial Assessment
Reduction of CO ₂ emissions	Reduction of CO ₂ emissions	Reduction of emissions by approximately 120,000 tons of CO₂ per year	Based on the market price of emission allowances (approximately €70–100 per ton of CO₂), the economic value of emission reductions is €8.4 to 12 million per year .
Reduction of noise and environmental pollution	Reduction of noise and pollution	Less noise due to modern technologies (e.g., lower rail wear, reduced vibrations)	Savings in health and reduced environmental damage (indirect costs, potentially amounting to hundreds of thousands of euros annually).
Increased competitiveness of rail transport	Increased competitiveness of railways	Increased speed and line load capacity, enabling faster and more frequent transport	Potential increase in revenues for railway operators, as competitiveness against road transport improves (additional revenues, depending on traffic

			volume, could reach several million euros per year).
Increased line capacity	Higher line capacity	Allows higher traffic on existing lines, reducing the need for new construction	Avoided costs of building new infrastructure or expanding the road network (savings of several million euros annually).

Other direct economically quantified benefits

Stray (wandering) currents occur in railway systems powered by direct current (DC). When the electric current from a locomotive returns to the traction substation (TS), it should ideally flow exclusively through the rails. In practice, however, rails are not perfectly insulated from their surroundings. As a result, the current seeks the paths of lowest impedance, including the ground and nearby metallic structures.

These currents have the following negative effects:

- Corrosion of metal structures: Metallic pipes, gas and water pipelines, bridge reinforcements, building structures, metal constructions, and other assets are electrochemically corroded by these currents, reducing their lifespan and causing maintenance and repair costs.
- Safety and operational reliability: Stray currents induce unwanted voltages in neighboring infrastructure, which can negatively affect the safety, reliability, and operation of energy, telecommunication, and other systems.
- Costs of protective measures: Preventive actions, such as cathodic protection, insulation, and regular inspections and measurements, are required, representing significant long-term financial costs.

Direct costs (easier to quantify):

- Routine maintenance and repair costs:
 - Replacement of damaged pipelines (gas, water), bridge structures, and rails
 - Costs of materials, labor, service interruptions, and lost revenue
- Investment costs for protective measures:
 - Installation of cathodic protection, insulation materials, and insulated joints
 - Conducting measurements, diagnostics, and monitoring systems
- Legal and compensation costs:
 - Reimbursement for corrosion-related damage to private or public entities

Direct costs can be estimated based on existing data for maintenance, replacement of damaged elements, material prices, and protective technologies.

Indirect costs (harder to quantify but significant):

- Reduced infrastructure lifespan:
 - leading to higher investment costs
- Environmental impact:
 - Pollution from leaks or damaged pipelines (costs of environmental remediation)
- Reduced safety and reliability:
 - Costs associated with disruptions of transport, energy, or communication systems

Indirect costs are more difficult to assess and usually require complex economic analyses (e.g., Life Cycle Cost Analysis – LCCA), considering expected infrastructure lifespan, risk of failure, environmental costs, and service reliability costs.

Impact on long-term financial sustainability

Transitioning to a 25 kV AC system will have a significant positive impact on the long-term financial sustainability of the Slovenian railway network, as it combines higher energy efficiency, lower maintenance costs, and reduced operational expenditures. Due to the greater energy efficiency of the system, which reaches up to 99.5% (compared to 65.5% for the 3 kV DC system), the railway network will significantly reduce energy losses during transmission and consumption, directly lowering electricity costs. These savings will be especially important on long routes and heavily loaded lines, where the current 3 kV DC system generates higher losses and increased costs due to high currents.

A key element of long-term financial sustainability is the reduction of capital and operational infrastructure costs. The 25 kV AC system allows for longer distances between traction substations, which can be increased from 10–25 km (in the 3 kV DC system) to 20–70 km. This means fewer substations are needed across the network, directly lowering investment and long-term maintenance costs. In addition, the 25 kV AC system reduces mechanical and electrical stresses on the overhead contact line, extending infrastructure lifespan and reducing the need for frequent renovations and costly repairs.

Initial investments for transitioning to 25 kV AC are higher due to the need to adapt infrastructure, substations, and rolling stock. However, the long-term savings achieved through lower energy and maintenance costs will more than offset these upfront expenditures. Rolling stock costs, including the purchase and adaptation of multi-system trains, will enable flexible operation during the transition period, when both 3 kV DC and 25 kV AC systems will operate concurrently. Multi-system vehicles will ensure

seamless interoperability with neighbouring networks, increasing the competitiveness of the Slovenian railway system in international transport.

Project financing will rely on a combination of EU funds, national budget allocations, and private investments. European funds, such as the Cohesion Fund and the Connecting Europe Facility (CEF), are expected to cover a significant portion of the required resources, relieving the national budget and enabling stable long-term financing. Distributing costs over decades, in line with phased implementation, will further reduce financial pressure on the state and allow flexibility in project execution.

Long-term savings from energy efficiency, reduced maintenance costs, and increased network capacity will provide the railway system with greater financial stability. This will free resources for further investments in network development, service improvements, and the introduction of modern technologies. A more powerful and efficient network will also enhance the competitiveness of rail transport, contributing to higher use of this sustainable mode of transport, reduced road traffic, and the strengthened economic importance of railways.

In the long run, the 25 kV AC system will ensure that the Slovenian railway network is financially sustainable, technologically advanced, and compliant with European standards. This will facilitate the development of railways as a key part of transport infrastructure, supporting economic growth, sustainable development, and international connectivity.

Risk and sensitivity analysis

In the case of transitioning to the 25 kV AC system, the risk analysis includes an assessment of possible negative impacts on project implementation, such as cost increases, technical difficulties in integrating the new system, delays in obtaining EU funding, uncertainties regarding traffic volumes, and potential changes in regulatory requirements. For example, if costs were to exceed the projected €1.2–1.5 million per kilometre due to rising material prices or delays, this could affect the financial feasibility of the project.

DISCUSSION

In this article, we analyzed the economic, technical, and strategic aspects of transitioning the Slovenian railway network to the 25 kV AC system. Throughout the study, we focused on the key challenges and opportunities this transition presents and assessed its long-term benefits for energy efficiency, maintenance, interoperability, and sustainable development (see also e.g. Davi-Arderius et al., 2023; Meegahapola et al., 2021).

The study showed that 25 kV is the most suitable solution for the Slovenian public railway infrastructure. The advantage of this voltage lies in lower energy losses, and it is also the most compatible with the systems of neighbouring countries. Such alignment would significantly simplify cross-border connections, contribute to better interoperability, and enhance the competitiveness of our railway network at the international level.

Transitioning to 25 kV would, of course, not be a simple or quick process; it would be a long-term investment carried out in multiple phases. Based on our calculations, we estimated that, with the support of European funding, this investment would pay off in approximately 15 years.

The transition project is long-term, and we expect it to extend beyond the investment payback period. Therefore, it would be sensible to gradually replace the existing, already outdated system components with new ones adapted for 25 kV AC. Such a phased transition would allow a smooth adaptation without causing significant inconvenience to railway users. Most importantly, it would ensure more reliable and punctual transport, which is the highest priority for passengers. This modernization would elevate the Slovenian railway system to a new level of efficiency and compatibility with international standards, while also providing sustainable foundations for future generations.

The selection of the optimal voltage system for Slovenian railway infrastructure is not merely a technical decision but a strategic move that affects energy efficiency, maintenance costs, investment requirements, and, above all, long-term interoperability with the European railway network. Through a comprehensive economic analysis, we demonstrated that considering a change in the power supply system is justified, provided that the final decision is supported by clear goals for sustainable development, international connectivity, and rational use of public funds. The key to success will be coordinated collaboration among all stakeholders and a long-term vision for the railway network of the future.

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