**Sustainable Development of Railway Transport: Assessing the Impact of Electrified Lines on Greenhouse Gas Emissions using**

**Abstract:**

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**1. Introduction**

Sustainable transportation has become a priority in the face of climate change and the need for decarbonisation. Since transportation significantly contributes to greenhouse gas (GHG) emissions, developing environmentally friendly transportation systems is a must for achieving global climate goals and ensuring a sustainable future. Among various modes of transportation, railways have a real potential to reduce GHG emissions and contribute to sustainable development significantly.

Trains are vital for reducing greenhouse gas emissions due to their inherent advantages. They are more energy efficient than road vehicles, making them eco-friendly for transporting people and goods long distances. Electric trains can replace fossil fuel-powered locomotives by electrifying railway lines, significantly decreasing direct emissions. Additionally, renewable energy sources can power electric trains, offering opportunities for achieving carbon-neutral or even carbon-negative railway operations.

Railways could significantly reduce greenhouse gas emissions, not just through their direct environmental benefits. They offer a feasible alternative to road transport, which can help ease traffic congestion, reduce the number of individual car trips, and decongest highways. Additionally, railways can improve connectivity between rural and urban areas, promoting regional development while reducing the need for energy-intensive air travel.

A sustainable transportation system also has social and economic benefits, such as job creation, enhanced public health, and increased energy security.

This research examines the correlation between the extent of electrified railway tracks and greenhouse gas emissions in European Union countries by creating a tool to calculate significant statistical indicators. Understanding the connection between railway electrification and GHG emissions is vital due to the importance of railways in sustainable transportation. This knowledge can help inform decisions on policies, investments in infrastructure, and advancements in technology that aim to maximise the environmental advantages of railways and speed up the move towards low-carbon transportation systems.

**2. Literature Review**

Recent studies in railway infrastructure have examined various environmental implications and solutions. These include the innovative use of plastic waste, studies on soil pollution, addressing environmental challenges in electrifying the railways, advancements in railway energy efficiency, sustainable frameworks for transportation infrastructures, and the role of high-speed railways in promoting eco-friendly tourism.

A study by Benga et al. in 2022 analysed the energy efficiency of European rail companies. The results revealed that the environmental performance of these companies is currently low, but there is significant potential for improvement in eco-efficiency. It also emphasised a positive trend in the energy-environmental efficiency scores of rail transport, indicating a move towards greater sustainability. The authors suggest policymakers focus on energy and environmental efficiency and propose implementing a common EU-level strategy to limit emissions, pollution, and energy consumption.

The railway construction could help reduce plastic waste. Carvalho et al. (2018) proposed a project to transform mixed plastic waste into high-value railway sleepers (crossings for railway lines), leading to the development of eco-friendly railway bridges. The research will focus on creating new material, primarily from mixed plastics, with additional loads to enhance its mechanical strength and other properties. The project will involve real-world testing of sleepers, conducting Life Cycle Analysis and Cost evaluations, and assessing environmental impacts.

Radziemska et al. (2021) investigate the accumulation of risk elements due to railway transport in soils and biological tissues along a railway serving electric and diesel trains. It was found that soil pollution strongly correlated with pollutant levels in biological tissues. It also indicated that certain areas with moderate ecological risk inhibited seed germination and root growth in particular species. The study suggests a comprehensive approach to assessing the environmental impact of railway transport, including soil pollution indices, biotests, and plant and fungal bioindicators.

Popović et al. (2017) emphasise that the expansion and electrification of Serbia's railway system aim to reduce air pollution but may increase noise and environmental issues in the nearby areas. The paper stresses that these environmental impacts cannot be viewed in isolation and require a comprehensive approach to planning, designing, and maintaining railway infrastructure, with particular attention to urban areas. Some considerations include slab track design, continuously welded rails, and the application of milling/grinding technology to control noise. The paper concludes that addressing environmental concerns early in the planning and design process is more cost-effective and impactful than rectifying issues after the infrastructure is operational.

Zhou (2022) focuses on improving railway energy efficiency through technological advancements, management improvements, and structural reconstructions to reduce energy consumption and carbon emissions. The research suggests re-optimising the energy structure, innovating energy-saving technologies, and optimising transportation organisations. Strategies include promoting electrified railway construction, increasing the use of renewable energy sources, and reforming railway transportation organisations. The research emphasises the need for supportive policies and measures such as guiding integrated transportation towards railway-oriented development, fostering innovation in energy-saving mechanisms, and strengthening policy incentives. The study also recommends improving the energy efficiency of railways through market behaviour and tracking new phenomena in the railway industry for analysis.

Santos et al. (2018) argue that promoting sustainability in the construction and maintenance of road pavements and railway track beds should be a guided process systematically assessed using a suitable framework. They created the SUP&R DST, a freely available tool that assists professionals in evaluating the sustainability of transportation infrastructure technologies from the design stage. It is also a valuable educational resource, teaching sustainability concepts and important considerations in sustainable transportation decision-making.

Watson et al. (2017) underline that economic growth and lifestyle changes have increased travel demands, heightening dependency on energy-intensive modes of transport, thereby contributing to greenhouse gas emissions, notably from the tourism industry. Their research investigates the potential of High-Speed Railways (HSR) to reduce these emissions and enhance tourism experiences. Due to growing awareness of environmental impacts and shifts in tourist destinations, rail travel presents an opportunity for a sustainable tourism model, with high-speed night trains offering a promising low-carbon alternative. To effectively reduce CO2 emissions, the tourism industry and rail services should cooperate, potentially integrating high-speed trains into holiday packages. This sustainable transition can result in environmental benefits, economic growth, and increased social inclusion.

These studies highlight the connection between railway construction and operation and ecological sustainability, emphasising innovative approaches and opportunities but also concerns.

**3. Methodology**

We conducted a rigorous ex-post quantitative analysis on the data indicators sourced from Eurostat, namely **railway transport - length of electrified lines** **and net greenhouse gas emissions**. To this end, we wrote a code that helped us calculate the r2, assess the statistical significance of the relationship at a 95% confidence level, and calculate the coefficient of determination for each country regarding the relationship between the abovementioned indicators. Finally, we constructed the regression equations for the top and least-performing countries and delivered insightful interpretations of our results, translating our complex analysis into understandable conclusions.

**Table 1: Railway transport - length of electrified lines, Total, Kilometre**

| **Country** | **2012** | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** | **2019** | **2020** | **2021** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Belgium | 3055 | 3055 | 3088 | 3088 | 3086 | 3092 | 3095 | 3100 | 3099 | 3127 |
| Bulgaria | 2862 | 2869 | 2861 | 2859 | 2869 | 2870 | 2870 | 2869 | 2871 | 3001 |
| Czechia | 3217 | 3216 | 3216 | 3237 | 3236 | 3237 | 3235 | 3231 | 3236 | 3234 |
| Denmark | 621 | 621 | 621 | 621 | 621 | 626 | 730 | 730 | 776 | 803 |
| Germany | : | : | : | 20726 | : | : | : | : | 21100 | : |
| Estonia | 132 | 132 | 132 | 132 | 132 | 132 | 132 | 138 | 138 | 225 |
| Ireland | 145 | 145 | 145 | 145 | 145 | 145 | 53 | 53 | 53 | 53 |
| Greece | 438 | 437 | 494 | 494 | 520 | 532 | 679 | 731 | 731 | 731 |
| Spain | 8786 | 9275 | 9223 | 9717 | 10383 | 10122 | 9840 | 10252 | 10419 | 10428 |
| France | 16116 | 15858 | 16031 | 15987 | 16097 | 16052 | 16053 | 16067 | 16013 | 16054 |
| Croatia | 984 | 985 | 970 | 970 | 970 | 970 | 970 | 970 | 970 | 994 |
| Italy | 11931 | 11969 | 11996[[1]](#footnote-1) | 12010[[2]](#footnote-2) | 12023 | 12022 | 12018 | 12016 | 12065 | 12160 |
| Latvia | 250 | 248 | 251 | 251 | 251 | 251 | 251 | 251 | 251 | 251 |
| Lithuania | 122 | 122 | 122 | 122 | 122 | 152 | 152 | 152 | 152 | 152 |
| Luxembourg | 262 | 262 | 262 | 262 | 262 | 254 | 254 | 254 | 254 | 254 |
| Hungary | 2982 | 2969 | 2968 | 2963 | 3018 | 3103 | 3069 | 3111 | 3111 | 3221 |
| Netherlands | 2266 | 2266 | 2307 | 2302 | 2314 | 2310 | 2224 | 2224 | 2225 | 2264 |
| Austria | 3852 | 3854 | 3874 | 3905 | 3926 | 3946 | 3951 | 3976 | 3992 | 4003 |
| Poland | 11920 | 11868 | 11830 | 11865 | 11874 | 11854 | 11858 | 11982 | 12113 | 12101 |
| Portugal | 1630 | 1629 | 1630 | 1639 | 1639 | 1639 | 1639 | 1696 | 1696 | 1791 |
| Romania | 4020 | 4029 | 4029 | 4030 | 4030 | 4030 | 4029 | 4029 | 4034 | 4035 |
| Slovenia | 500 | 500 | 500 | 500 | 500 | 610 | 610 | 610 | 610 | 610 |
| Slovakia | 1586 | 1586 | 1586 | 1587 | 1587 | 1588 | 1587 | 1587 | 1585 | 1585 |
| Finland | 3172 | 3172 | 3256 | 3262 | 3270 | 3331 | 3330 | 3331 | 3349 | 3359 |
| Sweden | 8194 | 8214 | 8232 | 8235 | 8184 | 8189 | 8217 | 8185 | 8184 | 8186 |

Source: Eurostat, (2023a).

**4. Electrified Railway Lines and Greenhouse Gas Emissions: Data Analysis**

Regarding the length of electrified lines, in the EU, Germany ranks first in 2021 with 21.100 kilometres, followed by France (16.054 km) and Italy (12.160 km). Romania ranks 7th with 4.035 km. The countries with the shortest electrified lines are Estonia (225 km), Lithuania (152 km) and Ireland (53 km).

**Figure 1: Railway transport - length of electrified lines, in 2021, Total, Kilometre**

Source: Author's representation of data provided by Eurostat (2023a).

In terms of percentage change between 2012 and 2021, Estonia registered the highest increase in the length of electrified lines (70,45%, and 93 km, respectively), followed by Greece (66,89% and 293 km) and Denmark (29,31% and 182 km). Romania increased its electrified lines by only 15 km (0,37%). Ireland (-63,45% and -92 km), Luxemburg (-2,93% and -8 km), and France (-0,38% and -62 km) close the EU hierarchy.

As to the length of electrified lines built between 2012 and 2021, Spain is the best performer in the EU (1.642 km), followed by Greece (293 km) and Hungary (239 km). Significant increases were registered in Italy (229 km), Finland (187 km) and Denmark (182 km). Romania added only 15 km, while Bulgaria 139 km.

**Table 2: Air pollutants and greenhouse gases, Total (excluding LULUCF and memo items, including international aviation), Tonnes per capita.**

| **Country** | **2012** | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** | **2019** | **2020** | **2021** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Belgium | 11.2 | 11.1 | 10.6 | 10.9 | 10.8 | 10.7 | 10.7 | 10.6 | 9.6 | 10.0 |
| Bulgaria | 8.2 | 7.6 | 8.0 | 8.5 | 8.2 | 8.6 | 8.0 | 7.8 | 7.0 | 7.9 |
| Czechia | 13.0 | 12.5 | 12.2 | 12.3 | 12.5 | 12.5 | 12.3 | 11.8 | 10.7 | 11.4 |
| Denmark | 10.3 | 10.5 | 9.8 | 9.2 | 9.5 | 9.1 | 9.0 | 8.3 | 7.5 | 7.7 |
| Germany | 11.7 | 11.9 | 11.3 | 11.3 | 11.2 | 11.0 | 10.6 | 9.9 | 9.0 | 9.4 |
| Estonia | 15.2 | 16.7 | 16.1 | 13.8 | 15.0 | 16.0 | 15.3 | 11.1 | 8.6 | 9.6 |
| Ireland | 13.4 | 13.4 | 13.2 | 13.7 | 14.0 | 13.8 | 13.8 | 13.1 | 12.1 | 12.6 |
| Greece | 10.4 | 9.6 | 9.4 | 9.1 | 8.9 | 9.3 | 9.0 | 8.4 | 7.2 | 7.6 |
| Spain | 7.7 | 7.2 | 7.2 | 7.5 | 7.3 | 7.6 | 7.4 | 7.0 | 5.9 | 6.3 |
| France | 7.6 | 7.6 | 7.1 | 7.1 | 7.1 | 7.1 | 6.8 | 6.7 | 5.9 | 6.2 |
| Croatia | 6.2 | 5.9 | 5.8 | 5.9 | 6.0 | 6.3 | 6.2 | 6.2 | 5.9 | 6.3 |
| Italy | 8.4 | 7.7 | 7.3 | 7.5 | 7.5 | 7.4 | 7.4 | 7.3 | 6.5 | 7.1 |
| Latvia | 5.5 | 5.6 | 5.6 | 5.6 | 5.7 | 5.8 | 6.1 | 6.1 | 5.6 | 5.8 |
| Lithuania | 7.1 | 6.8 | 6.9 | 7.0 | 7.2 | 7.3 | 7.3 | 7.4 | 7.3 | 7.3 |
| Luxembourg | 24.3 | 22.8 | 21.6 | 20.5 | 19.9 | 20.1 | 20.4 | 20.2 | 16.9 | 17.6 |
| Hungary | 6.3 | 6.0 | 6.0 | 6.4 | 6.4 | 6.7 | 6.7 | 6.7 | 6.5 | 6.7 |
| Netherlands | 12.3 | 12.3 | 11.8 | 12.2 | 12.1 | 11.9 | 11.6 | 11.1 | 9.8 | 10.0 |
| Austria | 9.7 | 9.7 | 9.2 | 9.4 | 9.4 | 9.6 | 9.2 | 9.3 | 8.4 | 8.8 |
| Poland | 10.5 | 10.4 | 10.1 | 10.2 | 10.5 | 10.9 | 10.9 | 10.3 | 9.8 | 10.7 |
| Portugal | 6.6 | 6.4 | 6.5 | 6.9 | 6.8 | 7.3 | 7.0 | 6.7 | 5.8 | 5.6 |
| Romania | 6.5 | 6.0 | 6.0 | 5.9 | 5.9 | 6.1 | 6.1 | 6.0 | 5.8 | 6.0 |
| Slovenia | 9.3 | 9.0 | 8.1 | 8.2 | 8.6 | 8.7 | 8.6 | 8.3 | 7.6 | 7.7 |
| Slovakia | 7.9 | 7.8 | 7.4 | 7.6 | 7.6 | 7.8 | 7.8 | 7.4 | 6.8 | 7.6 |
| Finland | 11.9 | 11.9 | 11.1 | 10.4 | 10.9 | 10.4 | 10.6 | 10.0 | 8.8 | 8.8 |
| Sweden | 6.2 | 6.0 | 5.8 | 5.7 | 5.6 | 5.5 | 5.4 | 5.2 | 4.6 | 4.7 |

Source: Eurostat, (2023b).

Regarding air pollutants and greenhouse gas emissions, Luxembourg ranks first in the EU in 2021 with 17.6 tonnes per capita. Ireland is the second in this hierarchy, with 12.6 tonnes per capita and Czechia (11.4) the third. Latvia (5.8 tonnes per capita), Portugal (5.6) and Sweden (4.7 tonnes per capita) close the ranking for 2021. Romania ranks 22 in the EU with 6.0 tonnes per capita.

**Figure 2:** **Air pollutants and greenhouse gases, 2021, Tonnes per capita.**

Source: Author's representation of data provided by Eurostat (2023b).

The highest decrease in the analysed timeframe was registered by Luxembourg (-6.7 tonnes per capita), followed by Estonia (-5.6 tonnes per capita) and Finland (-3.1 tonnes per capita). An increase was registered by Poland and Lithuania (0.2 tonnes per capita), Latvia (0.3 tonnes per capita) and Hungary (0.4 tonnes per capita). Romania decreased its emissions by 0.5 tonnes per capita and -7.69%, respectively.

As a percentage change, Estonia experienced the highest decrease in emissions (-36.84%) in 2021 compared to 2012, followed by Luxembourg (-27.57%) and Greece (-26.92%). The highest increase was recorded by Hungary (6.35%), Latvia (5.45%) and Lithuania (2.82%).

**5. Econometrical analysis**

**6. Discussion of Findings**

- Interpretation and discussion of the results obtained from the data analysis.

- Examination of the relationship between electrified railway lines and greenhouse gas emissions.

**7. Policy Implications and Recommendations**

**8. Conclusion**

- Summary of the main findings and their significance.

- Discuss the study's contributions to understanding sustainable railway transport and greenhouse gas emissions.

- Suggestions for future research directions in sustainable transportation and railway electrification.

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1. Average 2013-2016 [↑](#footnote-ref-1)
2. Average 2014-2016 [↑](#footnote-ref-2)