



## DECARBONIZATION POSSIBILITIES FOR TECHNICALLY DEMANDING NON-ELECTRIFIED RAILWAY LINES: A CASE STUDY OF THE SLOVAK REPUBLIC

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### Abstract

Rail transport is generally considered a sustainable mode of transport. However, the use of diesel traction reduces its sustainability, and in some cases CO<sub>2</sub>e emissions and other air pollutants may be higher than those generated by road transport. One possible solution is the electrification of railway lines. However, electrification may present economic and technical challenges. From an economic perspective, the required investments may not be recovered due to low traffic volumes. From a technical perspective, infrastructure constraints—such as tunnels or viaducts, may prevent electrification or make it highly capital-intensive. An alternative solution is the partial electrification of railway lines combined with the use of vehicles powered by alternative energy sources. In our case study, we focused on the partial electrification of a selected railway line in the Slovak Republic in combination with alternative propulsion systems. In addition to financial impacts, we also considered external cost savings resulting from the reduction of CO<sub>2</sub>e emissions and other air pollutants.

*Keywords: alternative energy sources, partial electrification, railway line, economic a social point of view*

### 1 Introduction

Rail transport belongs among sustainable modes of transport. Electrified rail transport is considered the most environmentally friendly and sustainable mode of transport, particularly when energy production is ecological. However, many train services are still operated by trains with internal combustion engines, which generate a significant amount of externalities. The possibilities for reducing these externalities can be implemented in several ways, such as the electrification of railway lines or the use of vehicles with alternative propulsion systems. The electrification of railway lines requires substantial financial investment in infrastructure but can deliver savings in traction energy, reduce greenhouse gas emissions, and shorten travel times [1]. However, the use of new materials in infrastructure modernisation may increase the ecological footprint [2], and electrification is not always economically efficient. In this context, battery-electric propulsion on non-electrified lines represents a potential alternative to internal combustion engines. Partial electrification can improve the reliability and performance of battery-electric vehicles [3]. While railway lines with high or medium traffic volumes are typically electrified, low-traffic lines often remain without electrification. In passenger transport, battery-electric multiple units (BEMUs) can be applied. In freight transport, however, the higher train weight compared to passenger services must be considered, requiring an assessment of the feasibility of battery use. Additional challenges include charging infrastructure, environmental sustainability, and battery production and disposal processes [4].

Simulation of BEMU operation on partially electrified lines has shown lower total energy consumption compared with a non-optimized model, while also extending battery lifetime [5]. Partial electrification may be more effective than using battery propulsion alone, as vehicles achieve a greater range and require fewer batteries [6]. Energy savings of up to 70% can be achieved when operating BEMUs on non-electrified lines. Another option for reducing emissions and energy intensity is the use of hybrid vehicles, which can deliver traction energy savings of around 20% [7]. A technical-economic analysis of replacing diesel with battery propulsion in railway freight transport included a cost–benefit assessment and pay-back calculation. The results confirm future potential for battery use, although replacement is feasible only under low freight transport performance [8]. Hydrogen fuel cell vehicles offer a viable solution for rail transport decarbonisation and greenhouse gas reduction. Hybrid electro-diesel vehicles can reduce emissions by approximately 27% compared with diesel vehicles, representing a cost-effective pathway toward more sustainable rail transport [9]. Rail transport decarbonisation options vary in investment and operational costs and in their actual emission reduction impact. A comprehensive assessment is therefore required, including life-cycle emissions, uncertainty analysis, and operational variability. Artificial intelligence can support such research through predictive modelling, simulation, data analysis, resource optimisation, and risk management [10].

In this study, we conduct a comparative analysis of costs associated with partial electrification in combination with the deployment of battery-electric multiple units (BEMUs) and conventional diesel traction, applying a synergistic approach. The analysis specifically includes investment and operational costs of electrification borne by the railway infrastructure manager, costs related to the BEMU vehicle fleet, as well as external costs.

## 2 Methodology

A change of traction or the use of alternative energy sources represents a significant change in the costs of providing railway transport services. The decision-making process should be based on a comprehensive model that integrates life-cycle emissions, uncertainty analysis, and operational variability. In our study, due to the lack of data under the conditions of the Slovak Republic, we focused on a comparison of the costs of the railway infrastructure manager for line electrification (capital and operating costs), the costs of providing railway passenger transport services (only vehicle costs, energy costs, and the charge for the use of railway infrastructure were taken into account, given that the other internal costs remain unchanged), and external costs (climate change, air pollution), taking into account data variability. Traction energy costs are directly proportional to traction energy consumption, while consumption depends on a number of factors, such as technical conditions of the lines, speed restrictions, etc. [11, 12]. However, for the purposes of modelling and cost comparison, a simplified calculation may be used, based on the average consumption and the price of traction energy, as presented in equation (1) [13]:

$$N_e = Q \cdot L \cdot m_e \cdot S_e \quad [\text{€}] \quad (1)$$

where  $N_e$  are energy costs,  $Q$  is total gross weight of train,  $L$  is journey length,  $m_e$  is average energy consumption and  $S_e$  is energy rate.

Costs for the use of railway infrastructure were calculated based on the Network Statement of ŽSR and Measure No. 2/2018 of the Transport Authority of the Slovak Republic. This component of the costs depends on the length of the journey, the train weight, and the use of the catenary system, according to the applicable calculation rates [14].

The costs for a locomotive or multiple unit are calculated using the following equation [13]:

$$N_{lc} = L \cdot S_{lc} \text{ [€]} \quad (2)$$

where  $N_{lc}$  are locomotive costs and  $S_{lc}$  is locomotive rate.

Within our methodology, climate change costs were selected as the societal costs considered. These societal costs include the impacts of global warming as defined in the Handbook on the External Costs of Transport. Climate change costs comprise air pollutant emissions from railway transport, depending on the type of traction used. According to the Handbook, electric traction generates zero external costs in this category. Therefore, climate change costs are primarily associated with diesel traction [15].

### 3 Results and conclusion

For our case study, we selected partially electrified railway lines in Central Slovakia. The selected railway lines are of primarily regional or interregional importance. A map of the monitored railway lines included in our case study is presented in figure 1. The railway line between Vrútky and Banská Bystrica is 75 kilometres long and is partially double-tracked. Electrification is provided only between Vrútky and Martin, using direct current at 3,000 V, and at Banská Bystrica station, using alternating current at 25,000 V and 50 Hz. The electrified section between Vrútky and Martin is only 6 kilometres long. The non-electrified portion of this railway line therefore totals 69 kilometres. At the nearby Horná Štubňa station, two regional railway lines originate. One of these forms a regional passenger route from Vrútky to Prievidza, with a total length of 76 kilometres. Electrification is again provided only between Vrútky and Martin, covering 6 kilometres. The total length of the non-electrified section of this line is 70 kilometres. The second railway line begins in Horná Štubňa and runs via Kremnica to Zvolen. The length of this section is 57 kilometres. Electrification is provided only between Hronská Dúbrava and Zvolen, using alternating current at 25,000 V and 50 Hz. The non-electrified portion of this line is 46 kilometres. The total distance between Martin and Hronská Dúbrava is 79 kilometres. Both regional railway lines are single-track [16].

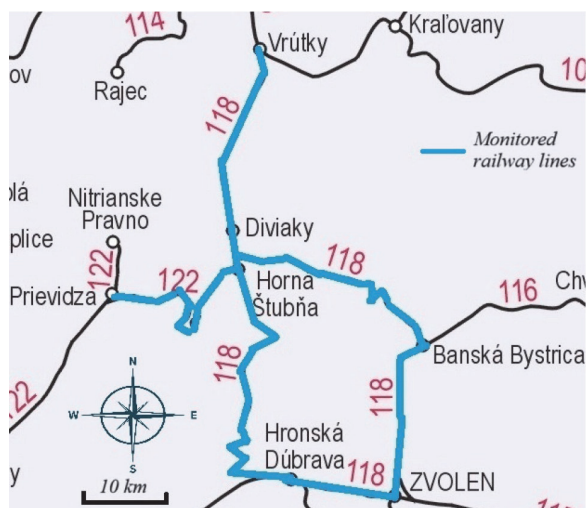


Figure 1 The map of monitored railway lines in the case study [17]

Currently, train services on these railway lines are operated predominantly with independent (diesel) traction. Passenger trains between Vrútky and Prievidza are typically operated by diesel multiple units of type 861 or 861.1. Passenger services between Horná Štubňa and Zvolen are usually operated by diesel multiple units of type 861.1 or by diesel railcars of type 812. Fast trains operating between Žilina and Banská Bystrica or Zvolen are hauled by diesel locomotives of type 757 with three coaches. Only on the section between Martin and Vrútky are some passenger services operated by electric multiple units, along with a small number of freight trains hauled by electric locomotives. Passenger trains between Vrútky and Prievidza operate at two-hour intervals. On working days, this interval is shortened by additional passenger services running between Vrútky and Horná Štubňa or Horná Štubňa Obec. During peak periods on working days, the interval between Vrútky and the Horná Štubňa area is reduced to one hour. Regional passenger services between Horná Štubňa and Zvolen operate with only four trains per day. Fast trains between Žilina and Banská Bystrica or Zvolen operate at two-hour intervals [18]. Freight trains are also operated on the monitored railway lines. These services consist mainly of through freight trains and handling trains. The majority of freight traffic is operated between Horná Štubňa and Vrútky. The approximate number of freight trains is, on average, ten per day across all monitored railway lines within planned freight operations. Freight services are primarily operated by diesel locomotives of type 756 or 736. On certain selected freight trains, other types of diesel locomotives may also be used [18]. The costs of electrification were calculated based on an expert estimate, drawing on the costs of railway line electrification projects implemented in the Slovak Republic in the recent past. In reality, electrification projects in Slovakia have typically been associated with the total or partial modernisation of railway lines. For the purposes of our case study, simple electrification was assumed. Therefore, an expert estimate was made of the cost of electrifying one kilometre of railway line. Based on this estimate, the total costs of electrifying the selected railway lines were calculated. The calculated costs of electrifying the selected railway lines are presented in table 1.

**Table 1** Costs of electrifying the monitored railway lines [19]

Relation	Distance [km]	Cost for electrification [mil. €]	Annually cost for maintenance [mil. €]
Martin - Horná Štubňa	32	84	1.65
Horná Štubňa - Banská Bystrica	41	71.75	1.41
Horná Štubňa - Prievidza	38	66.5	1.30
Horná Štubňa - Hronská Dúbrava	46	80.5	1.58
Total	157	302.75	5.94

As shown in table 1 and in the description above, the highest electrification costs are associated with the section between Martin and Horná Štubňa, where the railway line is double-tracked. Higher investment costs are also identified for the section between Horná Štubňa and Hronská Dúbrava. The lowest electrification costs are estimated for the section between Horná Štubňa and Prievidza. The electrification costs were calculated based on an expert estimate using data from an actual railway electrification project implemented in the Slovak Republic. The costs of maintaining the electric infrastructure were provided by the infrastructure manager. The actual costs of electrifying the selected railway lines may be higher depending on the specific line conditions. The railway sections between Horná Štubňa and Banská Bystrica, Horná Štubňa and Hronská Dúbrava, and Horná Štubňa and Prievidza include tunnels, viaducts, and other constraints related to the mountainous terrain. These lines are characterised by demanding track conditions, particularly due to tunnels and steep gradients [16].

At the same time, it is necessary to consider train performance on the monitored railway lines, as traffic volume is one of the key factors in decisions on electrification. For this reason, we propose electrifying the section between Martin and Horná Štubňa. This section was selected in order to reduce the length of non-electrified railway lines and to enable more efficient operation of BEMUs. On electrified sections, BEMUs can operate under electric traction and recharge their batteries while running on the electrified infrastructure. Without the proposed partial electrification, the operating range of BEMUs on several passenger service variants would be insufficient or close to the limit of battery capacity.

Considering these factors affecting the effectiveness of railway electrification, namely train performance and track conditions, we assess where electrification would be technically simplest and operationally most effective within the monitored railway network. Based on previous research and the identified conditions, we propose partial electrification combined with the use of battery-electric multiple units (BEMUs) in passenger transport. The operating range of BEMUs is approximately 80–100 km. The lengths of the monitored non-electrified sections are therefore suitable for the application of partial electrification. According to the literature review, battery lifetime can be extended if the distance between charging points is relatively short. At the same time, in extraordinary situations, such as temporary service disruptions for various reasons, shorter distances between charging points are advantageous. In this study, charging may be ensured either through extended catenary sections or through slow charging via a heating cable. In freight transport, the use of powerful locomotives is required due to longer distances and demanding track conditions. In this context, electro-diesel locomotives represent a suitable solution. One possible option would be to change the locomotive at the last electrified station to a diesel locomotive. However, this solution may be less efficient for operators, as it requires maintaining different types of locomotives for relatively short distances. In addition, additional time is required for locomotive changes, which may be unattractive for operators in certain cases.

In our case study, a synergistic effect can be identified, as partial electrification would be applicable in three directions: from Vrútky to Prievidza, and from Vrútky to Zvolen via Banská Bystrica and via Kremnica. In all cases, the lengths of the non-electrified sections are suitable for the operation of battery-electric multiple units in passenger transport. In freight transport, electro-diesel locomotives can be used in all directions.

**Table 2** Comparison of operating costs for BEMU and diesel trains over 30 years in mil. € [15, 19]

Performance – train km	BEMU			Diesel traction		
	20% less	Current state	20% more	20% less	Current state	20% more
Vrútky - Prievidza	39.80	48.39	56.82	71.24	90.02	103.22
Vrútky - Zvolen	19.18	19.09	25.89	30.66	29.24	42.36
Vrútky - Banská Bystrica	83.07	109.85	121.74	121.97	143.38	179.33
Electrification/Emission costs	83.34	83.34	83.34	24.24	30.30	36.36
Total costs in 30 years	225.39	260.67	287.80	248.12	292.94	361.27

Our results indicate that, at the current level of transport performance, the internal costs of BEMUs, including partial electrification, are approximately equal to the costs of diesel multiple units. In the case of lower transport performance, the use of diesel units becomes more economically advantageous. However, this calculation has certain limitations, as average values were applied due to the unavailability of detailed operational cost data for the vehicles (which are subject to commercial confidentiality). When external costs are also considered, the use of BEMUs becomes significantly more advantageous.

In this case, the total costs of operating diesel units would be equal to the total costs of BEMUs only if the current transport performance decreased by 37.9%. This result is primarily due to the fact that Slovenské elektrárne (the supplier of electricity to the railway infrastructure manager) reduced its direct CO<sub>2</sub> emissions to zero in 2024, as electricity is generated mainly in nuclear power plants and from renewable energy sources.

## 4 Conclusion

Measures implemented on other railway lines may yield positive outcomes in the decarbonisation of railway transport, similar to the effects observed on the railway lines examined in this study. By deploying BEMUs, it is possible to introduce new operational concepts in passenger transport. Given their technical parameters, BEMUs are generally well suited for short-distance services. For longer distances, further research and development are required to identify alternative propulsion vehicles for long-distance trains with performance parameters superior to those of diesel locomotives. At the same time, additional research and development are needed in the field of environmentally friendly locomotive propulsion systems for freight transport, particularly for heavy freight trains operating on lines with demanding gradients. The operation of electric vehicles is more attractive to passengers and may have a positive impact on passenger numbers. For operators, it may contribute to the unification of the vehicle fleet, especially if similar vehicles are already operated in neighbouring regions of the country. A unified fleet can improve maintenance efficiency and reduce maintenance costs. In our future research, we will focus on developing a universal methodology for decision-making regarding railway line electrification or the use of vehicles with alternative propulsion systems. The proposed methodology will be applicable to both passenger and freight railway transport.

Our research is subject to certain limitations related to simplified assumptions. The costs associated with the use of electric traction in comparison with alternative energy sources depend on multiple factors. In future research, we intend to focus on a comprehensive assessment of the economic and environmental viability of alternative energy sources and railway electrification under the conditions of the Slovak Republic. The analysis will consider life-cycle emissions, both for railway electrification and for the operation of battery-electric multiple units (BEMUs), as well as different operational patterns and infrastructural constraints of railway lines. We plan to develop a comprehensive model using simulation tools, particularly those based on AI. Since no railway vehicles powered by alternative energy sources are currently in operation in the Slovak Republic, the model will be calibrated using data from the Czech Republic and Germany, where alternative energy sources are already being applied on selected regional railway lines.

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