Study on the Harmonisation of Electrification Systems

2026

EUROPEAN
UNION
AGENCY
FOR RAILWAYS

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The key findings and recommendations contained in this report are based on the expert judgement of ERA staff, supported by the evidence collected.

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Abbreviations

AC	alternating current
DB	Deutsche Bahn (German national railway company)
DC	direct current
EMU	electric multiple unit (i.e. trainset)
ERA	European Union Agency for Railways
ERTMS	European rail traffic management system
EU	European Union
OCL	overhead contact line
RFI	Rete Ferroviaria Italiana (Italian rail infrastructure manager)
TEN-T	trans-European transport network
TSI	technical specification(s) for interoperability
TSI ENE	technical specifications for interoperability relating to the energy subsystem
TSI LOC & PAS	technical specification for interoperability relating to the 'rolling stock — locomotives and passenger rolling stock' subsystem

Executive summary

The European Commission requested the European Union Agency for Railways to analyse the potential for greater harmonisation of railway electrification systems in Europe.

Four TSI-compliant systems exist, namely 1.5 kV DC, 3 kV DC, 15 kV AC and 25 kV AC. For historical and technological reasons, each system can be found across Europe.

Rolling stock needs to be specifically designed to operate on one or several of these systems. This study shows that electric locomotives are increasingly able to operate on all four systems, thus mitigating the barriers that differing voltages present to cross-border operations. For (high-speed) trainsets, this is less often the case. Multi-system vehicles remain, however, more expensive to produce and operate.

In some cases lines have been re-electrified to a different voltage. An analysis of past and ongoing re-electrification projects highlights the complications and high costs of vehicle and line adaptations. The benefits are strongly case specific and several studies of national re-electrification plans showed no positive benefit–cost ratio.

Arguments in favour of and against re-electrification were evaluated from a European perspective too. The analysis suggests that the benefits of a large-scale re-electrification programme would probably not balance the costs. Moreover, its feasibility from financial and operational perspectives was questioned.

Yet, as case studies offering evidence in favour of specific re-electrification projects do exist, and more may follow, the study provides the following recommendations.

- No absolute requirement should be introduced into the TSI ENE for 1.5 kV DC and 3 kV DC lines to be re-electrified to 15 kV AC or 25 kV AC upon upgrade or renewal.
- Analyse which instruments and requirements could facilitate the harmonisation of the voltage of lines if relatively small DC sections are found along current or future predominantly AC corridors.
- A study on cross-border sections should assess which stations would benefit from being connected by alternative electrification solutions or a different voltage to facilitate cross-border traffic.

The study highlights several other aspects of the energy subsystem, beyond voltage and frequency, that increase costs and pose barriers to interoperability. On that the following recommendations are made.

- Perform a comprehensive evaluation on the level of compliance of fixed installations with the requirements of TSI ENE.
- Study the costs and benefits of greater harmonisation of overhead contact line geometry, focusing both on greater harmonisation of the 1 950 mm and 1 600 mm systems (for all line speeds) and the progressive removal of non-TSI-compliant overhead contact line geometries, particularly those stemming from national rules and specific cases related to compatibility with 1 450 mm pantograph heads.
- Perform a study on specific cases in the TSI ENE and the TSI LOC & PAS to assess their duration and impact on interoperability.

Finally, in view of the recently published high-speed rail plan and the impact that the energy subsystem will have on future developments, this study gives rise to the following recommendation.

- Conduct a comprehensive analysis to determine whether there is a feasible path to simplifying the energy subsystem requirements for high-speed trainsets by re-electrifying specific lines or points or by building bypasses. Additionally, the analysis should reflect on the impact of national rules on the interoperability of the high-speed rolling stock fleet. Finally, the analysis should evaluate the options for promoting multi-system high-speed trainsets with greater areas of use.

1. Background and research scope

When the technical specifications for interoperability relating to the energy subsystem (TSI ENE) were drafted in 2009, the conclusion was that there was no economic rationale for mandating a single electrification system (1). Subsequently, the four main electrification systems (i.e. 1.5 kV DC, 3 kV DC, 15 kV AC and 25 kV AC) were all integrated into TSI ENE.

The European Commission asked in the 2024 TSI revision request for an additional study on the harmonisation of electrification systems. The purpose of the study, which is the subject of this report, is to explore whether the underlying assumptions that supported the choice to maintain four systems still apply today and whether there are feasible scenarios for increased harmonisation of the energy subsystem that would strengthen the single European railway area. The Commission's request was worded as follows:

Investigating whether the European railway electrification system should be (more) harmonised is important due to the current variation in voltage standards across countries. Harmonisation could offer potential benefits, such as improved interoperability, enabling trains to move across borders without needing multi-system locomotives. This might reduce operational complexities and maintenance requirements. However, the costs associated with transitioning to a more harmonised or entirely unified system, including infrastructure upgrades and retrofitting existing rail networks, could be significant. Any consideration of harmonisation would need to balance these potential benefits with the economic and logistical challenges involved.

The main goal of the study is to provide a comprehensive assessment of the status of European electrification systems with regard to voltage and frequency, including the impacts of re-electrification. In addition, the study will reflect on the barriers to interoperability that non-electrification and the requirements of the energy subsystem other than those relating to voltage and frequency may pose. The report is structured as follows:

- the status of electrification systems in Europe (Chapter 3),
- national experiences of and perspectives on re-electrification (Chapter 4),
- a European perspective on re-electrification (Chapter 5),
- conclusions (Chapter 6).

It should be noted that the Europe-wide scope of the study necessitates some approximations and simplifications, and thus the results should not be used directly in the context of any specific railway project.

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(1) European Union Agency for Railways (ERA), *Conventional Rail Energy TSI: Impact assessment report*, 2009, p. 3.

2. Methodology

2. Methodology

The feasibility of harmonising electrification systems has been assessed on numerous occasions. This report leverages insights from existing research, databases and inputs provided by interviewees. The main data sources are listed in the Annex and footnotes are added where needed.

A draft version of this report was distributed to stakeholders for comment in October 2025. Detailed feedback was provided by 18 organisations and the comments were reviewed for an update of the report.

Finally, a hybrid workshop was organised on 10 December 2025 to discuss the study's main findings and recommendations. The comments received during the workshop were used to make final refinements to the report.

The authors wish to thank the contributors for their time and valuable comments.

3. Electrification systems in Europe

3.1. Rail electrification: a brief overview

The electrification of European railways started over a century ago. Today there are four main systems: two systems with direct current (DC) and two systems with alternating current (AC), as shown in Table 1.

Each country opted for a given system based on the technologies available in the year when electrification was introduced and because it was deemed the optimum solution from operational, economic and political perspectives. Generally, the system that an infrastructure manager operates today is the same system that was initially chosen.

Table 1: Overview of the main electrification systems

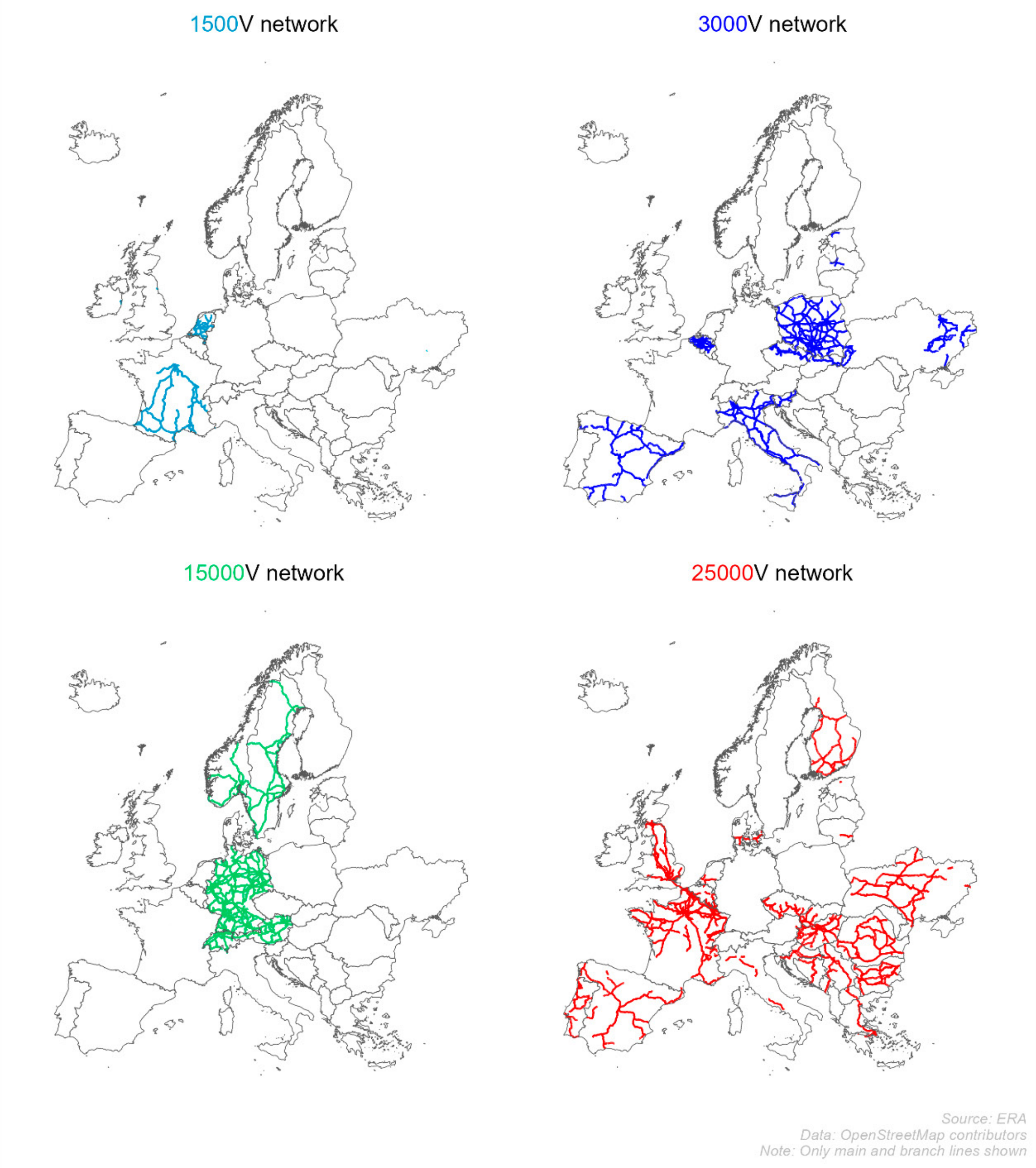
	1.5 kV DC	3 kV DC	15 kV AC	25 kV AC
Introduced	1920	1930	1912	1954
Number of substations	High	Medium	Low	Low
Grid connection	Three-phase	Three-phase	AT, CH, DE: separate system; NO, SE: converter	Single-phase
Acceleration	Low to medium	Medium	High	High
Overhead contact lines	Heavy lines	Medium lines	Light lines	Light lines
Power loss	Medium to high	Medium	Low	Low
Relative fixed installation capital expenditure	Medium to high	Medium	Low	Low
Relative fixed installation operational expenditure	Medium	Medium	Low	Low
Relative rolling stock capital expenditure	Low	Low to medium	Medium to high	Medium to high
Relative rolling stock operational expenditure	Low	Low to medium	Medium to high	Medium to high

NB: The estimates above are indicative. Actual results may differ depending, inter alia, on how the system is implemented, the age of the system and the operational profile of the traffic.

3.2. Infrastructure: state of play

Figure 1 shows the four main electrification systems and where they are installed across Europe.

Figure 1: Main electrification systems in Europe



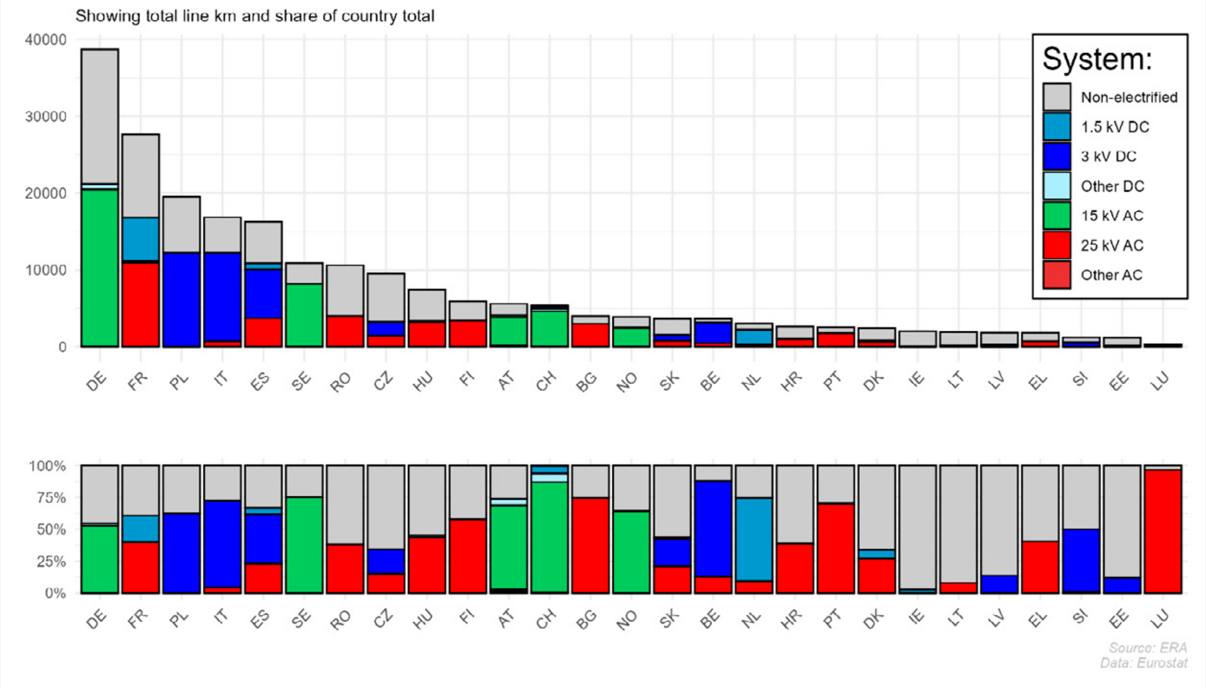
Source: ERA
Data: OpenStreetMap contributors
Note: Only main and branch lines shown

The 1.5 kV DC system is present in France and the Netherlands, and also in several isolated networks and city networks in other countries. The 3 kV DC system is more pervasive across Europe, albeit fragmented. The 15 kV AC system is used in neighbouring Austria, Germany and Switzerland and in Norway and Sweden. The 25 kV AC system, finally, is used in many countries that have electrified their networks in more recent times or where dedicated high-speed lines were introduced amid DC networks.

Some countries, including Czechia, Spain, France and Slovakia, have two main systems in place that work in parallel with or separately from each other. Here, too, there are technological and operational reasons for the implementation patterns. At the same time, many countries still have a significant number of non-electrified lines.

Figure 2 shows the line kilometres for each main system, other DC systems, other AC systems and non-electrified lines by country, in kilometres and as a percentage of the total for the country. It highlights that the share of non-electrified lines remains high across Europe.

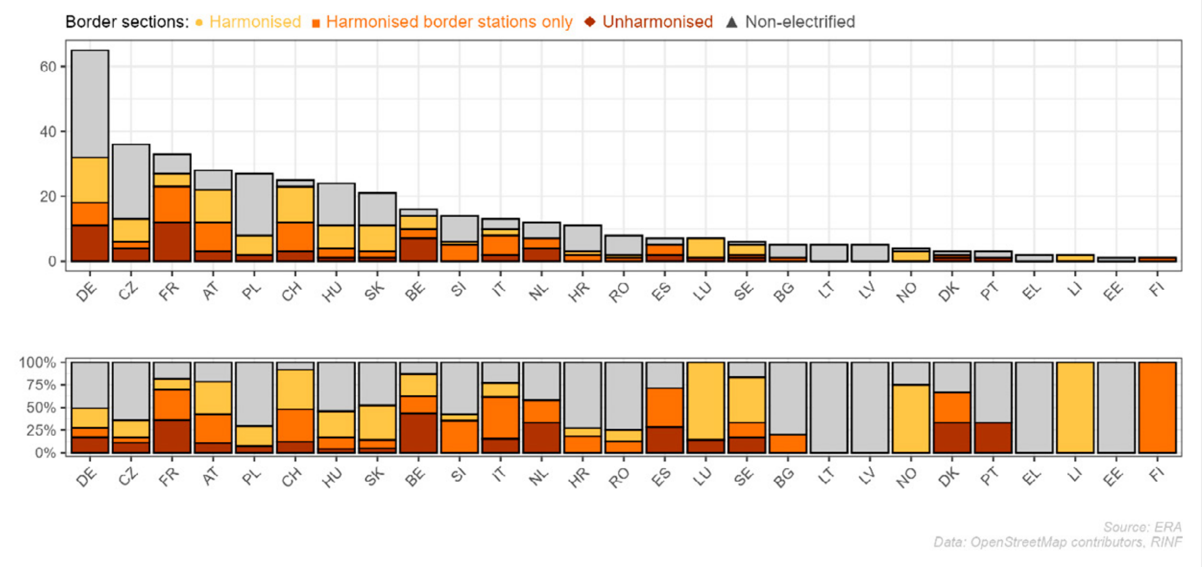
Figure 2: Line kilometres by electrification system in 2023



Source: ERA
Data: Eurostat

Figure 1 might seem to suggest that rail traffic between several countries can cross borders with relative ease using the same electrification system. This idea should be nuanced. Figure 3 shows those border sections (a) where a train can cross borders and access large operational points using the same electrification system ('harmonised'), (b) where only the border stations on a section have the same electrification system but not the subsequent lines ('harmonised border stations only'), (c) where the section is electrified using different systems ('unharmonised') and (d) where the section is not electrified on one or both sides of the border ('non-electrified').

Figure 3: Electrification of EU cross border sections by country

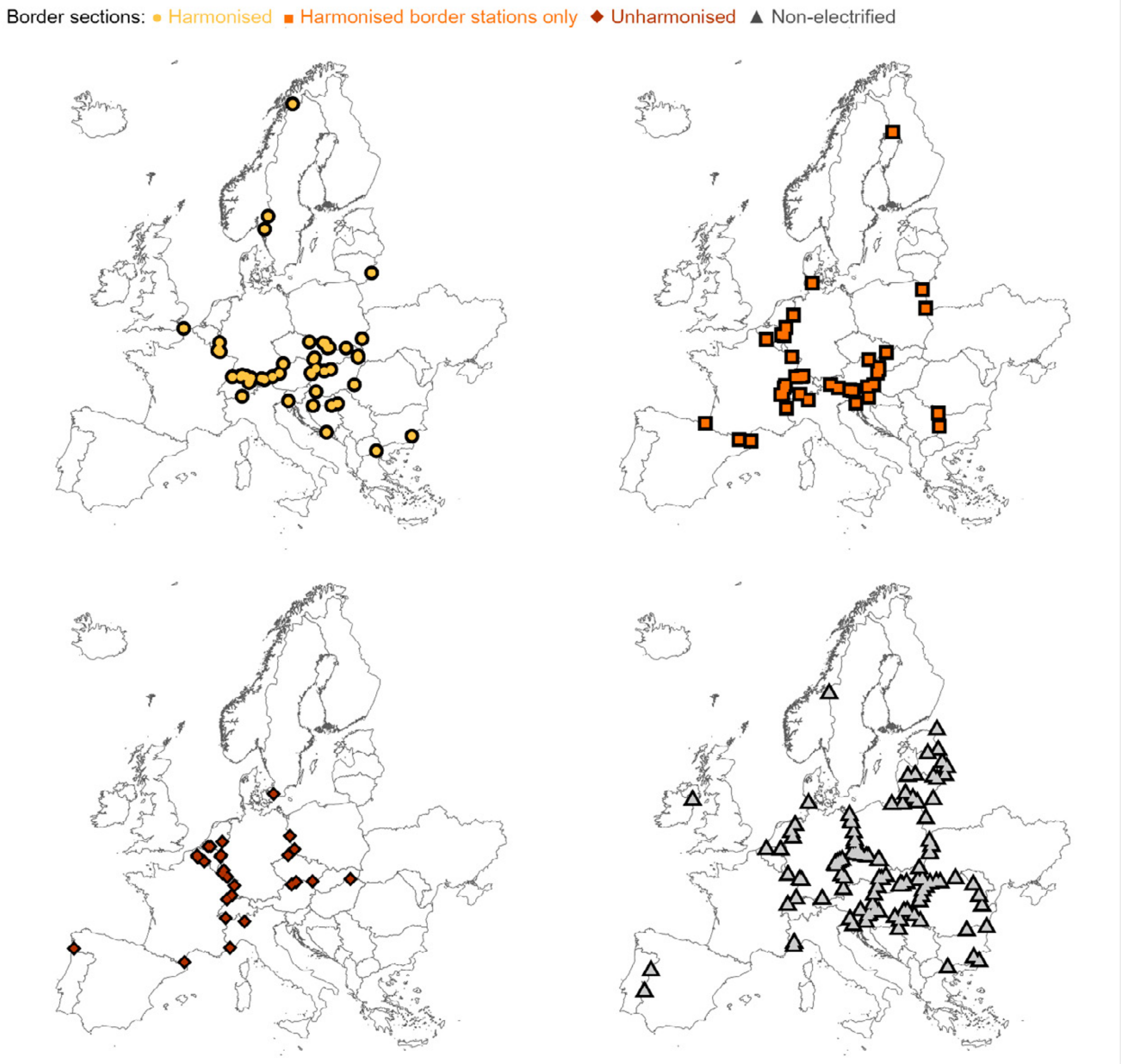


Source: ERA
Data: OpenStreetMap contributors, RINF

In total, 241 border sections were analysed, of which 59 (24 %) are harmonised, 36 (15 %) have harmonised border stations, 27 (11 %) are electrified using different systems and 119 (49 %) are non-electrified. As shown in Figure 3, the prevalence of each category depends on the country.

Figure 4 shows the exact locations of the various sections. A general observation is that, in central and eastern Europe in particular, there is a high share of non-electrified border sections – this despite the fact that many of the countries have electrified a large part of their network using the same 25 kV AC system. Between Germany and Czechia and Germany and Poland, the share of non-electrified crossings is large, too.

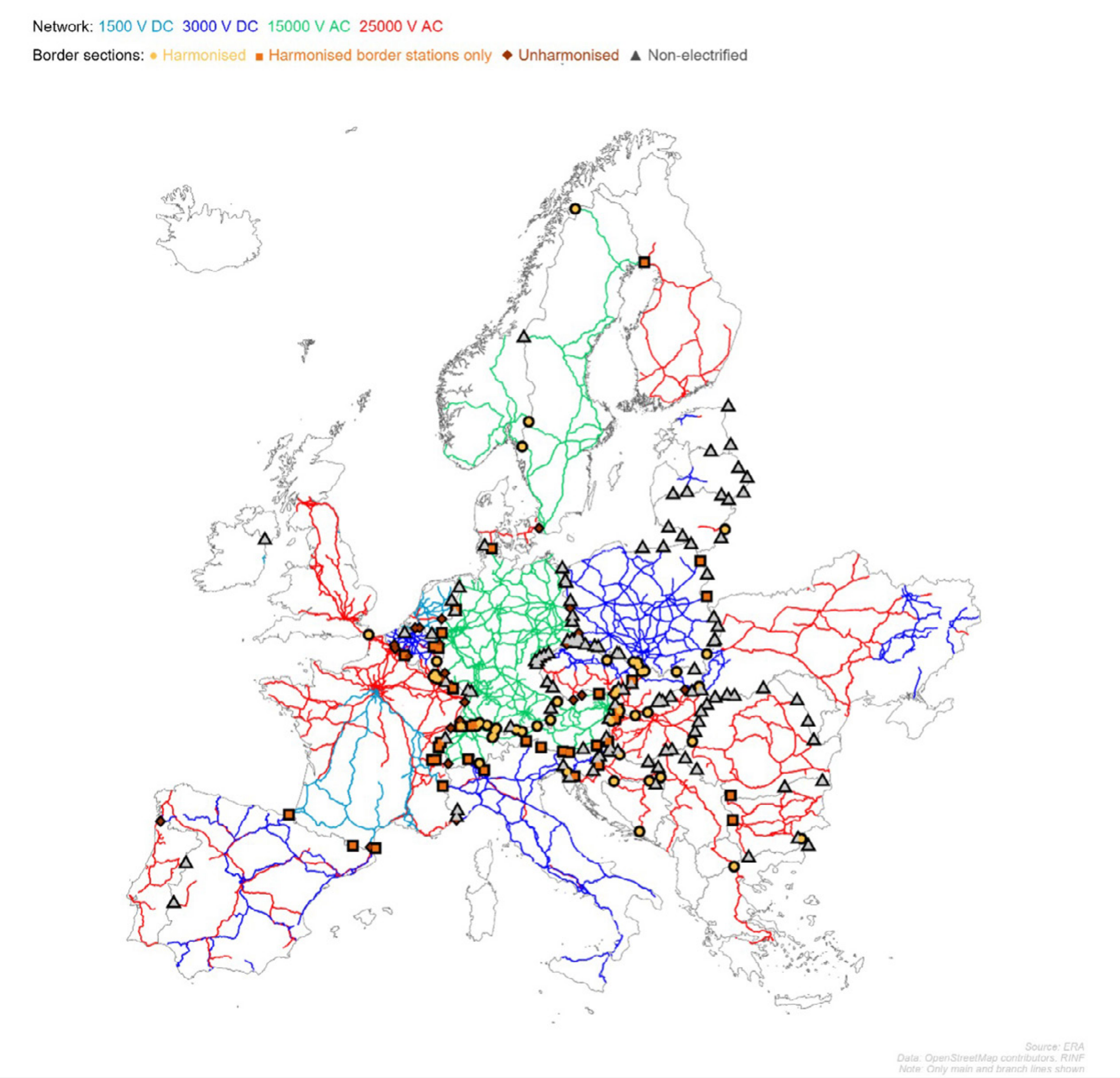
Figure 4: Electrification status of border section



Source: ERA
Data: OpenStreetMap contributors, RIN
Note: Only main and branch lines show

Figure 5 integrates the findings on systems and border sections, highlighting the complex and fragmented nature of European rail electrification systems and, importantly, the lack of electrified border sections.

Figure 5: Electrification status in Europe



Source: ERA
Data: OpenStreetMap contributors, RINF
Note: Only main and branch lines shown

The infrastructure statistics associated with the above figures are shown in Table 2. Non-electrified lines and border sections are by far the most common. Border sections with 1.5 kV DC only are rare and often present only on one side of the section. AC systems are more prevalent at border sections, as more countries have implemented these systems.

Table 2: Statistics on the main electrification systems and non-electrified network

	1.5 kV DC	3 kV DC	15 kV AC	25 kV AC	Non-elec.
Number of EU Member States / EFTA countries with this system ([a])	10	11	12	21	27
Total line length (kilometres) ([b])	9 160	36 328	39 525	36 775	86 869
Share of all lines (%) ([c])	4.4	17.3	18.8	17.5	41.3
Number of border sections with this system ([d])	8	59	94	103	210
Share of all border sections (%) ([c])	1.7	12.4	19.7	21.6	44.1

([a]) The number is determined taking into account main, branch, regional and local lines.

([b]) May exclude some networks that are not reported to Eurostat, such as urban or functionally separated networks.

([c]) Percentages do not add up to 100 %, as there are also other, minor electrification systems.

([d]) Considering each side of the border separately.

That said, even when a border section is electrified using the same system, there are barriers to interoperability related to the energy subsystem that go beyond voltage and frequency. Pantograph requirements are a particularly salient issue.

Overhead contact lines and pantographs

The pantograph–catenary interface represents one of the major barriers to rolling stock interoperability. Harmonisation would facilitate cross-border operations, reducing maintenance, operational complexity and the risk of dewirement ([2]), especially in windy conditions.

Historically, a wide range of pantograph heads have been used across Europe, stemming from decades of national railway development in which overhead contact line (OCL) systems were optimised based on local geography, voltage standards and engineering practices. Through the TSI, the number of permitted head geometries has been limited to the 1 600 mm Europantograph and a larger head geometry of 1 950 mm ([3]). Figure 6 shows where the TSI-compliant pantograph heads are accepted across the European railway network.

However, TSI ENE includes some specific cases for the use of different pantograph head geometries at the national level. As shown in the same figure, there are several lines where it is permissible to run with a pantograph head of 1 450 mm, too. Data for Switzerland is missing, but there are several lines there where operations are only possible with a 1 450 mm pantograph head, as mandated by permanent specific case CH-TSI ENE-001 ([4]). These specific cases mean that, currently, new traction vehicles are still fitted with 1 450 mm pantographs.

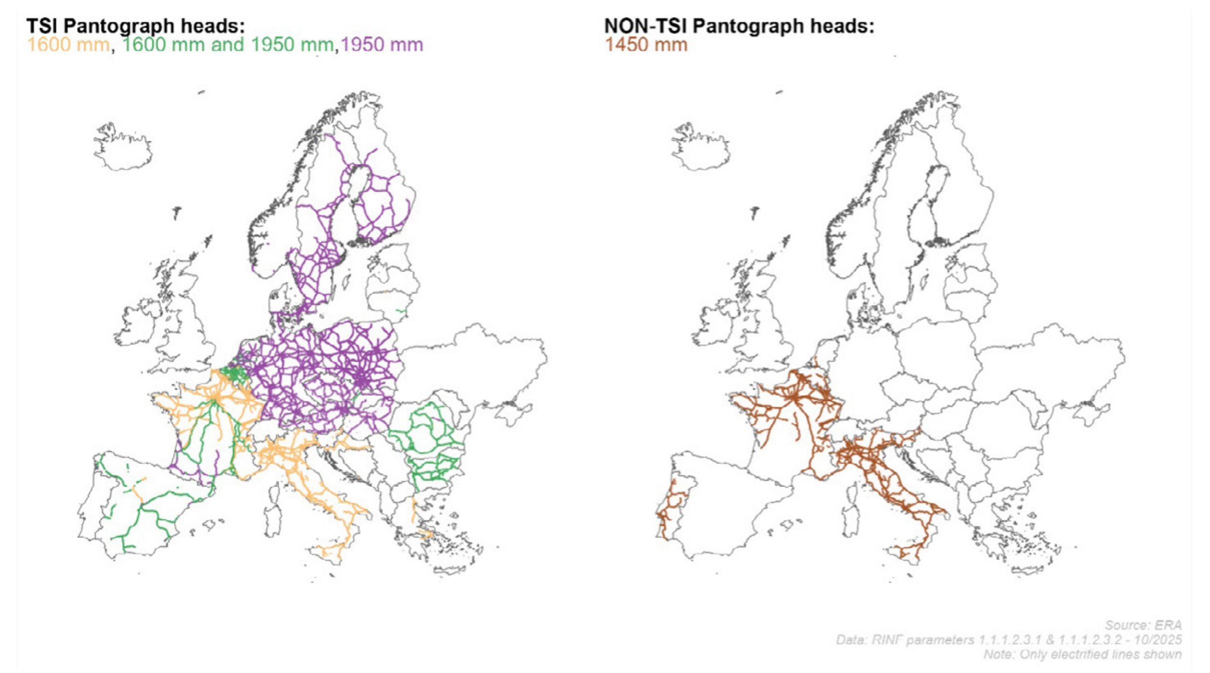
Beyond head geometry, the material used for the pantograph's contact strip adds another compatibility constraint. A contact strip may not be compatible with more than one electrification system, so a pantograph head that is geometrically compatible with several OCL configurations can still be unsuitable for use with different electrification systems. That said, the impact of the contact strip material on system compatibility is comparatively minor when assessed against the influence exerted by the pantograph's geometric configuration.

([2]) An incident where an electric train, tram or trolleybus becomes disconnected from the overhead contact wire, typically due to the pantograph losing contact or pulling down the wire.

([3]) The diversity of pantograph designs complicates interoperability and increases maintenance costs; for example, the related maintenance costs per train are estimated at 2 % of capital expenses per year, i.e. about EUR 120–160, for each additional pantograph required. Additionally, a mounted pantograph adds about 150 kg of dead weight, causing extra energy consumption estimated at about EUR 100 per year and per pantograph for a freight train. See ERA, 'Impact assessment report, ENE TSI', 2009, p. 41.

([4]) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02002A0430%2803%29-20241213.

Figure 6: Pantograph compatibility across Europe



TSI Pantograph heads:
1600 mm, 1600 mm and 1950 mm,1950 mm

NON-TSI Pantograph heads:
1450 mm

Source: ERA
Data: RINF parameters 1.1.1.2.3.1 & 1.1.1.2.3.2 - 10/2025
Note: Only electrified lines shown

TSI ENE and the technical specifications for interoperability relating to locomotives and passengers (TSI LOC & PAS) set out specifications for permissible pantograph–OCL interfaces, taking into account the advantages and disadvantages of various designs. OCLs allowing wider pole spacing can reduce infrastructure costs, but wider pole spacing may increase the lateral deviation of the contact wire. Therefore, these OCLs may require longer pantograph heads to ensure reliable contact during lateral wind deviation. Tighter spacing and restrictive gauges in tunnels and overpasses favour shorter heads, especially in 25 kV AC systems. The distance between poles in catenary systems varies significantly across European countries. These variations can be attributed to differences in design standards, historical development and technical and performance requirements. Some key observations on these issues follow.

- Specified in TSI ENE (5), the maximum lateral deviation of the contact wire is a critical parameter for interoperability, and it is strongly related to both length and shape of the pantograph, as mentioned above (6).
- Railway networks with widely spaced support poles may require significant investment to adjust the lateral position of the contact wire, because the sideways deviation in existing catenary systems with long pole spacing is considerable. Moreover, variations in catenary point spacing distances across European countries (e.g. from 55 m to 80 m) contribute to an additional challenge: if the pantograph is short and the span between support points is too wide, loss of contact or mechanical instability may occur, potentially leading to dewirement or similar issues.
- Differences between OCL design target widths and the pantograph head actually used can create operational and safety risks. When an OCL is designed for a 1 950 mm pantograph, using a 1 600 mm pantograph may increase dewirement risk in crosswind because the smaller head provides fewer usable lateral contact positions. When an OCL is designed for a 1 600 mm pantograph, operating with a

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(5) For the 1 600 mm pantograph, the maximum lateral deviation is 400 mm, while for the 1 950 mm pantograph it is 550 mm. On this, the TSI ENE provides flexibility to adjust the values taking into account the movement of the pantograph and track tolerances.

(6) Adapting the lateral deviation of an existing catenary with long pole spacing can cost between EUR 0.1 million and EUR 0.15 million per kilometre of line (costs for 2000; see ERA, ‘Conventional rail energy TSI: Impact assessment report’, 2009).

1 950 mm pantograph can cause infringement of mechanical gauges and electrical clearances in tunnels, stations and other civil structures. Secondarily, the longer 1 950 mm contact strip may suffer uneven wear on networks with low wire stagger that were originally laid out for smaller pantographs (7).

- Larger 1 950 mm pantograph contact strips may not perform efficiently when operated on infrastructure designed for smaller 1 600 mm heads, which were originally optimised for 1 450 mm pantographs with relatively small stagger values, as this could lead to particularly uneven wear of the contact strip (8). That said, contact strip material is thought to have become a smaller barrier over time.
- The impact of pantograph compatibility on switch and crossing areas varies depending on their local density and design (9). It was found to be a non-optimal changeover (10) between different contact wires when a 1 950 mm pantograph ran on lines designed for 1 600 mm OCLs; the contact wire could be deflected in tangential switches when a 1 600 mm pantograph ran on a 1 950 mm OCL. Moreover, when clamp-free or dropper-free zones were not respected while operating with a different pantograph type, the contact wires experienced premature wear (11).
- When using the 1 950 mm pantograph head, a larger lateral deviation of the contact wire under the influence of side wind (550 mm) is permitted compared with the 1 600 mm pantograph head (400 mm). A system using the wider head can have greater pole distances than one using the 1 600 mm head. Therefore, a system using the wider pantograph and with a larger permissible lateral deviation will lead to lower investment costs in most cases.

The impact on interoperability of the pantograph–OCL interface was investigated in a 2024 study by the Brenner Corridor Platform (12). It evaluated the conditions under which the multiple-voltage locomotives currently in service with a maximum of four different pantographs will be able to continue operating along the corridors via the Gotthard and Brenner passes. The results highlight that interoperability along the Munich–Verona corridor is limited by mismatches in OCL designs, pantograph head geometries (1 450, 1 600 and 1 950 mm) and contact strip materials, forcing multi-voltage locomotives to carry multiple pantographs (even where the same head geometry is acceptable, as different contact strips are needed) and complicating cross-border operations. That study demonstrates that the lack of harmonisation of fixed installations imposes additional complexity on the vehicle design.

Specific cases and national rules

Specific cases relate to special national provisions in the TSIs and can be either temporary or permanent. National rules impose binding technical requirements and are adopted by a Member State. Both specific cases and national rules can be sources of unharmonised requirements.

A review of TSI ENE and TSI LOC & PAS shows that 24 specific cases exist with regard to the energy subsystem. These cover various points, including electrification, OCL, regenerative braking and phase separation sections.

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(7) P. Tobback and J. Hauben, *Study on Interface EURO/1950 pantographs and OCL design*, ERA/2013/INTEROP/OP/01, TUC Rail, 2013, https://www.researchgate.net/publication/360962876_Study_on_Interface_EURO1950_pantographs_and_OCL_design_ERA.

(8) P. Tobback and J. Hauben, *Study on Interface EURO/1950 pantographs and OCL design*, ERA/2013/INTEROP/OP/01, TUC Rail, 2013, https://www.researchgate.net/publication/360962876_Study_on_Interface_EURO1950_pantographs_and_OCL_design_ERA.

(9) The additional costs of adapting switch areas can range from EUR 2 800 to EUR 20 000 per kilometre of line (values as at 2009).

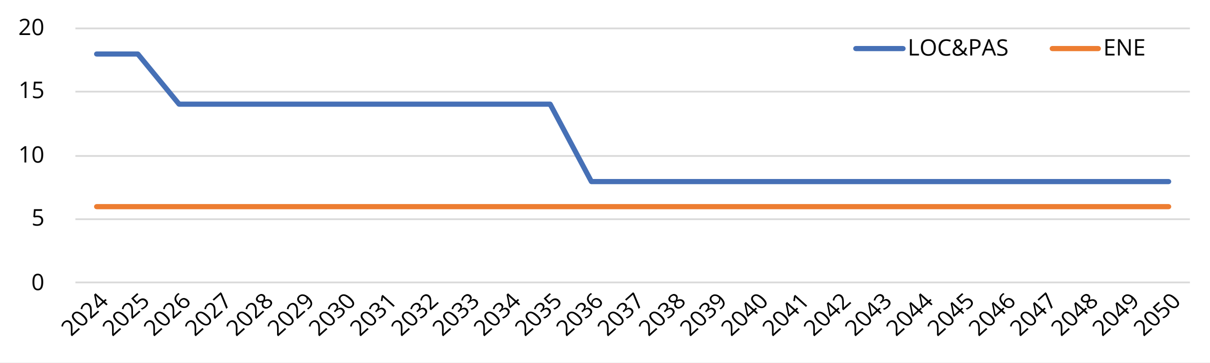
(10) This may refer to the following situations: the pantograph does not smoothly follow the wire path, the contact wire is deflected or forced sideways, electrical contact continuity is unstable or mechanical stress increases, leading to premature wear or risk of dewirement.

(11) P. Tobback and J. Hauben, *Study on Interface EURO/1950 pantographs and OCL design*, ERA/2013/INTEROP/OP/01, TUC Rail, 2013, https://www.researchgate.net/publication/360962876_Study_on_Interface_EURO1950_pantographs_and_OCL_design_ERA.

(12) The outputs from the study are available at https://www.bcplatform.eu/corridorstudies/.

Figure 7 shows that several of these specific cases remain valid until 2035. Another 14 specific cases are categorised as permanent or have no end date set (i.e. they fall into category T0).

Figure 7: Number of specific cases on energy parameters



Source: ERA.

Many of the specific cases were introduced and categorised when TSI ENE and TSI LOC & PAS were first drafted. For a broader evaluation of the harmonisation of electrification systems, it would be beneficial to reflect on what their impacts are and what end dates would be suitable.

Similarly, multiple national technical rules related to the energy subsystem endure, including on pantograph head geometry (France, Germany, Italy, Switzerland), pantograph contact force (Austria, Switzerland) arrangement of pantographs (Germany, France, Portugal) and contact strip geometry and assessment (Germany, Poland). Such national rules should be reassessed in view of the clean-up process in relation to national rules for vehicle authorisation.

The cleaning-up of national rules and a review of specific cases are particularly important, as these requirements affect vehicle design and limit the possibility of rolling stock performing international operations.

Summary

In conclusion, for over a century the European rail network has steadily been electrified. The technological state of play when networks were electrified and other requirements influenced which system was selected. The subsequent path dependencies led to a patchwork implementation.

At the same time, over 40 % of the network is still not electrified, as are over 44 % of border sections. The prevalence of non-electrification depends on the region.

Beyond voltage and frequency, other energy subsystem requirements, such as those concerning OCLs, pose additional impediments to interoperability. For several parameters, such as voltage, the TSIs accept different systems. At the same time, national rules and specific cases impose additional requirements on rolling stock and fixed installations. These topics should be considered in conjunction with a review of the feasibility of greater European harmonisation of voltage and frequency.

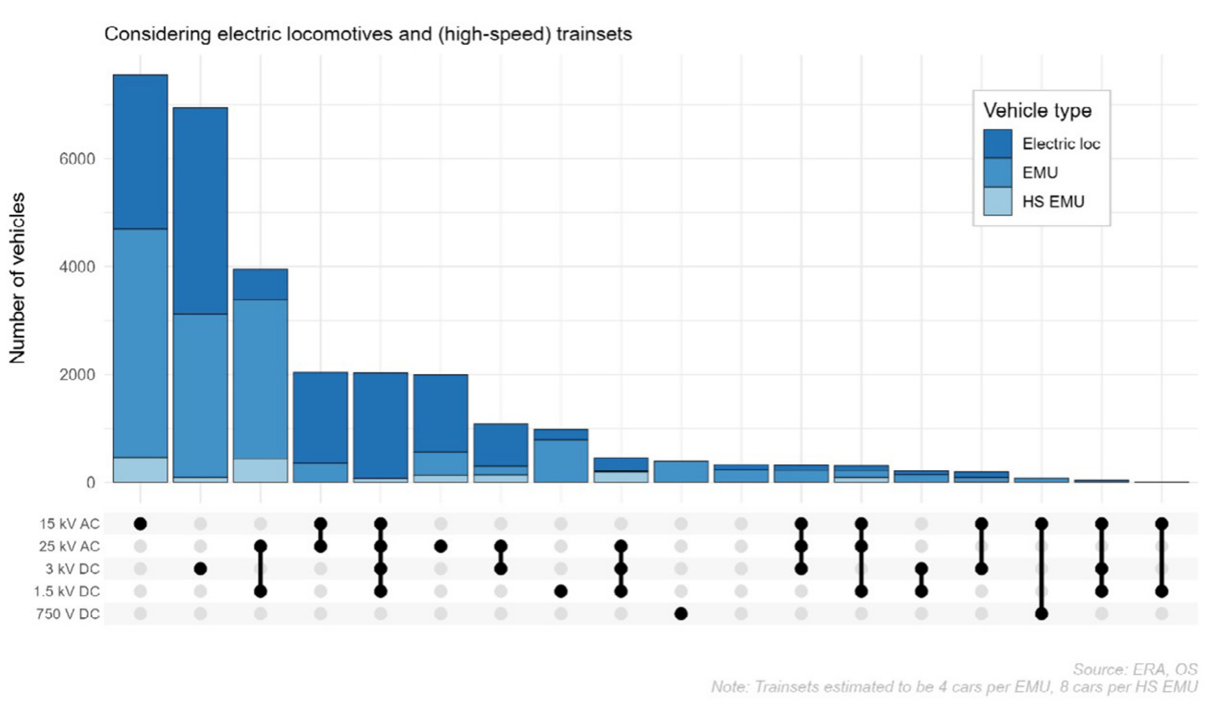
Building on this state of play of fixed installations and the legislative framework, the analysis will now turn to the railway fleet.

3.3. Fleet: state of play

The analysis that follows is based on the dataset that was created for the 2024 European Union Agency for Railways (ERA) railway fleet analysis. That report showed that the majority of European traction vehicles are electrified.

Figure 8 shows numbers of electric traction vehicles by vehicle type and (combination of) systems on which they can run.

Figure 8: Number of vehicles by electrification system combination

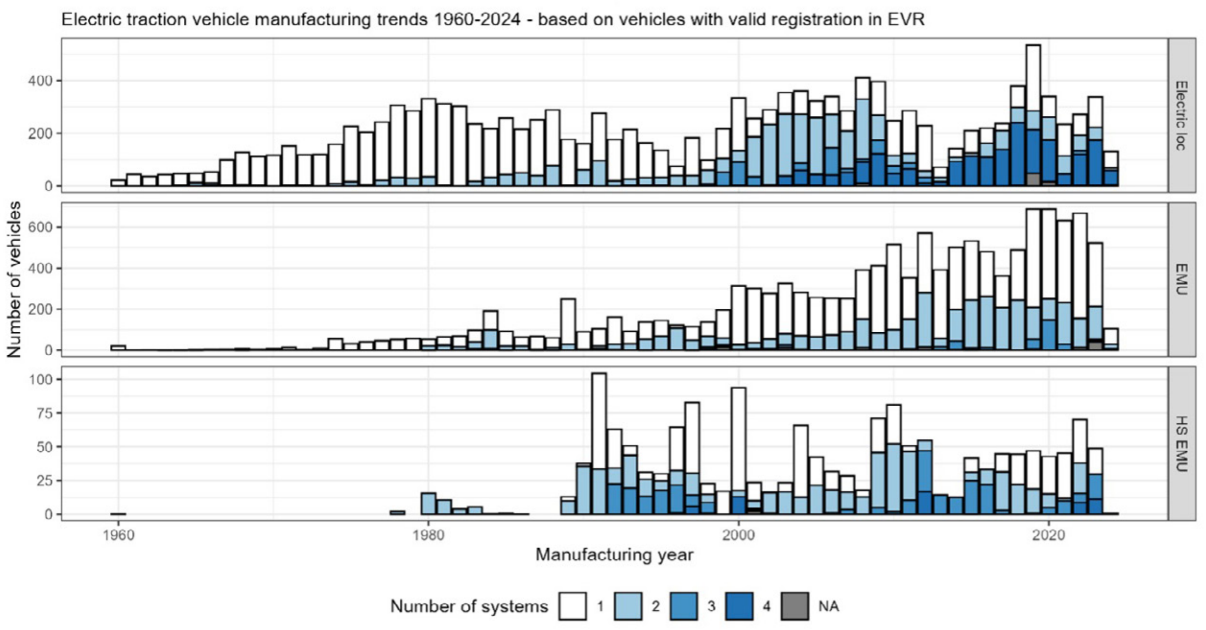


Source: ERA, OS
Note: Trainsets estimated to be 4 cars per EMU, 8 cars per HS EMU

The figure shows that most vehicles are designed to run on a single system. That can be explained by the limited number of cross-border passenger services. Trainsets that can operate on two systems are primarily used in countries with two systems (e.g. Czechia and France).

Figure 9 shows numbers of vehicles by manufacturing year, type and number of systems they can run on. Importantly, it shows that multi-system locomotives have gained prominence since 2000 and that by now the four-system locomotive is the most commonly manufactured type. This can be explained by the introduction of multi-system models, such as the Alstom TRAXX and Siemens Vectron models, which are commonly used for international freight operations. Moreover, locomotives are increasingly purchased by lessors, who want to have vehicles that can cater to the needs of various customers. This trend is believed to be structural, so that four-system locomotives will represent an increasingly high share of total manufactured locomotives.

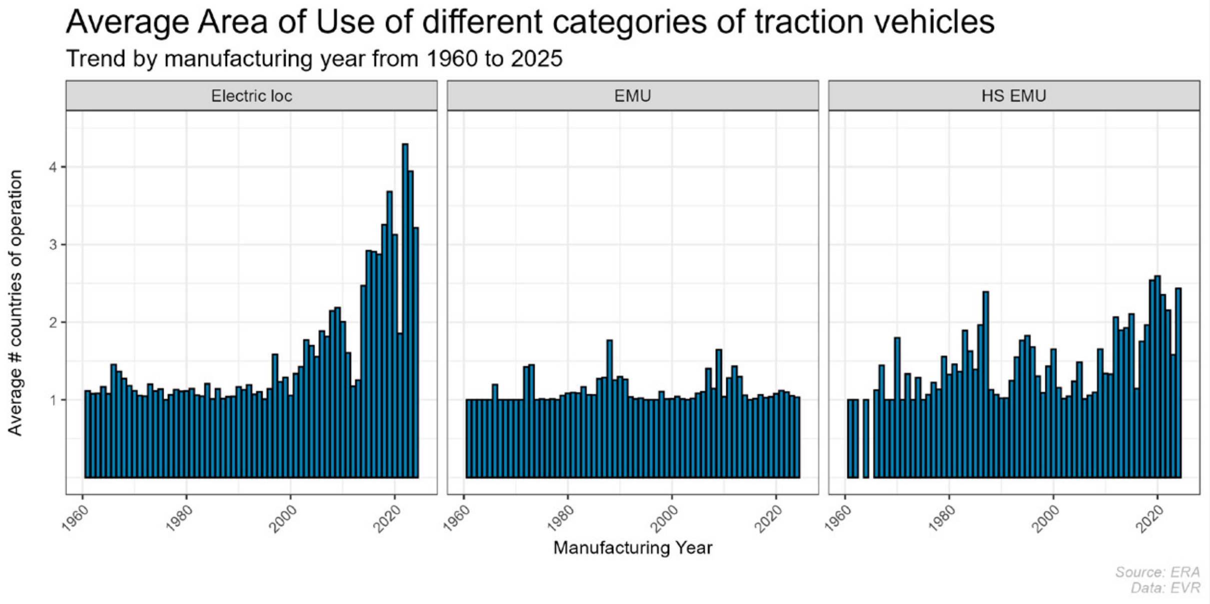
Figure 9: Number of systems on which the vehicle can operate



Source: ERA
Data: EVR and OS data
Note: Trainsets estimated to be 4 cars per EMU, 8 cars per HS EMU

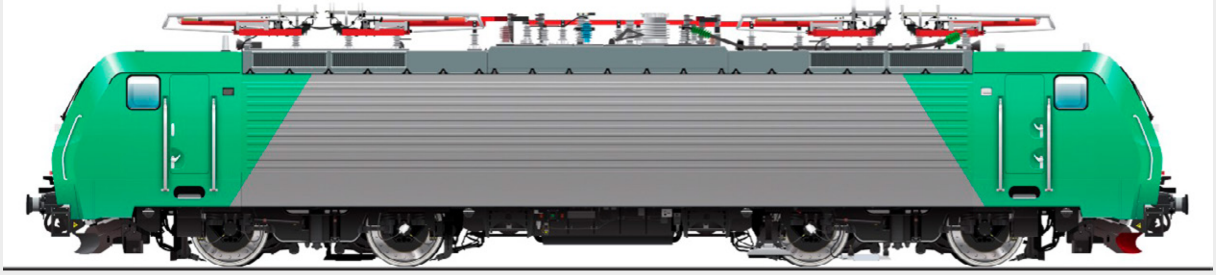
The relatively late emergence of four-system vehicles can be explained by technological constraints and legislative and economic considerations. On the technological side, it was a challenge to develop a vehicle that could fit the required components (transformers, pantographs, transistors, etc.) while respecting other boundary conditions such as weight restrictions. On the economic side, the opening of the rail freight market can be seen as a major impetus. The prevalence of multi-system locomotives also translates into a greater average number of countries of use, as shown in Figure 10. For trainsets, however, this trend is not visible.

Figure 10: Average Area of Use of different categories of traction vehicles



A multi-system locomotive does carry a cost premium, both in terms of purchasing price and maintenance costs. However, benefits in greater operational flexibility are achieved because rail freight has become increasingly European, increasing the need for rolling stock that can easily cross borders. An example of a multi-system locomotive (the Siemens ES 64 F4 E) is shown below in Figure 11.

Figure 11



Source: Railcolor

As can be seen, one element adding to the cost of such a multi-system vehicle is typically the fitting of four pantographs, with different widths and usable on different voltages. As regards the internals, such vehicles need the appropriate transformers, rectifiers, inverters and software, as well as automatic voltage detection and switching systems. Logically, this adds to the costs. Costs per vehicle are dependent on numerous variables other than the electrification system, but it can be assumed that:

- DC vehicles are generally cheaper than AC vehicles, as they do not need to be equipped with a transformer or rectifier;
- a 1.5 kV DC only locomotive is generally cheaper than a 3 kV DC only locomotive, which needs stronger cabling and components to deal with higher voltages;

- bi-mode AC vehicles, or bi-mode DC vehicles, are generally cheaper than vehicles that offer both DC and AC traction, as, particularly for retrofits, adding a different system greatly increases the costs;
- the increased scale of manufacturing of multi-system locomotives means that they are at a price point where, also taking into account operational flexibility and residual value, they are increasingly appealing compared to single-system locomotives.

So, while multi-system locomotives are more expensive to purchase and operate, the benefits frequently compensate for these costs, especially when international operations are envisaged. The increasing market share of such rolling stock is testimony to this.

As regards passenger transport operations, the average area of use of multi-system trainsets is markedly lower. There is no technical barrier per se to fit electric multiple units (EMUs) and high-speed EMUs with multiple systems. The likely reason for the low average area of use is that trainsets are largely purchased by (incumbent) railway undertakings with single-country operations – instead of lessors with an international scope, as in the case of rail freight. Another point links to the challenges in setting up and exploiting cross-border operations.

In the light of the findings on fixed installations and rolling stock, the report now turns to national cases and studies on re-electrification.

4. National perspective: re-electrification projects and studies

This chapter maps past, ongoing and upcoming re-electrification projects and from studies that investigated re-electrification but resulted in its not being implemented. The aim is to provide a balanced overview of the arguments in favour of and against re-electrification as used across Europe.

4.1. Re-electrification projects

A selection of re-electrification projects is shown in Table 3.

Table 3: Re-electrification projects

From	To	Country	Scope	Years
1.5 kV DC	25 kV AC	France/Switzerland	Bellegarde-sur-Valserine to Geneva, 32 line kilometres	2014
1.5 kV DC	25 kV AC	Portugal	The 25.4 km long Lisbon–Cascais line is the only 1.5 kV DC line in Portugal	2025–2027
3 kV DC	25 kV AC	Belgium	Lines in south-east Belgium, connecting with Luxembourg	1999–2030
3 kV DC	25 kV AC	Luxembourg	Line between Luxembourg City and the Belgian border	2018
3 kV DC	25 kV AC	Croatia	Zagreb–Rijeka line	2012
3 kV DC	25 kV AC	Czechia	Large-scale re-electrification plan	Since 2025
3 kV DC	25 kV AC	Slovakia	Large-scale re-electrification plan	Since 2015
3 kV DC	25 kV AC	Spain	Monforte de Lemos–Orense–Vigo line, with a cross-border connection with the north of Portugal	2028–2030

Source: ERA

In these cases, the re-electrification concerned migration from 1.5 or 3 kV DC to 25 kV AC. No examples were found of long sections of 15 kV AC lines that have been or are to be re-electrified to 25 kV AC.

In all examples, the migration strategy required long-term planning, as changes generally required adaptations to the power grid, infrastructure and rolling stock. The cost of the projects is strongly influenced by topography, structures, line layout and grid and by whether upgrades to the train detection and protection systems occur.

The projects impacted rolling stock purchase strategies and in some cases led to the retrofitting of existing rolling stock. Retrofitting of vehicles to a different electrification system is a rare occurrence. The main reason is the technical complexity of fitting transformers, invertors, circuit breakers, electronics and insulators. This is particularly challenging for vehicles that have not been designed with this possibility in mind. Moreover, the subsequent testing, certification and authorisation steps add further costs.

From what could be ascertained from the research carried out for this study, retrofitting has happened primarily in Czechia and Slovakia. For instance, many 162/163 series locomotives have been or will be retrofitted (13). However, the retrofitting of vehicles, if it is even technically possible, typically increases the weight of the vehicle. This in turn leads to higher axle loads, which limit the operational flexibility of the vehicle.

4.2. Re-electrification studies

As part of this study, a literature review was carried out on cost–benefit assessments of conversion to a different electrification system. It is understood that many countries with-

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(13) See https://cs.wikipedia.org/wiki/Lokomotiva_163 and https://railcolornews.com/2024/08/08/locomotive-make-them-multisystem-regiojet-class-162-awaits-major-conversions/.

out a 25 kV AC system have assessed the feasibility of migrating to 25 kV AC. Unfortunately, many of those studies have not been made publicly available or shared with the Agency.

Building on the available information, the arguments in favour of and against retrofitting will be presented in this section to the fullest extent possible for four scenarios:

- re-electrify 1.5 kV DC to 3 kV DC,
- re-electrify 1.5 kV DC to 25 kV AC,
- re-electrify 3 kV DC to 25 kV AC,
- re-electrify 15 kV AC to 25 kV AC.

The analysis is complicated by the fact that each argument is very much dependent on the specific circumstances in which re-electrification occurs. The contingencies should be duly considered when interpreting the findings below.

Re-electrifying from 1.5 kV DC to 3 kV DC

The re-electrification of the Dutch mainline network is the only large-scale example of this scenario for which studies were available. The main arguments in favour of converting the network from 1.5 kV DC to 3 kV DC were:

- the 3 kV DC system has substantially lower energy losses than the 1.5 kV DC system;
- the higher voltage allows trains to accelerate faster and maintain higher speeds, which would translate into greater network capacity if all other subsystems of the network were suitable;
- migration to 3 kV DC requires fewer energy infrastructure adaptations, so the operational disturbances would be far smaller than in a conversion to 15 kV AC or 25 kV AC.

In opposition to those points, the studies highlighted the following, among other considerations.

- The investment costs required to adapt the infrastructure would still be substantial.
- Existing rolling stock designed for 1.5 kV DC would need to be retrofitted or replaced to operate on 3 kV DC, adding substantial costs.
- There was uncertainty as to whether the existing 1.5 kV DC OCL would be TSI-compliant in a 3 kV DC system. Hence, there was a risk that a TSI exemption would need to be requested.
- The migration process would entail severe operational disruptions.
- Often, the traction system is not the factor limiting capacity in the Netherlands. Other technical barriers, such as track carrying capacity preventing increased traffic or limitations near level crossings, are often the main problem. The costs of adapting these systems would therefore need to be considered too ([14]).

The analyses conclude that the 3 kV DC system is generally technically superior to the existing 1.5 kV DC one, but there is a substantial price tag on migration arising from above points. The studies equally point to significant uncertainties around and low feasibility of such a migration, due to workshop restrictions and uncertain costs. The available workshop capacity and authorisation costs are therefore a cause of significant uncertainty.

Considering all these points, in the 2022 Dutch ProRail & NS study the conclusion was that, in terms of benefits and costs, re-electrification would at best break even and would entail significant operational, technical and financial risks. In addition, it was noted that, in

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([14]) See ProRail, 'Feitenrapport systeemkeuze TEV', 2022, pp. 35–37. The report can be downloaded from https://www.tweedekamer.nl/ [..] /detail?id=2022Z21971&did=2022D47380.

comparison with the conversion scenario, other solutions would offer more cost-efficient means of addressing the limitations of the 1.5 kV DC system.

Re-electrifying from 1.5 kV DC to 25 kV AC

Studies in 2012 and 2017 on converting the Dutch 1.5 kV DC network to 25 kV AC concluded that this would be economically unfeasible due to technical, organisational and operational challenges and high investment costs. They concluded that, during a period of one or more decades, operations would be substantially impaired, hampering both passenger and freight operations. One of the main points of concern was that the track construction for the 25 kV AC system, including changes to meet clearance requirements, would require substantial adjustments to tunnels and bridges. It would also require adjustments to train detection systems. That being the case, this scenario was not considered to be a feasible option. That said, there are several newly built lines in the Netherlands (high-speed and freight lines) that operate on 25 kV AC.

In France, the situation is somewhat different, as 1.5 kV DC and 25 kV AC systems have both been widely in use for many decades. A large part of the fleet is therefore fitted to operate on both systems. However, French studies also point out the complexities of re-electrification.

Some of the benefits mentioned in Dutch and French documents in favour of re-electrification from 1.5 kV DC to 25 kV AC are:

- the number of substations is substantially lower in a 25 kV AC system;
- copper consumption for the catenary substantially lower in a 25 kV AC system;
- energy losses are substantially lower in a 25 kV AC system;
- the total cost of ownership is substantially lower in a 25 kV AC system;
- 25 kV AC eliminates the conversion stage (AC to DC) in the substation, resulting in greater efficiency;
- a 25 kV AC system allows natural regeneration of braking energy (regenerative braking);
- the catenary is lighter, meaning less material used and easier geometry control;
- in 25 kV AC fixed installations the construction, operating and maintenance costs would be significantly lower.

The counterarguments are as follows.

- All substations would need to be replaced or upgraded, implying large capital expenditure.
- AC substations, due to the imbalance they produce in the network, must be connected to the very-high-voltage network, which is sometimes unavailable and connection to which would involve high-cost adaptation systems.
- Some of the fleet would need to be adapted or purchased, adding to procurement and retrofit costs.
- Several existing train detection systems are incompatible with 25 kV AC and thus would need to be replaced. In the Netherlands, as the systems are linked to the interlocking of the Dutch Class B train protection system, this would require simultaneous migration to ERTMS on all affected lines.
- Signalling, return current and electromagnetic compatibility issues would need to be resolved when changing voltage.
- A 'migration catenary' would be needed, adding complexity and cost.
- Traffic would be disrupted during the conversion works, with line closures.

- A piecemeal migration within a large 1.5 kV DC network would create difficulties in the exploitation of the network.

The fact that, even though the technological superiority of 25 kV AC over 1.5 kV DC is generally accepted, there are still many line kilometres using 1.5 kV DC suggests that there is no clear-cut economic case in favour of this scenario.

Re-electrifying from 3 kV DC to 25 kV AC

There are several examples of lines that have been re-electrified from 3 kV DC to 25 kV AC, notably in Belgium, Czechia, Croatia, Luxembourg and Slovakia. In addition, there are several cases where 25 kV AC lines for high-speed trains have been introduced in parallel with existing 3 kV DC lines. This has taken place notably in Belgium, Spain and Italy.

The Italian infrastructure manager, Rete Ferroviaria Italiana (RFI), investigated the feasibility of migrating from a 3 kV DC to a 25 kV AC system. The key motivation for this investigation lay in the higher energy efficiency and reduced infrastructure requirements of the 25 kV AC system, which allows for greater spacing between substations due to its higher voltage and lower current, thereby minimising transmission losses and installation costs. However, the results showed that, while the investment could theoretically be recouped over a very long time horizon (e.g. over 50 years), the operational impacts would be substantial. These would include major disruptions to rolling stock compatibility, significant effects on traffic circulation and extended service interruptions beyond those typically associated with construction works. As a result, the project was ultimately shelved and did not proceed further. Nevertheless, efforts are under way by RFI to improve the efficiency of the existing 3 kV DC system through several initiatives, such as regenerative braking systems, energy storage and smarter substation control to reduce energy losses. These measures improve efficiency and resilience while minimising disruption (15).

In Czechia and Slovakia, it was decided to convert larger stretches of the 3 kV DC network to 25 kV AC. Large parts of the Czech and Slovak networks are already electrified using 25 kV AC, as can be seen in Figures 1 and 2.

Received inputs pointed to the following benefits:

- 25 kV AC provides for greater tractive effort, allowing faster trains, better acceleration and the ability to haul heavier loads.
- Conversion aligns the network with neighbouring 25 kV AC networks, facilitating cross-border interoperability.
- Higher voltage supports higher line currents, enabling more trains per hour, shorter travel times and tighter timetables.

The following challenges were identified.

- Full line closures are usually necessary, requiring replacement bus services.
- Low underpasses and tunnels may need to be enlarged to meet the clearance required for 25 kV AC overhead lines.
- AC can interfere with existing DC-type signalling, making extensive rewiring or replacement is often necessary.
- Operators need multi-system locomotives or new battery EMUs to run on the new AC voltage, representing a significant capital expenditure.

It should also be noted that some lines, such as Bánovce nad Ondavou–Humenné, are electrified using 3 kV DC but prepared for a relatively fast conversion to 25 kV when adjacent lines are converted.

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(15) Further information is available at https://www.rfi.it/it/Sicurezza-e-tecnologie/tecnologie/energia/energia-di-trazione.html.

Re-electrifying from 15 kV AC to 25 kV AC

Migration from 15 kV AC to 25 kV AC has been assessed in three studies from Deutsche Bahn (DB), the national railway company, for Germany; Vienna University of Technology, for Austria; and Bane NOR, the national railway company, for Norway ([16]). These studies all date from before 2000.

The main requirements forming barriers to conversion that were mentioned in the German study are (as reported in the 2009 ERA impact assessment):

- complete replacement of all existing substations, switching posts and sectioning posts;
- replacement of insulators and switches because of the higher voltage;
- extension of bridges and tunnels because of the larger clearance required for 25 kV AC;
- replacement of all track control circuits;
- construction of numerous phase separation sections;
- decommissioning of all existing power plants, transformers, frequency converters, etc., with resulting excessive write-offs;
- the time required to change the system, which would amount to several decades during which huge operational restrictions would apply;
- withdrawal from service of existing traction units well ahead of scheduled time.

During the consultation process, the further argument was made that the main German electric traction power network provides benefits in terms of reliability compared with relying solely on the supply of the 110/220/380 kV grid. Additionally, energy procurement prices were deemed more favourable under the current system, as energy contracts can be negotiated for the dedicated 110 kV, 16.7 Hz grid. Finally, energy procurement can be controlled via the high-voltage network, which is not possible with a 25 kV AC network.

The Austrian study concurs with most of these points and adds that neighbouring countries (Germany and Switzerland) already have 15 kV AC, so re-electrification would in fact hamper cross-border traffic for a prolonged period, rather than facilitate it.

The Norwegian study added, in a similar vein, that the neighbouring Swedish network operates on 15 kV AC too. As there were no indications that Sweden was considering re-electrification, interoperability would be reduced by the migration. In addition to this, the study pointed to a range of technical challenges with 25 kV AC in comparison with 15 kV AC, considering Norwegian topography and the operational profile of the network. The study concluded that the total cost would be multiple billions for adapting the OCL system alone and that a migration period of several decades would be required. As a result, re-electrification was not pursued.

While the studies cited are somewhat dated, the arguments are generally believed to hold true today.

4.3. Summary of findings on national projects and studies

The arguments in favour of and against re-electrification that the projects and studies discussed above presented are summarised in Table 4, which includes an assessment of the relative relevance of each argument for specific types of re-electrification.

([16]) https://nva.sikt.no/registration/01994c8f6633-7d340227-e16d-42dd-80bc-b6e6e238ea60.

It should be noted that the actual costs and benefits are largely dependent on the specific requirements for the project area. Therefore, the results should be interpreted only as offering a general overview of arguments in favour of and against re-electrification, with an indication of their relevance.

Table 4: Overview of arguments in favour and against re-electrification

	1.5 kV to 3 kV	1.5 kV to 25 kV	3 kV to 25 kV	15 kV to 25 kV
Arguments in favour of re-electrification				
Lower energy loss	++	++	+	~
Faster acceleration of vehicles	+	+	x	x
Higher maximum speed	+	+	+	x
Increased capacity thanks to better performance of subsystem	++	++	x	x
Greater international operational flexibility of vehicles after transition phase	+	+	+	+
Lower energy subsystem capital expenditure	+	++	++	~
Lower energy subsystem operational expenditure	+	++	++	~
Direct energy supply from grid	x	++	++	+
Arguments against re-electrification				
Rail energy system adaptation costs	+	++	++	++
Electricity grid adaptation costs	+	+	+	++
Adaptation of tunnels, bridges and other infrastructure	~	++	++	+
Train detection and protection system adaptation costs	~	++	++	+
New rolling stock purchase costs	++	++	++	+
Existing rolling stock retrofit costs	++	++	++	++
Operational disruptions	+	++	++	++
Less operational flexibility if selected lines are adapted	+	+	+	+
Fragmentation of national networks	+	+	+	+
No operational need for increased power	++	++	++	++
DC system improvements are an alternative to increase efficiency	+	+	+	x
Limited financial ability to invest in re-electrification due to other investment priorities (e.g. the future railway mobile communication system, the ERTMS, etc.)	++	++	++	++

NB: ++, strong relevance; +, medium relevance; ~, partial relevance; x, irrelevant.

As Table 3 shows, there are several cases where it was decided to move forward with re-electrification. On the other hand, several studies comprehensively assessed re-electrification and concluded that the costs outweighed the benefits.

Overall, it is believed that the feasibility of re-electrification is affected to a great extent by the following points.

- **The level of electrification.** The greater the extent of the lines and the greater the interconnectedness of the network, the more difficult re-electrification becomes.
- **The complexity of the network.** The greater the number of tunnels and bridges, the more difficult and costly re-electrification becomes.
- **State of the fleet.** Vehicles have a long life cycle, and the fewer the vehicles that operate on the network that can cope with the target system, the more costly and lengthy any re-electrification process will be.
- **Cost of adapting interfaces.** The cost of re-electrification depends on the subsequent investments that would be required as a result of the change. For instance, in some countries re-electrification from DC to AC class would lead to issues with train detection and protection, effectively necessitating the simultaneous adaptation of those systems and thus increasing the costs.

The findings set out above make clear that at the national level there is no straightforward answer on the feasibility of re-electrification. The next chapter will build on these findings and assess the arguments in favour of and against re-electrification from a European perspective.

5. European perspective on re-electrification

The national analyses clarified that determining the economic impacts of re-electrification is a difficult task. A broad range of arguments has been considered and carefully assessed. Yet some aspects that are relevant at the European level, and could make a stronger case for promoting re-electrification, should be considered further.

The purpose of this chapter is to provide a broader reflection on the impacts of re-electrification from a European perspective. **Considering the complexity of the cost assessments, as noted in Chapter 4, the calculations should be understood as indicative efforts to determine the order of magnitude of the implications of various re-electrification scenarios. The numbers should not be used for specific re-electrification projects.** The assessments are used to facilitate a comprehensive debate on re-electrification.

5.1. What would the cost of re-electrification across Europe be?

National projects and studies confirm that re-electrification efforts almost exclusively involve a migration to the 25 kV AC system. The cost of converting from a 1.5 kV DC system to a 3 kV DC system was also considered, as several Dutch studies have identified this as a more feasible option than switching to 25 kV AC. Based on those findings, the following scenarios will be investigated to illustrate the scale of impacts at the European level:

- replacing 1.5 kV DC electrification systems with 3 kV DC,
- replacing 1.5 kV DC electrification systems with 25 kV AC,
- replacing 1.5 kV DC and 3 kV DC electrification systems with 25 kV AC,
- replacing all systems with a single, harmonised electrification system at 25 kV AC.

Assumptions

Before the costs are calculated the following points should be considered.

- Every study and project emphasized that re-electrification requires a long-term perspective on adapting both fixed installations and rolling stock. The more extensive the re-electrification envisaged, the longer the time horizon for migration should be.
- Assuming a long-term implementation period and considering the long life cycle of rolling stock (around 40 years), each scenario would require retrofitting of vehicles to ensure that existing rolling stock could be utilised efficiently. For illustrative purposes, it can be assumed that 25 % of the current mono-system fleet needs to be adapted and no vehicle needs to be scrapped before its end of life.
- Likewise, during the migration period there is a need to purchase (at least) bi-current vehicles to operate on the network, to ensure operational flexibility. The number required is put at 75 % of the current fleet.
- The number of vehicles and line kilometres that are impacted under each scenario are based on the ERA analyses of the fleet and the network as presented above.
- From a European perspective, it is difficult to determine the migration costs per line and vehicle, due to the large number of variables that impact the cost of each scenario. The estimated costs used below are derived from the projects that were identified in Section 4.1 and should be understood as **rough 'top-down' estimates to paint a general picture at the European level**.
- The costs of retrofitting vehicles cover:
  - the cost of taking a vehicle out of service (idle time);

  - the technical adaptations required for the change from DC to AC, meaning the fitting of, for example, transformers, invertors, circuit breakers, electronics, pantographs and insulation;
  - the cost of testing, certification and authorisation of each type.
- The costs of retrofitting lines cover:
  - adaptations to the OCL, including to structures;
  - adaptations to the grid and substations.

It should be noted that adaptations to the train detection and protection systems would be needed too. These costs are not included here, as they would be covered by other budget lines, as per national ERTMS implementation plans.

- As the scenarios imply a large-scale conversion, it is assumed that economies of scale and learning effects would positively impact the cost figures. Issues regarding migration capacity and economic feasibility would push the cost figures. Some reflections on these points follow later in this section.

- The final costs are expressed as a range, to reflect the significant uncertainties regarding the costs of adapting infrastructure and vehicles on a European scale. Therefore, the total costs in Table 5 are expressed as a range from 10 % below to 10 % above and above the estimated value.

Based on the aforementioned sources and assumptions, the vehicle- and infrastructure-related costs under the selected scenarios are estimated in Table 5.

Table 5: Estimation of the magnitude of costs per re-electrification scenario as per the assumptions set out above

From	To	Vehicles						Infrastructure		Totals (bn EUR)		
		Type	Count	Vehicles to be retrofit-ted	Retrofit costs (EUR per vehicle)	Bi-current vehicle purchases	Extra cost v mono-system (EUR per vehicle)	Line km	Retrofit cost (EUR/km)	Vehicle cost range	Infrastructure cost range	Total cost range
1.5 kV	**3 kV**	Loc.	174	44	545 000	131	250 000	9 160	1 000 000	0.5–0.7	8–10	8–12
		EMU	753	188	1 400 000	564	500 000					
		HS EMU	0	0	n/a	0	n/a					
1.5 kV	**25 kV**	Loc.	174	44	1 090 000	131	500 000	9 160	1 500 000	1–1.2	12–15	12–18
		EMU	753	188	2 800 000	564	800 000					
		HS EMU	0	0	n/a	0	n/a					
1.5, 3 kV	**25 kV**	Loc.	4 137	1 034	1 090 000	3 103	500 000	45 488	1 500 000	7.3–9	61–75	62–92
		EMU	3 989	997	2 800 000	2 992	800 000					
		HS EMU	102	26	7 000 000	77	1 600 000					
1.5, 3, 15 kV	**25 kV**	Loc.	7 085	1 771	1 090 000	5 314	500 000	85 013	1 500 000	16–19.5	115–140	118–176
		EMU	8 843	2 211	2 800 000	6 632	800 000					
		HS EMU	566	141	7 000 000	424	1 600 000					

n/a, data not available.

The calculations show that the upgrading of lines and vehicles could cost anywhere between EUR 8 billion and EUR 176 billion, depending on the scenario. For context, the Europe-wide expenditure on the upgrade of railway infrastructure was EUR 13.39 billion in 2022 ([17]). This implies that, on the infrastructure side alone, the scenarios would cost from 0.6 to 10.5 times the total annual European budget for infrastructure upgrades.

Operational impacts

In addition to the infrastructure- and vehicle-related costs, the operational impacts would be substantial. Such extensive works would inevitably disrupt traffic flows and services, especially on high-density corridors or in areas where the railway infrastructure offers limited rerouting alternatives. Network capacity would be reduced for years, with significant implications for freight and passenger operations during the re-electrification phase, affecting timetables/reliability and the environment.

For illustrative purposes, the re-electrification of a 66 km section in south-east Belgium (i.e. Barnich–Hatrival) will be considered. Over several years, a stepwise replacement of the single 3 kV DC catenary to a mixed 3 kV DC / 25 kV AC catenary took place, during which traffic could be maintained. After completion of the catenary replacement, the preparation of the 25 kV AC sectioning took place. Works covered the installation of power supplies at substations and the installation of a neutral zone. These works were carried out at night. The actual voltage change, which took place in 2018, required the complete closure of the line for three weeks. This approach, with migration catenaries, was also taken in other projects, such as the Geneva–Bellegarde project, and is one option to limit the operational impacts of re-electrification.

Considering only the complete line closure and extrapolating that to the entire European network suggests that 416 weeks (scenarios 1 and 2), 2 068 weeks (scenario 3) or 3 864 weeks (scenario 4) of line closures for similar section lengths could be expected across the continent. Again, this is a considerable simplification. On some lines, efficiency gains could speed up the process. On other, more complex, lines, the process could last longer (e.g. lines with large operational points, yards or lines with sections that are not electrified). In any case, the actual line closure is just a relatively short phase of a project that can last many years per line, with intermittent interruptions during the process.

The exact economic impact of such closures would need to be determined line by line, considering the amount and type of traffic and the existence of alternative routes. It is, however, reasonable to say that the costs would be substantial.

A second type of operational impact is that, during the migration phase, the area of use of existing mono-system rolling stock would likely be negatively affected. This would require timetables to be adapted and rolling stock to be shifted. It is, once more, difficult to come to a plausible assessment of such costs at the European level. It is, however, important to acknowledge that the costs of this would also be large.

Feasibility considerations

It is necessary not only to determine the costs of re-electrification but also to understand if it is feasible in terms of technical, organisational and financial capacity. A complete assessment goes beyond the scope of this report, but two points can be highlighted.

First, the retrofitting of vehicles could be obstructed by limited workshop availability, which would effectively impose a phased introduction. Moreover, based on the limited evidence from past cases, it is believed that it would be difficult to find a company that is willing to engage in a vehicle re-electrification project at a reasonable price. If a large-scale retrofit exercise were to occur, the capacity constraints would be further exacerbated and

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[17] See https://transport.ec.europa.eu/transport-modes/rail/market/rail-market-monitoring-rmms_en.

additional investments in workshop capacity would probably be required. Those costs should be taken into account, too.

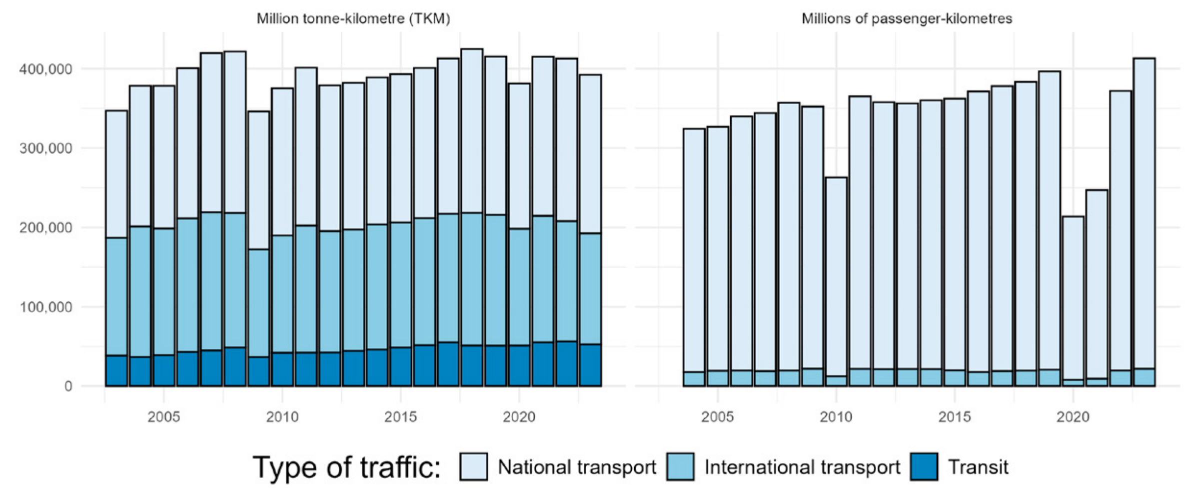
Second, other major European initiatives are ongoing, such as ERTMS and future railway mobile communication system retrofitting projects. Several stakeholders have expressed concerns with regard to the financial feasibility of allocating substantial resources to a different topic. Having insufficient resources to finance an optimal migration scenario would come with additional costs, which should also be considered in assessing the feasibility of the migration scenarios.

5.2. Is re-electrification needed to improve cross-border operations?

One of the possible benefits of increased harmonisation of electrification systems is the facilitation of cross-border traffic. To evaluate the potential impact, it is important to understand how cross-border traffic operates today and the extent to which different electrification systems pose barriers. These questions will be examined based on the aforementioned findings, research on operational data and interview feedback.

During the past 20 years, about 50 % of freight traffic and about 7 % of passenger traffic has been international, as can be seen in Figure 12.

Figure 12: Evolution of freight and passenger traffic in Europe



Source: ERA
Data: Eurostat [rail_go_typepas][rail_pa_typepas]

The question is to what extent these flows are facilitated by harmonised electrification systems or hampered by the lack thereof. Finding an answer to this is complicated by the many confounding factors. For one, electrification systems are only one of the technical specifications that enable interoperability. For instance, a locomotive that does not comply with a certain specific case or national rule would not be authorised to operate in a neighbouring country regardless if the line has the same voltage in both countries. In addition, freight and passenger patterns are influenced by a range of economic and sociological factors. By no means can such patterns be attributed to electrification alone. That said, the presence or absence of harmonised electrification systems has implications for the cost and speed of cross-border rail transport.

Figure 5 showed neighbouring countries where electrification systems do not pose any barriers to interoperability in terms of voltage and frequency. Table 6 shows the fully harmonised clusters that exist today.

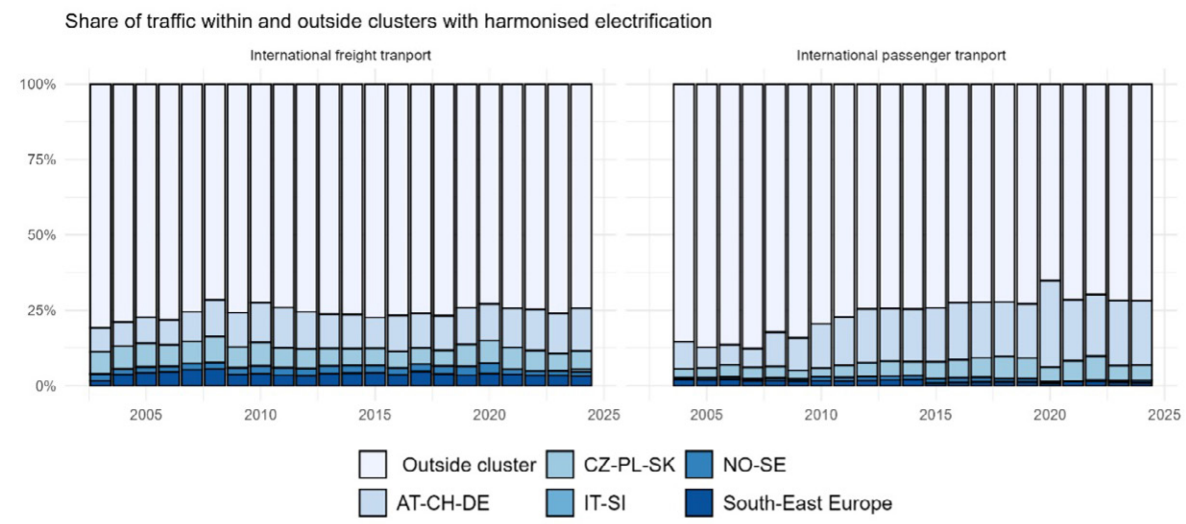
Table 6: Overview of country clusters with the same electrification system

System	Clusters of neighbouring countries with same system (and area covered by that system)
1.5 kV DC	None
3 kV DC	▪ Italy (fully) and Slovenia (fully) ▪ Czechia (north), Poland (fully) and Slovakia (north)
15 kV AC	▪ Austria (fully), Germany (fully) and Switzerland (fully) ▪ Norway (fully) and Sweden (fully)
25 kV AC	▪ France (partial), Luxembourg (fully) and the United Kingdom (partial) ▪ Portugal (fully) and Spain (partial) ▪ Bosnia and Herzegovina, Bulgaria, Croatia, Czechia, Greece, Hungary, Montenegro, North Macedonia, Romania, Serbia and Slovakia (fully, except Czechia and Slovakia, to a large extent)

At first glance, there are quite a few clusters, but the extent to which each of these clusters functions as a single area is limited by the lack of electrified border crossings, by the presence of border crossings that are electrified but using different systems and by other technical and operational limitations. It is nevertheless worthwhile to see if countries with harmonised electrification systems have greater transport flows between them.

Figure 13 shows statistics for those clusters where meaningful cross-border connections exist. Both for freight and passenger transport, a large share goes to destinations outside the electrification cluster, highlighting that harmonised electrification alone is not a prerequisite nor a key explanatory variable for transport flows.

Figure 13: Evolution of international rail transport



Source: ERA
Data: Eurostat [rail_go_intcmng][rail_pa_intcmng]

One part of the explanation for the large share of the 'outside clusters' category lies in the 36 border stations with an electrification system that is harmonised with the electrification system of the neighbouring country. Particularly around Austria and Switzerland, this was found to be common.

Beyond these infrastructure adaptations, it also happens that, for short-distance cross-border operations, 3 kV DC vehicles travel on a 1.5 kV DC network with a reduced power output. This occurs, for instance, between Antwerp (Belgium, with a 3 kV DC system) and Roosendaal (the Netherlands, with a 1.5 kV DC system). Another example is Ventimiglia, which is a rare station in Italy with a 1.5 kV DC system, allowing 3 kV DC vehicles to enter the station running on lower power, while at the same time enabling most French-registered vehicles (which typically run on both 25 kV AC and 1.5 kV AC) to enter the border station.

Harmonised cross-border stations and operational adaptations between 3 kV DC and 1.5 kV DC networks explain how electrified rail transport runs between countries with different systems. Yet the large percentage of international traffic outside harmonised clusters that is shown in Figure 13 cannot be explained by infrastructural and operational adjustments alone. To understand that, it is important to analyse the vehicles used in greater depth.

The analysis presented in Section 3.2 identified 27 cross-border sections that are electrified using different systems. The fleet analysis showed that an increasing number of multi-system locomotives can cross such sections. For passenger trainsets, however, this often remains an issue, as dedicated rolling stock would be required to cross these sections seamlessly.

When it comes to passenger traffic, international flows consist almost entirely of single vehicles that go from origin to destination. International freight transport statistics on the other hand, cover flows by a single electric traction vehicle (that can operate on one or more systems), flows by diesel vehicles and flows in which wagons are 'handed over' to another locomotive at a border station. Although there is insufficient data to quantify which option is most used, it is plausible that the approach in which freight wagons are passed to a different locomotive and operator is still the most common model. At the same time, in part due to the liberalisation of the rail freight market and technological innovations such as the multi-system locomotive, it is believed that international freight transport using a single locomotive is increasingly common.

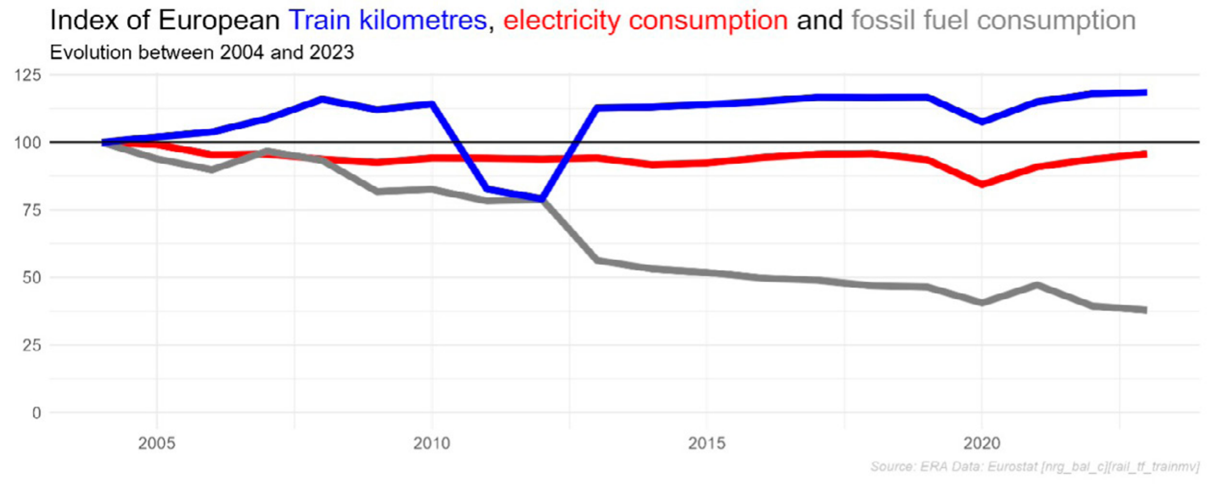
In conclusion, it can be said that international traffic covers a large percentage of rail freight and a small percentage of rail passenger transport. For both segments, transport within harmonised electrification clusters is about 25 % of all international traffic. Hence, it is believed that infrastructure and vehicle solutions have enabled rail to overcome the interoperability barriers imposed by the divergences in electrification systems.

While acknowledging that unharmonised electrification systems do not pose an insurmountable barrier to international rail transport, the question remains whether it would not be more beneficial to move towards the greater harmonisation of those systems. For instance, could there be cases where the lack of appropriate rolling stock or where the additional costs of multi-system locomotives or modular traction technologies impose insurmountable barriers to operating a line that could have been run profitably in a Europe with harmonised systems? And could the overall production and operational costs be greatly reduced if electrification systems were to be more harmonised? Those points will be addressed in the following sections.

5.3. What would the Europe-wide energy savings of re-electrification be?

Beyond greater operational flexibility across borders, another major argument for re-electrification is the energy saving potential. A first consideration is how much energy is consumed by railways. Figure 14 shows the consumption trends since 2004 for electricity and fossil fuel (i.e. diesel) consumption in rail operations and total train kilometres. Clearly, a strong decrease in diesel consumption is visible, whereas electricity consumption has remained rather stable, despite an increase in train kilometres. The chart suggests that the rail network and/or fleet has become increasingly efficient. These trends cannot be explained by re-electrification; rather, they relate to the electrification of lines and the replacement of diesel traction with electrified vehicles. Additional explanations are the introduction of regenerative braking and the phasing out of less efficient electric vehicles, for instance those that used thyristor-based convertors. In absolute numbers, for 2023, this translates into an estimated rail power consumption across the Member States of 175 petajoules of electricity and 42 petajoules of fossil fuel.

Figure 14



Source: ERA Data: Eurostat [nrg_bal_c][rail_tf_trainmv]

Figure 15 shows electricity consumption by electrification system. Acknowledging the simplified assumption of a linear relationship between system line kilometres and consumption, it is estimated that most electricity is consumed on 15 kV AC lines (18).

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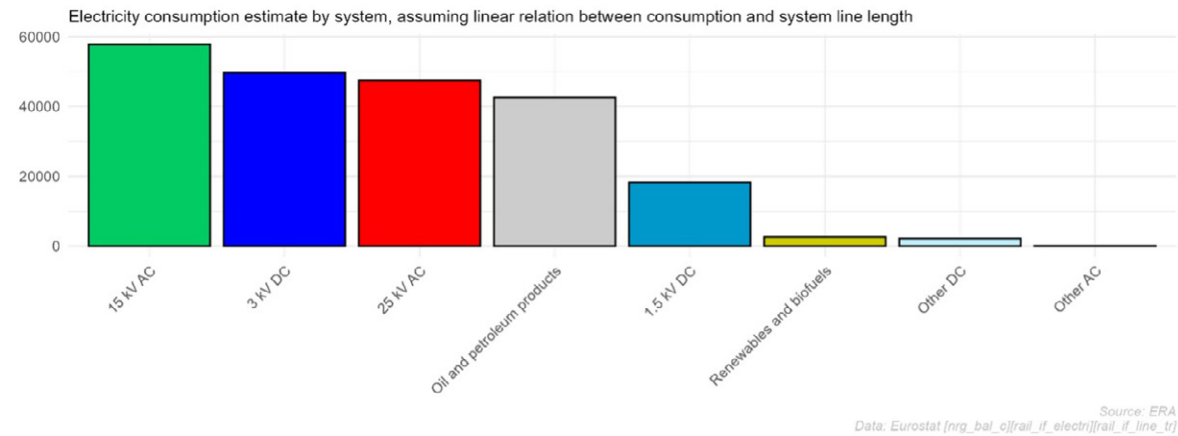
(18) An analysis of consumption per train kilometre for the various systems could not be performed because statistics at that level of disaggregation are not publicly available at the European level.

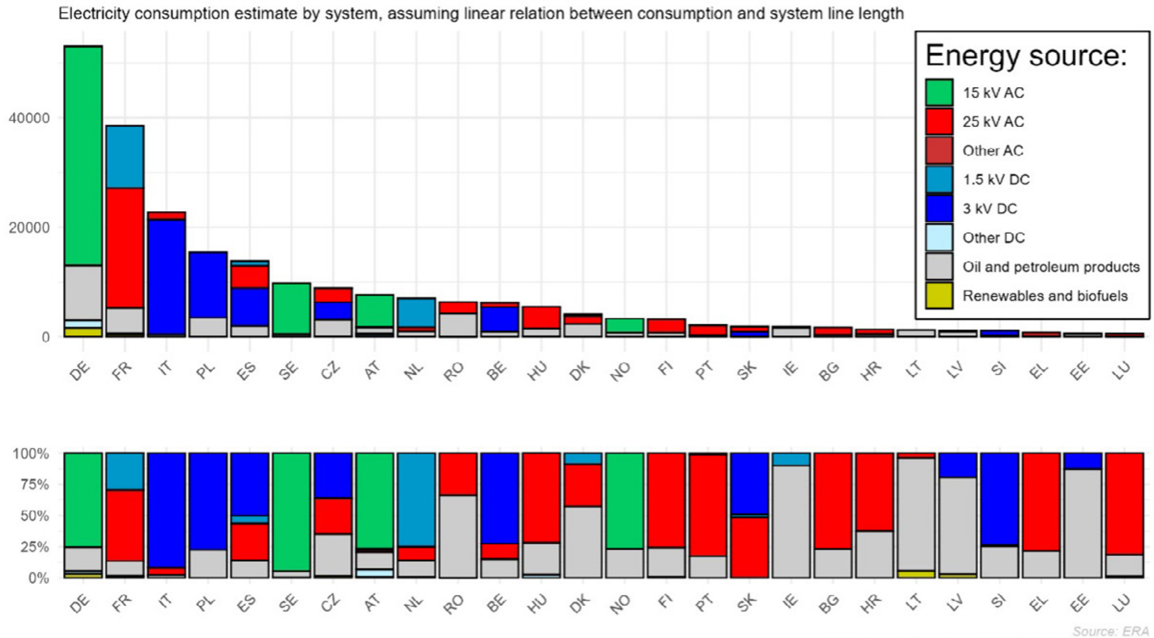
Figure 15: Total European energy consumption (TJ) in rail transport in 2023



Source: ERA
Data: Eurostat [nrg_bal_c][rail_if_electri][rail_if_line_tr]

Figure 16 emphasises variations in consumption between countries. It confirms that some countries with fewer line kilometres consume more electricity than countries with more line kilometres because of higher degrees of electrification and higher track utilisation rates.

Figure 16: Total energy consumption (TJ) in rail transport in 2023



Source: ERA
Data: Eurostat [nrg_bal_c][rail_if_electri][rail_if_line_tr]

Estimating the potential energy savings is, once again, complicated by the wide variation in performance of systems in different geographical areas. For this exercise, we resort to numbers from various studies to calculate an approximate range of savings.

The assumption is made that 25 kV AC generally has 13.5 % lower energy losses than 1.5 kV DC, 7 % lower losses than 3 kV DC and 7 % lower losses than the decentralised 15 kV AC system used in Norway and Sweden, but no energy loss advantage over the centralised 15 kV AC system used in Austria, Germany and Switzerland (19). Applying that assumption, the calculations indicate that a full re-electrification to 25 kV AC would reduce energy consumption by 6.7 petajoules. This translates into a 4 % energy efficiency increase for the entire European railway system.

While by no means negligible, the numbers may appear relatively small in relation to the total consumption of fossil fuel, where big strides can still be made. In addition, there are several approaches that can be taken to increasing the energy efficiency of operations on non-25 kV AC systems so that the actual long term energy savings of re-electrification may be lower (see, for example, Europe's Rail, 2024; ProRail and NS, 2018).

An additional consideration is that energy savings in operations need to be offset against the energy costs and environmental impact of the re-electrification of the system. These impacts, if re-electrification were to occur on a European level, would not be negligible.

5.4. What would the benefits of re-electrification for railway undertakings be?

As indicated in Section 3.3, different electrification systems impose different requirements on vehicle designs. By creating modular platforms, manufacturers aim to create economies of scale for their vehicles while allowing for the adaptations that are necessitated by the various infrastructure requirements and client specifications.

Evidently, there would be greater economies of scale if just one electrification system was in place across Europe. This would simplify vehicle design substantially and lead to reduced certification and authorisation costs.

The complexity of handling multiple electrification systems is particularly great for vehicles produced in small quantities, such as special vehicles, as research and testing costs cannot be spread across a larger number of vehicles. These costs ultimately are borne by the railway undertakings that purchase or lease the rolling stock.

In addition to higher purchase costs due to reduced economies of scale, there are also inherent differences in the technical specifications of rolling stock and their price tags. As a general principle, it can be stated that single-system rolling stock is cheaper than multi-system vehicles, and DC-only vehicles are cheaper than AC-only ones.

An example can indicate the impacts in practice. A Dutch study has indicated that a multi-system locomotive costs about EUR 10 000 to EUR 15 000 more per month to lease/operate than a bi- or single-system locomotive (20). Unfortunately, no large-scale dataset could be accessed to assess the various leasing rates. However, based on anecdotal evidence, it can be considered that leasing costs can be 15–20 % higher for a multi-system locomotive than for a bi- or single-system locomotive. It was not possible to assess to what extent the higher vehicle costs are due to the complexity of the on-board power systems or to other features such as multiple on-board train protection systems.

As indicated previously, some AC networks are interrupted by DC sections, effectively requiring the use of multi-system rolling stock. If 100 locomotives could be switched from

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(19) Note that 2 x 25 kV AC would be more efficient than 25 kV AC, but no reliable figures could be retrieved for the estimation exercise.

(20) https://zoek.officielebekendmakingen.nl/blg-1060095.pdf.

multi-system to AC only, with the reference values above, potential savings of EUR 12 million to EUR 18 million per year could be made on that specific line.

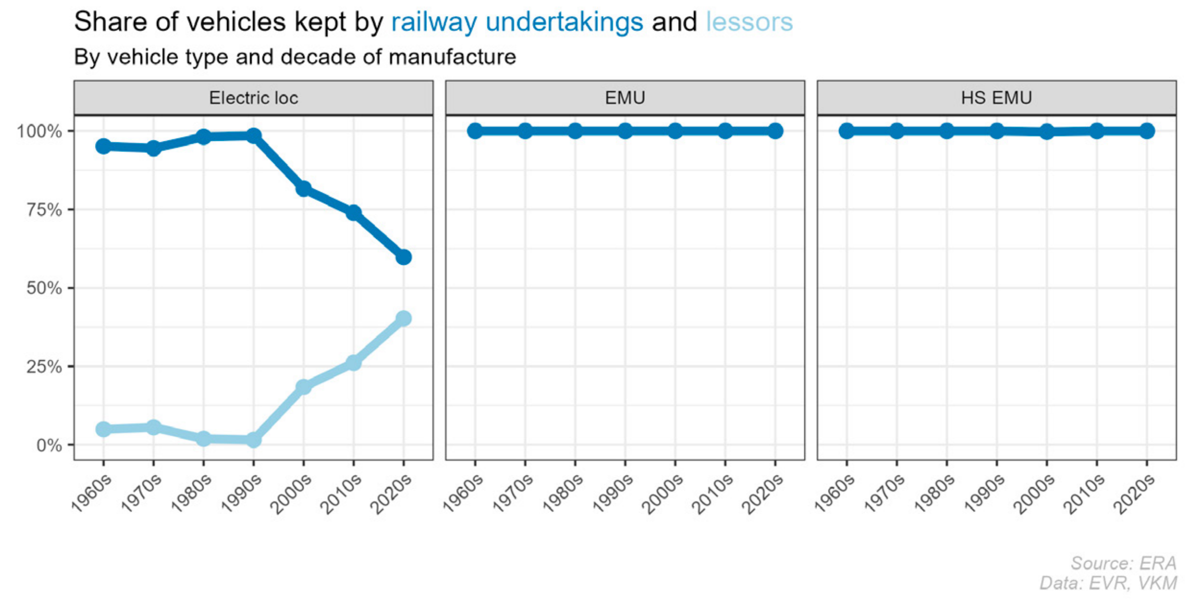
The issue is that re-electrification also may impose other limitations on the network, such as lower capacity for the existing single-system rolling stock. Another limitation is that AC-only rolling stock would experience reduced route compatibility, limiting operational flexibility in the event of line closures.

Therefore, even though the savings for operators could be substantial, the system benefits of re-electrification need to be assessed on a case-by-case basis. For this reason, and considering data availability issues, assessing the benefits of various migration scenarios at the European level is arguably more complex than assessing the costs.

5.5. What would the impact of re-electrification on market competition be?

A request for information on the impact of re-electrification on competition has so far yielded limited feedback. Lessors indicate, however, that, for freight transport, they would not expect much of an impact, as the majority of the fleet that is leased consists of multi-system locomotives. In other words, rail freight entrants and incumbents do have access to vehicles that can operate on multiple systems and compete internationally. This pattern is confirmed by Figure 17, which shows that a large share of newly produced electric locomotives are kept by lessors.

Figure 17



The figure also points to a diametrically different situation for the EMU and high-speed EMU fleet, which is basically kept entirely by railway undertakings. However, as argued before, the lack of multi-system trainsets and a practically non-existent (high-speed) EMU leasing market are not consequences of diverging electrification systems. Rather, if markets for international rail passenger transport were to become more open and attractive, it could be expected that the share of multi-system trainsets and lessor-owned vehicles would increase.

No feedback has been provided indicating that greater harmonisation of electrification systems is a prerequisite for or key enabler to foster greater market competition. At the same time, as seen above, having a more harmonised network would reduce operational costs for operators substantially, and this would probably make new routes economically feasible.

5.6. Is there a case for re-electrifying trans-European transport network corridors only?

Section 5.1 calculated the costs of re-electrifying entire networks. In view of the substantial costs, it is worth asking whether it would be beneficial to re-electrify selected DC lines only, such as those on the trans-European transport network (TEN-T) corridors. This scenario would concern mostly 3 kV DC lines, as there are relatively few 1.5 kV DC lines in the TEN-T corridors. The assumption, then, would be that this approach could strike a balance between the costs of re-electrifying and the benefits of improving cross-border connectivity and achieving lower operational costs on the railway undertaking's side and lower costs for the broader network and fleet.

A first necessary remark is that TSI ENE 7.1.1 already mandates that new lines with speeds greater than 250 km/h must be supplied with one of the AC systems. This requirement has existed in the TSI ENE since 2014. Hence, new high-speed lines on the TEN-T corridors have introduced and will in future introduce AC lines to DC networks.

A second point is that most countries with a mainly DC network have already introduced 25 kV AC lines on large parts of the TEN-T corridors. However, these AC lines are often interrupted by relatively small DC sections. For instance, in Belgium, France, Italy and the Netherlands, stations between AC sections operate on DC. This imposes a requirement for vehicles to be able to run on both AC and DC, hence ruling out any possible benefits of running AC-only rolling stock.

Resolving this would require those sections, including stations, to be fully or partially re-electrified. Interviewees pointed to the difficulties they anticipated with re-electrifying congested operational nodes, as this would effectively decrease operational flexibility and thus capacity. Indeed, it should be carefully assessed whether the benefits of creating homogeneous AC lines outweigh the costs that would be imposed on the broader network and fleet.

Another counterargument is that the full re-electrification of selected lines to AC in a predominantly DC network would still require vehicles to be capable of running on DC in case of line closures or rerouting. The importance of such an argument depends on the context. For instance, the Eurostar service to London operates on a single 25 kV AC line between a 750 kV DC network, on which these trains cannot run. So, while the situation may be suboptimal, it should be emphasised that it is not a prohibiting factor per se.

Another argument is that the re-electrification of a line would be drastically expensive because it would not be compatible with the Class B train protection and train detection systems, requiring research and investment for the adaptation of those systems or the introduction of TSI-compliant products. This would mean that the re-electrification project would entail a broader upgrade, with associated higher costs.

These barriers to re-electrification should be acknowledged. Indeed, the preceding analyses highlighted that any re-electrification project of a single line or operational point cannot be assessed in isolation from the broader network and the fleet that runs on it.

Hence, a recommendation with pan-European relevance on the desirability of converting DC sections to AC lines cannot easily be provided. The discussions did clarify that re-electrification needs to be considered in the broader context of other national implementation plans and corridor studies.

What can be clearly stated is that there are substantial issues with the lack of electrification on TEN-T corridors, particularly on cross-border sections.

Figure 18 shows sections of the TEN-T core corridors that are in 2025 not electrified on one or both sides of the border. Many of these sections are found at borders with candidate countries for EU membership, but there are several cases involving only Member States. This effectively means that border crossings would require the use of a diesel locomotive or other autonomous power system, greatly limiting operational flexibility and the cost-effectiveness of long-distance operations.

Figure 18: Non-electrified border sections on TEN-T Core Corridors

Source: ERA
Data: OpenStreetMap contributors, RINF, TENTEC
Note: Only main and branch lines shown

Extending the analysis to the entire TEN-T would add several dozens of non-electrified cross-border sections. As in the case of re-electrification, the costs and benefits of electrification require a case-by-case analysis to assess the economic feasibility. However, the pervasiveness of non-electrified sections in the network suggests that a lot can still be achieved through electrification.

6. Conclusions

Based on the above analyses, this study reaches the following conclusions.

Point 1: (re)electrification

The study identified that there would be substantial benefits to having a single electrification system. However, there is no straightforward migration scenario or clear economic case for re-electrification to a target system, thus confirming the conclusions of the ERA 2009 impact assessment on the TSI ENE.

In fact, the study found that interoperability barriers created by differences in voltage and frequency are mitigated by multi-system traction vehicles. The fleet analysis showed that the share of multi-system locomotives is increasing, with four-system locomotives being de facto the standard.

Large-scale re-electrification projects have often been considered, but in most cases they have not been pursued. However, several examples of re-electrification projects highlight that cases exist in which re-electrification was deemed beneficial.

This report therefore does not recommend a complete Europe-wide, large-scale re-electrification, but would support reflection on whether there are specific sections of the network that could be re-electrified to benefit the railway system (e.g. where AC lines are interrupted by relatively small DC sections). Such reflection should occur in broad consultation with infrastructure managers and operators, on a case-by-case basis, with a long-term perspective. The right forum, instruments and requirements should be sought to instigate those discussions.

In addition to looking at the issue of re-electrification, this study made several observations regarding the status of electrification. It found that numerous non-electrified border sections exist, including on the TEN-T corridors. Some countries, like Bulgaria and Romania, are therefore ill-connected despite the fact that the electrification system and pantograph head geometry that they use are the same. Furthermore, between Germany and Czechia and Germany and Poland a large share of border sections are non-electrified. A lack of electrification can increase the cost of cross-border operations due to locomotive changes and associated delays. Thus, non-electrified border crossings can be impediments to international traffic.

That said, this study does not suggest that all border crossings and lines need to be electrified. Other solutions, such as battery trains, may be more cost-efficient, including for cross-border areas where lines with multiple voltages exist. Additionally, there are several border crossings where the voltage of one country is extended to the first station after a border, enabling passengers to cross borders without necessitating the usage of multi-system rolling stock. This solution could reduce operating costs while still allowing cross-border operations, with a switchover happening at the border station.

Based on these considerations, the study makes the following recommendations.

- No absolute requirement should be introduced into the TSI ENE for 1.5 kV DC and 3 kV DC lines to be re-electrified to 15 kV AC or 25 kV AC upon upgrade or renewal.
- Analyse which instruments and requirements could facilitate the harmonisation of the voltage of lines if relatively small DC sections are found along current or future predominantly AC corridors.
- A study on cross-border sections should assess which stations would benefit from being connected by alternative electrification solutions or a different voltage to facilitate cross-border traffic.

Point 2: other energy subsystem requirements

Multiple parties indicated that different voltages and frequencies are less of a concern than different pantograph head dimensions and the associated voltage and protection standards. The heterogeneity of these requirements forces operators to equip rolling stock with multiple pantographs, to maintain several distinct regimes of operation and to accept higher risks of loss of contact, excessive wear or clearance violations when a train crosses a border.

Contributors indicated that the feasibility and benefits of harmonising the pantograph–OCL interface are greater than those of harmonising voltage and frequency. While this question was not covered by the initial scope of the study, several analyses and findings have been included to give an indication of the issues at hand.

It was observed that Europe has converged on OCL geometries that comply with the 1 600 mm and 1 950 mm pantograph requirements. The question of if there is an economically feasible path towards a fully harmonised system remains.

At the same time, there is still a quite large number of lines where 1 450 mm pantograph heads are allowed or even required. Particularly due to the Swiss, Italian and French special cases, new traction vehicles remain fitted with 1 450 mm pantograph heads. Hence, the lack of harmonisation on the infrastructure side has a material impact on rolling stock.

Regarding contact strip material, it was noted that this poses a relatively minor problem compared with the compatibility of the pantograph with the OCL, because manufacturers can develop alternative contact strips compatible with both electrification systems.

In addition to these points, it was noted that there are other interoperability barriers arising from other requirements related to the energy subsystem. This study has not assessed these in detail but considers that there is room for additional analysis.

Several other interoperability barriers that are caused by specific cases and national rules were identified, too. Improvements in the data quality of RINF enable the monitoring of tracks' TSI compliance. Future updates should facilitate a greater understanding of the TSI compliance of the European network according to a range of parameters. Such insights would be of great value to understand bottlenecks and help to assess the feasibility of removing interoperability barriers, in particular with regard to the evaluation of the OCL geometry and specific cases for other parameters.

Based on these considerations, the study makes the following recommendations.

- Perform a comprehensive evaluation on the level of compliance of fixed installations with the requirements of TSI ENE.
- Study the costs and benefits of greater harmonisation of OCL geometry, focusing both on greater harmonisation of the 1 950 mm and 1 600 mm systems (for all line speeds) and the progressive removal of non-TSI-compliant OCL geometries, particularly those stemming from national rules and specific cases related to compatibility with 1 450 mm pantograph heads.
- Perform a study on specific cases in the TSI ENE and the TSI LOC & PAS to assess their duration and impact on interoperability.

Point 3: high-speed rail

Given that it seems clear that multiple electrification systems will endure for a long time, the need for multi-system traction vehicles has to be acknowledged.

In the case of locomotives, it was observed that market dynamics have de facto made multi-system solutions the standard, despite the additional complexity and costs compared with mono-system options. Economies of scale and innovation have reduced the costs sufficiently to make multi-system locomotives commercially attractive. In the case of trainsets, however, no large-scale deployment of multi-system vehicles could be observed.

The recently published high-speed rail plan (21) emphasises the need for interoperable rail infrastructure and rolling stock. The argument is that the harmonisation of requirements reduces costs, improves production rates and ensures greater areas of use.

Since 2014, the TSI ENE has mandated that new lines with speeds greater than 250 km/h must be supplied with one of the AC systems. The consequence is that predominantly DC networks also integrate AC lines. Yet it is common for parts of the high-speed line (e.g. in stations or urban areas) to be DC lines, thus requiring high-speed rolling stock to run on DC.

From a European system development perspective, it is important to determine whether it is more beneficial to focus on the development of multi-system high-speed trainsets to handle different voltages, similar to what has happened for locomotives, or to invest in the re-electrification of selected DC sections along AC high-speed lines or in bypasses to separate AC and DC networks.

Based on these considerations, the study makes the following recommendation.

- Conduct a comprehensive analysis to determine whether there is a feasible path to simplifying the energy subsystem requirements for high-speed trainsets by re-electrifying specific lines or points or by building bypasses. Additionally, the analysis should reflect on the impact of national rules on the interoperability of the high-speed rolling stock fleet. Finally, the analysis should evaluate the options for promoting multi-system high-speed trainsets with greater areas of use.

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(21) https://transport.ec.europa.eu/transport-modes/rail/high-speed-rail-plan_en

Annex. Sources and copyright

A1. Sources of data

- Register of Infrastructure
- OpenStreetMap
- The TENtec TEN-T information system
- European Vehicle Register
- Open-source vehicle data
- Eurostat.

A2. Documents

No	Organisation	Title (as given in the document)	Year	Scope
1	Vienna University of Technology	*Vergleich der heutigen zentralen Bahnstromversorgung mit Eigenerzeugung mit einer dezentralen Versorgung des 162/3 Hz-Bahnstromnetzes über Umfonnerstationen aus dem SO Hz-Netz*	1993	AT
2	Norges Statsbaner Bane	*25 kV, 50 Hz matesystem ved NSB. Videre utredning*	1995	NO
3	ERA	*Conventional Rail Energy TSI – Impact assessment report*	2009	EU
4	ERA	*Revision TSI ENE – Impact assessment report*	2013	EU
5	TUC Rail	*Study on Interface EURO/1 950 Pantographs and OCL Design*	2013	EU
6	ERA	*TSI ENE – Technical Opinion 2017-3, light impact assessment*	2017	EU
7	ProRail and Nederlandse Spoorwegen	*Een maatschappelijke kosten-baten analyse van een verbeterde tractie-energievoorziening*	2018	NL
8	Revue general des chemins de fer 308	*Large review of electrification systems and re-electrification in France*	2020	FR
9	ProRail and Nederlandse Spoorwegen	*Vervolgonderzoek Systeemkeuze tractie-energievoorziening*	2022	NL
10	Instytut Kolejnictwa	*Change of the electric traction power supply system in Poland from 3 kV DC to 25 kV AC*	2023	PL
11	Brenner Corridor Platform	*Brenner Corridor Platform Study – Subgroup 'pantographs'*	2024	EU
12	Europe's Rail	*Energy Saving in Rail: Consumption assessment, efficiency improvement and saving strategies, overview report*	2024	EU
13	European Commission	*Connecting Europe through High-speed Rail*	2025	EU
14	International Union of Railways (UIC)	*How to manage DC electric traction power supply systems in the future*	2025	EU

A3. Interviews / written inputs received

Type of organisation	Number of inputs
Infrastructure managers	7
Railway undertakings	2
Lessors	1
Manufacturers	6
Financiers	2

A4. Images

All images were created by ERA, with the exception of Figure 11, created by Railcolor. The ERA images can be reproduced provided reference is made to this report.

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