Expansion Strategies for Electric Road Systems (ERS) in Europe

A working paper from the CollERS2 project

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Content

1. Executive Summary

The market development of alternative powertrains in European road freight transport will only be successful, if a network of alternative energy supply infrastructure is available. Electric road systems (ERS) powering battery electric trucks are one of the discussed alternative propulsion systems. They enable electric driving and dynamic battery charging and thus form a synergetic supply system to be combined with stationary charging of trucks. The ERS technology has been tested in several countries and its potential has been examined in further studies for other European countries. In the central regulation at European level, the Alternative Fuel Infrastructure Regulation (AFIR), the technology is mentioned, and important next steps are defined, but no concrete expansion targets are formulated.
Against this background and in view of the current market situation with a strong focus on battery-electric trucks, a centrally coordinated ERS expansion plan in Europe is yet not to be expected in the near future. It is therefore all the more interesting to look at national ERS actions and to examine possible expansion strategies that can be derived from national or bi-national activities.
The analysis of studies of eight European countries on application potential of ERS shows a high overlap of the prioritized routes at the national level with the European TEN-T core network and a relatively coherent connection of the national routes to cross-border, European corridors (see Figure I).

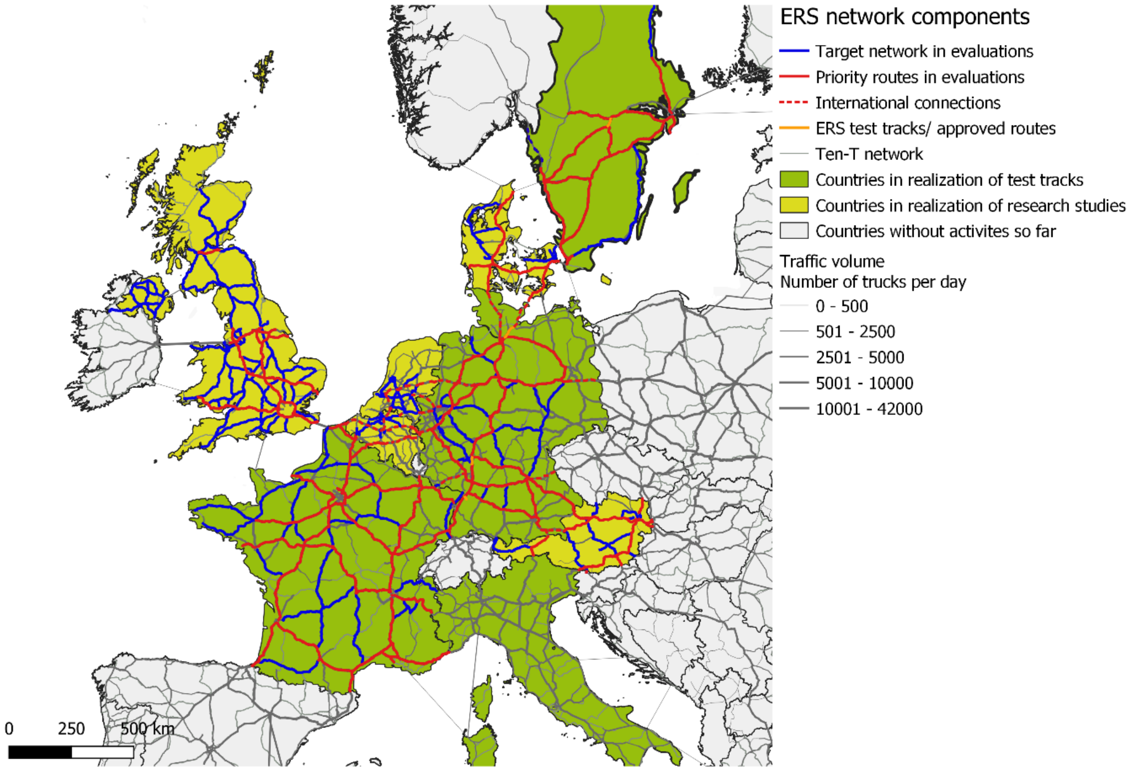

Figure I. ERS on European route network based on national ERS studies. Source: Own Illustration based on: Speth et al. (2022). Traffic volume database by Fraunhofer ISI. TEN-T network database source European Commission - DG Move - TENtec Information System (2022)

Based on data on traffic volumes in European road freight traffic, particularly promising ERS corridors can be identified for early network development (see Figure II). These represent important north-south and east-west connections in European road freight transport and are concentrated in Central Europe. The map presented is intended to stimulate further European discussion and provide an initial basis for a joint European planning process and negotiations on the best routes and European rollout for a full electric road freight transport system. Moreover, a joint approach regarding ERS implementation could help to relieve foreseeable disadvantages of the stationary only charging systems in terms of scarcity and allocation of charging points, restrictions in available building areas along highways and equalising electric power demands.

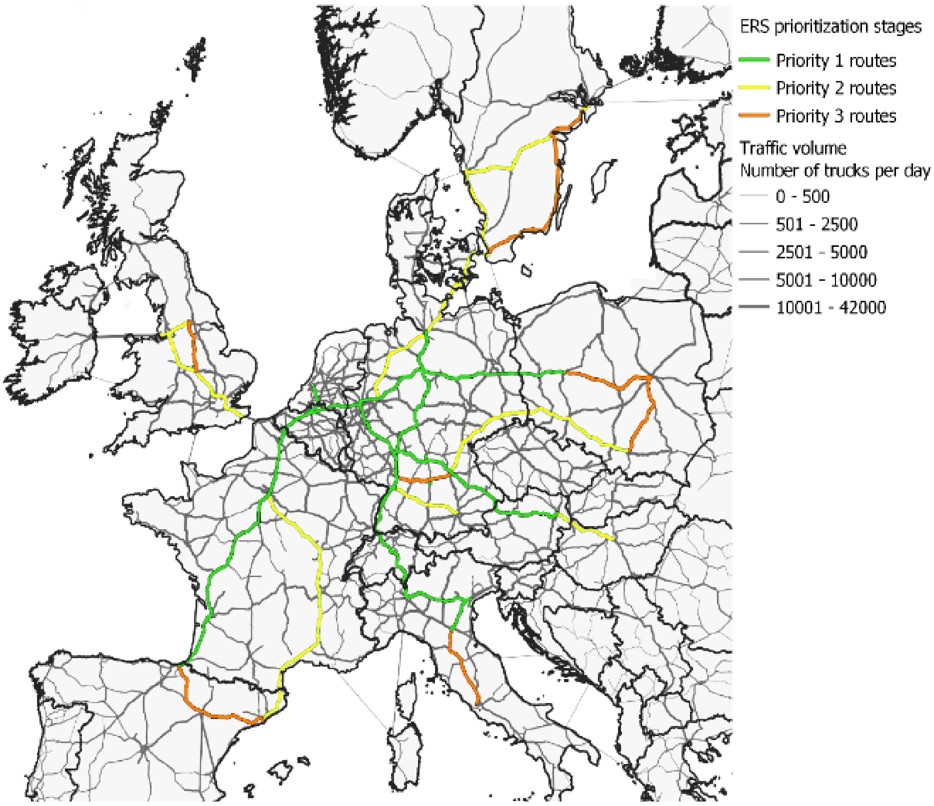

Figure II. Potential EU-wide extension stages of ERS in Europe. Own illustration based on (Speth et al. 2022b)

If there is no European coordination, it is conceivable that the ERS expansion could begin in some large countries, which the neighboring countries ("second movers") could then use for orientation. In an early market phase without an existing ERS network, point-to-point connections between important freight handling points are of great importance as they can already guarantee high infrastructure utilization. In this context, the first transnational corridors could be realized at an early stage and take on the role of a "flagship project" in the European context.

The analysis of the planning aspects of a bilateral implementation of ERS shows possible implementation options that can be carried out relatively independently of European coordination and are also used for other types of cross-border transport infrastructure projects. The economic analyses based on possible cross-border example corridors show that the refinancing of an ERS infrastructure via the users requires a high proportion of ERS vehicles on ERS routes. It can therefore be assumed that state pre-financing will be necessary in the early market phase.

For the further development of ERS, both a holistic strategy (pan-European coordination of expansion and standardization) and the incremental further development of technology and infrastructure driven by member states could play a role. The analyses presented in this paper attempt to provide guidelines for both approaches to an expansion strategy. On the one hand, the derived target network can serve as a background for the European coordination of the ERS expansion. The corridors shown for early implementation and the discussion of the planning aspects in the case of bi-national implementation offer starting points for a less centrally coordinated approach to the ERS network expansion. International projects along TEN-T corridors would ideally serve as “flagship projects” enforcing interoperability by limiting technical varieties. Assuming the success of such flagship projects they could stimulate a market driven pull for a joint European approach. This would then ultimately pave the way for a full electric European road freight network that synergistically combines ERS and stationary charging.

2. Introduction

Global warming and its consequences are one of the big challenges of our time. For the reduction of global warming, several countries want to become carbon-neutral in the next decades, while the EU has set the goal to be carbon-neutral by 2050 and reduce emissions by 55 % compared to 1990 by 2030 (European Commission 2019). As there will be remaining carbon emissions, e.g., for agriculture, that must be compensated through direct air carbon capturing and storage (DACCS) or with biomass (BECCS), sectors like transport have to be emission neutral in Europe by 2050.

The transport sector makes up 25 % of all European emissions and is particularly challenging as it is still increasing and has been compensating all incremental technological improvements so far (European Environment Agency (EEA) 2022). Thus, European transport emissions have not been reduced sufficiently over the last three decades. More than two thirds of European transport emissions (71 %) stem from road transport and one third of that (or about 20 % of transport emissions in total) stems from heavy-duty trucks with a gross vehicle weight of 12 tons and above while their vehicle stock is below 1 % of all road vehicles in Europe (European Environment Agency (EEA) 2022). Moreover, most of the long-distance driving is performed on the Trans-European Transport Network (TEN-T network) which makes it especially interesting for so-called electric road systems (ERS) (European Union (EU) 2013; Speth et al. 2022a).

Electric road systems allow charging while driving (or dynamic charging) of battery electric trucks. Currently, three main technologies are considered: charging via pantograph from overhead lines, charging via electricity collector through a rail in the road or via induction through magnetic coils (Widegren et al. 2022). All three technologies are tested in field trials or pilot projects in Europe (see the following chapters), while the overall technological readiness level (TRL) of all necessary components is at stage 8 for overhead lines, at TRL7 for the rail solution and even lower for inductive systems (Widegren et al. 2022). Further analyses indicate that battery-electric trucks with or without dynamic charging are already or will soon become the solution with lowest total costs of ownership in many European countries (Andersson et al. 2023). Also, their well-to-wheel emissions are lower than those of conventional trucks soon, while ERS-BEV would be even better due to smaller batteries (Andersson et al. 2023). In the second discussion paper from the CollERS2 project, it was argued that the AFIR and TEN-T provide a suitable framework for regulating the European roll-out of Electric Road Systems (ERS) in European law, insofar as it is politically desired. (Anderson et al. 2022) The proposal for a new AFIR of 2021 already contains a definition of ERS together with a standardisation mandate to the "European standardisation bodies". Art. 4 AFIR sets specific quantity targets and timescales for the development of electric recharging infrastructure dedicated to heavy-duty vehicles, differentiated between the TEN-T core network and the TEN-T comprehensive network. Insofar as concrete expansion targets are to be set for ERS in the future, an orientation towards and coordination with these targets for stationary recharging infrastructure would be obvious (Anderson et al. 2022).

The aim of this paper is to discuss the development of a future ERS network for Europe and to outline possible implementation steps. The following section discusses the derivation of potential first corridors and a possible target network. Two exemplary cross-border pilots will then be used to discuss the potential of the technology (Section 4) and to provide an overview of national planning aspects of the cross-border implementation (Section 5). The final section summarises the main findings of the paper and discusses which strategies for the cross-border development of ERS in Europe can be derived therefrom and which European or bilateral coordination processes would be necessary for this purpose.

3. Derivation of a possible ERS target network

3.1. The European long-distance road network

In view of the high level of economic interdependence between the member states of the European Union, cross-border traffic and the trans-European transport network are of great importance in the development of drive alternatives and the development of the necessary alternative energy supply infrastructure.

The Trans-European Transport Network (TEN-T) can be divided into two levels. The so-called core network comprises the most important European interconnections linking the most important European hubs. Within this core network, nine core network corridors represent the most important transport axes (see Figure 1). The much more comprehensive overall network encompasses all European regions and includes corridors that are less important in terms of transport (see Figure 2).

In this context, the Alternative Fuels Infrastructure Regulation (AFIR) (European Commission 2023) refers to the core network with its requirements for the development of alternative energy supply infrastructure (European Commission 2023). The following discussion on the derivation of a possible European ERS infrastructure is consequently based on the European TEN-T core network in view of its great importance in European long-distance road freight transport and the development of alternative energy supply infrastructure.

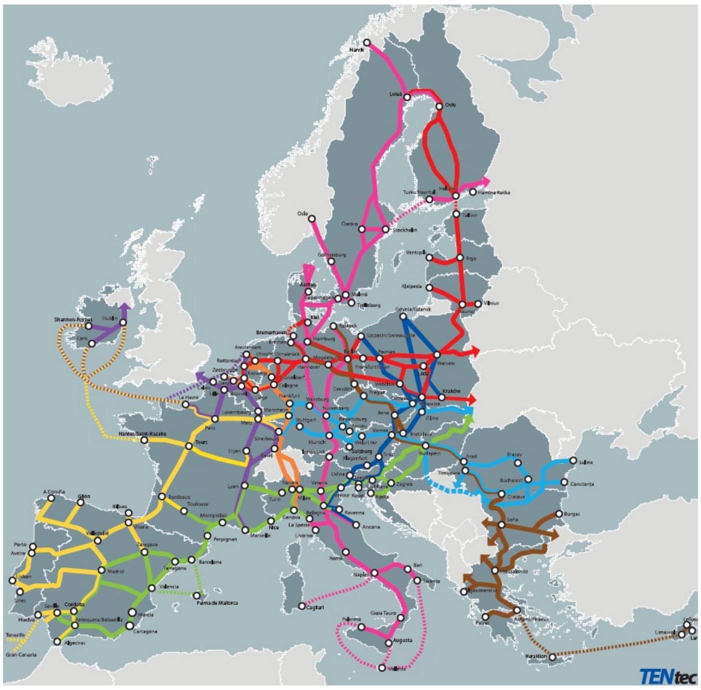

Figure 1. Trans-European traffic axes (TEN-T) Source: (BMDV 2021)

Figure 2. Traffic volume of European road freight transport. Source: Own Illustration based on (Speth et al. 2022b)

3.2. Requirements for ERS corridors at different expansion stages

Although it is still unclear which drive technology and thus energy supply infrastructure will prevail for long-distance road freight transport, there is widespread agreement that the TEN-T core network is of outstanding importance in infrastructure development, irrespective of the technology, and that it must be developed with comprehensive coverage and an efficient energy supply infrastructure in the future. Beyond this relatively secure target picture, possible expansion steps in successive infrastructure development are still vague. This is particularly true for ERS, for which no expansion plans have yet been defined in the AFIR. In addition, their linear extension means that successive densification would be mutually intertwined with a growing network of stationary charging points and implemented truck battery capacities. As both technologies require grid connections to high voltage utilities ERS installations can provide power supply along network segments where power demands exceed stationary building area, network capacity and flexibility demands.

In Hacker et al. (2022) the importance of different evaluation criteria over time was assessed. In further studies for different European member states (see following section), similar considerations were made. The core results on the importance of different evaluation criteria and the recommendations derived from them for a successive development of an ERS network can be summarized as follows.

In the future, an ERS network will be particularly relevant on highly frequented highway corridors with great importance for long-distance freight transport (see TEN-T core network). Since the demand for electricity will be particularly high there, ERS can reduce the need for stationary charging points and driver breaks for charging the batteries of long-distance trucks (Plötz et al. 2021). In addition, a high utilization of the infrastructure can be achieved there.

At earlier stages, other criteria are at the forefront of route selection, since (in some cases only national) individual routes and sub-networks are not yet eligible for European long-distance transport. At this early time, in addition to the high volume of traffic, the structure of the traffic plays a greater role. Particularly in the case of a high proportion of journeys that end and begin not far from the electrified corridor, routes are particularly suitable. This is also true if there is a high proportion of commuting, since the same vehicles then travel the same section or the electrified subnetwork more frequently. Proximity to logistical transfer points (such as ports or other hubs of commerce and industry) can be of advantage and create a "base load" of suitable traffic.

To date, the focus of many analyses has been on national transports (see also subsequent section), as cross-border implementation is considered difficult in the short term. The AFIR, for example, has not yet taken ERS into account with concrete expansion specifications. In perspective, however, especially long-distance, international traffic on highly frequented highways is relevant for ERS and should therefore be considered at an early stage.

Particularly in the early phase, routes should be selected where planning and approval processes are less complex and, for example, nature conservation concerns are not affected in view of sensitive areas or the acceptance of the population due to a strong proximity to settlements. With regard to route characteristics, routes should first be selected that do not pose any special construction challenges that would entail more elaborate planning and implementation. For example, long tunnel stretches, challenging topography, or a highway with fewer lanes may hinder rapid implementation at an early stage of development.

Given the European goal of shifting more freight traffic to rail, ERS infrastructure should be developed especially along corridors where freight traffic is expected to continue to grow and a shift back to rail is difficult (e.g., given an already high utilization of rail infrastructure).

3.3. National perspective on the development of a European ERS infrastructure

In recent years, ERS technology has been tested in several European countries (Sweden, Germany) as part of pilot projects on public roads or at a smaller scale on test sites (e.g. France, Italy). Many other European countries have followed these activities with interest and have also started considering a national expansion of ERS infrastructure (Austria, Netherlands, Denmark, Belgium, United Kingdom). Other European countries (including Italy) have also recently looked at ERS technology, but have not yet developed nationwide analyses.

The approach and main findings of the mentioned country analyses are presented in the following. They form the basis for the subsequent considerations for a pan-European ERS network (see following section). Regarding the studies, it should be mentioned that they have been approached from different perspectives (including academic science, policy consulting, administration) and have chosen different methods and are therefore not fully comparable. Nevertheless, they can provide important first indications for a possible network development from a national and European perspective.

3.3.1. Germany

Germany has ambitious goals for decarbonizing its transport sector, aiming for a 48 % reduction in greenhouse gas emissions by 2030 (compared to 1990 levels), and climate neutrality by 2045 (Bundes-Klimaschutzgesetz, 2021). ERS are seen as a potential part of this strategy, with a goal of having one third of road freight travel via electric powertrains or e-fuels by 2030 (Bundesregierung, 2019).

Germany, as an early adopter of the technology in several pilot applications (see Figure 3, ERS test tracks/approved routes), has examined possible target networks and expansion stages in numerous studies (Hacker et al. 2022). These envision a long-term target network of about 4000 km along the busiest, single-digit highways. Early build-out should be along high-volume corridors, with a focus on connections between major freight hubs and high commuting volumes. In an early stage, international corridors are not considered relevant in Hacker et al. (2022) until a European network expansion progresses. As a country in the center of Europe with a high share of international traffic, however, high potentials for international ERS corridors through Germany are emerging in the future.

Early expansion (Phase 1) of routes is recommended, especially from Hamburg in the direction of the Ruhr region and the center of Germany (Kassel). The connection of the Ruhr area and Rhine-Main or Rhine-Neckar are also recommended at an early stage. The connection of those important industrial centers in the direction of Kassel and eastward to Munich and Nuremberg could follow (Phase 2). With a view to international traffic, important east-west connections between the Ruhr area and Berlin and to the southeast in the direction of Austria could be developed. An important connection to the south is the connection to Basel (Phase 3).

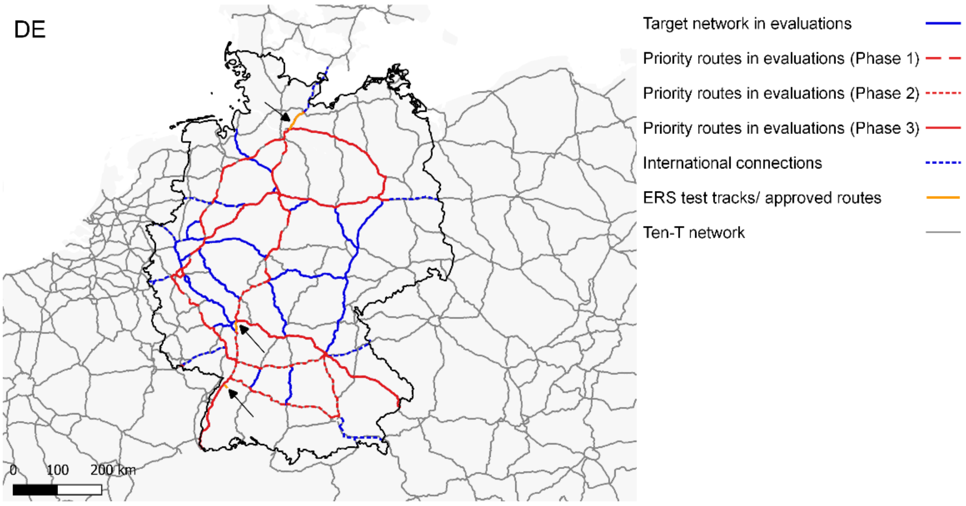

Figure 3. ERS target network and potential priority routes and partial networks in Germany. Source: Own illustration based on (Hacker et al. 2022). Ten-T network data by European Commission - DG MOVE -TENtec Information System (2022)

3.3.2. Sweden

The Swedish government has established a target of reducing greenhouse gas emissions from the transportation sector by 70 % by 2030 and attaining net zero emissions by 2045 (Naturvårdsverket, 2023).

Sweden is a pioneer in the development of electric road systems (ERS). In addition to overhead contact lines, other power supply options (conductor rail and inductive) are also being tested and pursued. Beyond the pilot tests, a longer ERS line between Hallsberg and Örebro (see Figure 4, ERS test tracks/ approved routes) is currently being planned. The long-term target network is the electrification of a trunk road network of 2,400 kilometers in length. Given the relatively low traffic density, the development of ERS infrastructure is initially seen primarily in southern Sweden between the main cities on the TEN-T core network and with international connections. In previous analyses, options for a possible international ERS corridor between Sweden and Germany were investigated based on different implementation options (Hacker et al. 2020b; Jöhrens et al. currently unpublished).

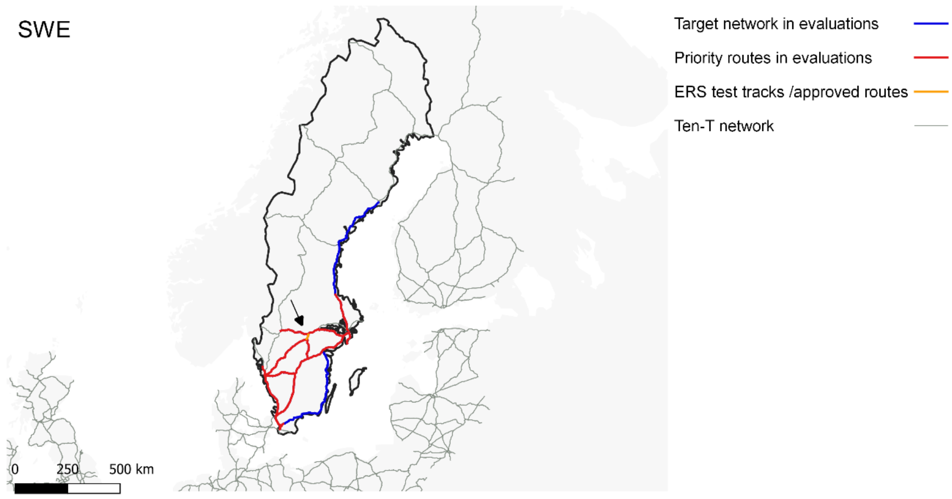

Figure 4. ERS target network and potential priority routes in Sweden. Source: Own illustration based on (Ullström 2021) (The Swedish Transport Administration). Ten-T network data by European Commission - DG MOVE -TENtec Information System (2022)

3.3.3. France

The goal of France is climate neutrality by 2050 as part of its national low-carbon strategy (Gouvernement France 2022).

The use of ERS in road freight transport has recently been increasingly discussed in France and investigated in several feasibility studies (WG 1 of Transport Infrastructure Directorate of the Ministry of Transport 2021; RGRA 2022)

The system is also seen as a dynamic energy supply option for passenger cars and ground-based solutions are therefore preferred. The national TEN-T network including the connection from Paris to Rennes with a total length of 4,900 kilometers is seen as the priority network. With this network, every location in France would be a maximum of 125 kilometers away from the ERS network, and it would be possible to cover a maximum of 50 % of the transport performance of heavy goods vehicles. In the long term, it is conceivable that this network could be extended to cover a total of 8,850 kilometers of trunk road.

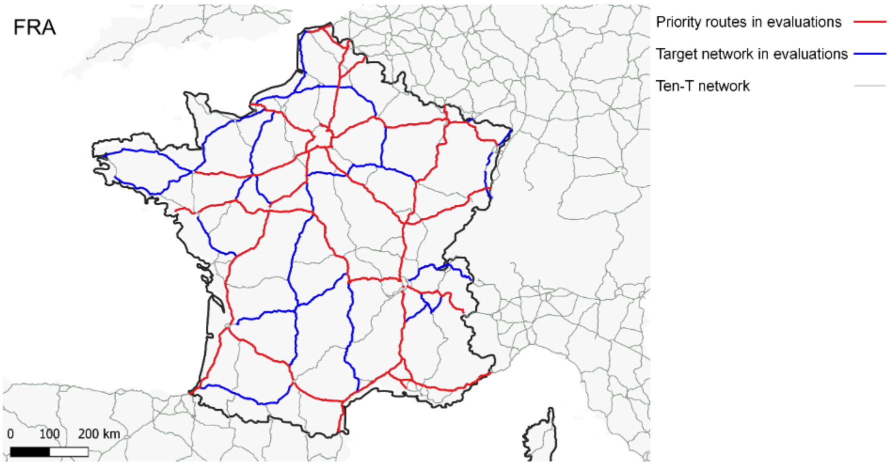

Figure 5. ERS target network and potential priority routes and partial networks in France. Source: Own Illustration based on (RGRA 2022). Ten-T network data by European Commission - DG MOVE -TENtec Information System (2022)

3.3.4. Austria

Austria has set ambitious climate protection targets and plans to achieve emission-free heavy road freight transport by 2035.

The country is characterized by a high share of transit traffic and, as an alpine country, has a challenging topography with many uphill stretches and numerous tunnels. Overhead lines are seen as an option in long-distance transport. An existing feasibility study of the Austrian energy agency (Austrian Energy Agency 2022) forms the basis for the prioritized routes presented. They represent the most important routes of the TEN-T core network with correspondingly high traffic volumes and high importance for international freight traffic. On the other routes of the core network, construction-related implementation difficulties predominate, resulting in a lower suitability rating.

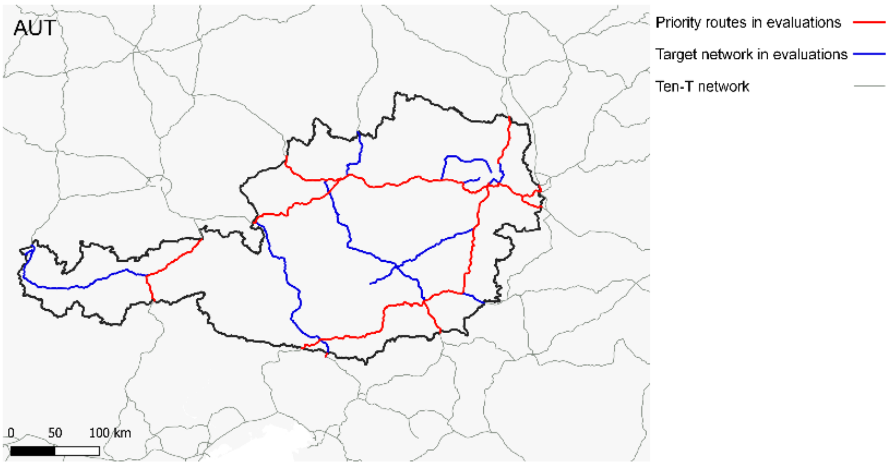

Figure 6. ERS target network and potential priority routes and partial networks in Austria. Source: Own Illustration based on Austrian Energy Agency (2022). Ten-T network data by European Commission - DG MOVE -TENtec Information System (2022)

3.3.5. Netherlands

The Netherlands has ambitious goals for decarbonizing the transport sector, as outlined in the 2019 Climate Agreement (Netherlands, 2019). This includes a target of a 49 % reduction in greenhouse gas emissions by 2030 (compared to 1990 levels) and a 95 % reduction by 2050.

The construction of an ERS network has been the subject of several recent studies (Movares 2020; van Ommeren et al. 2022). The analyses point to the high cost-efficiency of the expansion on main routes. In selecting priority ERS routes, particular importance is attached to seaports and their international connections. An ERS network on the main highways would have a length of 980 kilometers. A possible extension to the entire network would mean the electrification of a total of 2,500 kilometers of highway.

In view of the high interdependencies of freight transport with neighboring countries, the Netherlands is showing great interest in ERS activities in these countries.

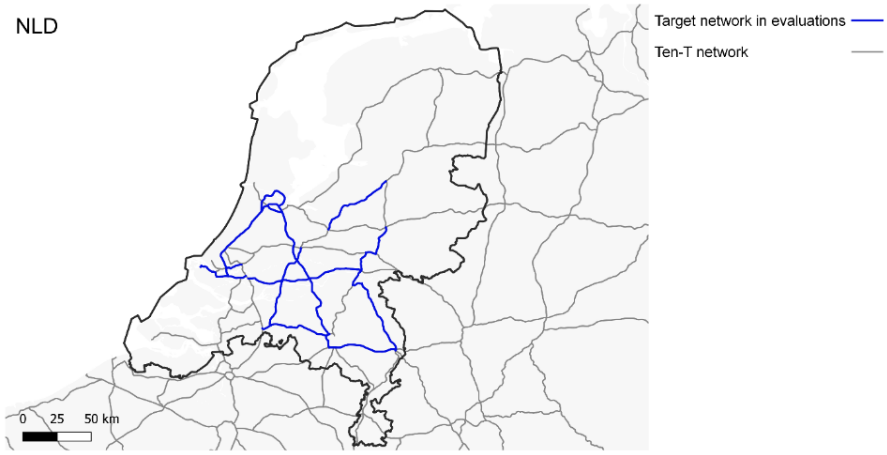

Figure 7.ERS target network and partial networks in Netherlands. Source: Own Illustration based on (van Ommeren et al. 2022). Ten-T network data by European Commission - DG MOVE -TENtec Information System (2022)

3.3.6. Denmark

In 2019, Denmark passed a climate law that stipulates a 70 % reduction in greenhouse gases across sectors by 2030. A possible expansion of ERS has been investigated in several studies (Conolly 2016; Domingues-Olavarría et al. 2018).

The national motorway network with a length of 4,500 kilometers is considered as a possible target network. Priority routes run along the busiest motorways with international connections to Sweden and Germany.

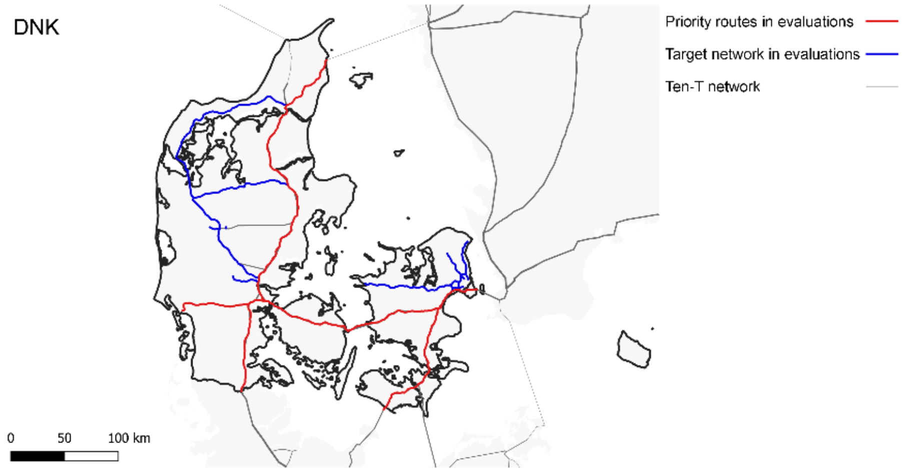

Figure 8. ERS target network and potential priority routes and partial networks in Denmark. Source: Own Illustration based on Conolly (2016). Ten-T network data by European Commission - DG MOVE -TENtec Information System (2022)

3.3.7. Belgium

In its decarbonization strategy, Belgium sets a target of reducing transport-related greenhouse gases by 27 % by 2030 compared to 2005 levels.

The potential of ERS was investigated in a research project for the Flanders region (Aronietis und Thierry 2021). At government level, there is no positioning on the technology so far. The scientific analyses have prioritized suitable routes based on economic considerations. Comparable to the Netherlands, the connection of the seaports (Zeebrugge and Antwerp) and their international connection to Germany and France is of particular importance in Belgium. With a final extension of 1,200 kilometers, all national and international road freight traffic could be handled by ERS.

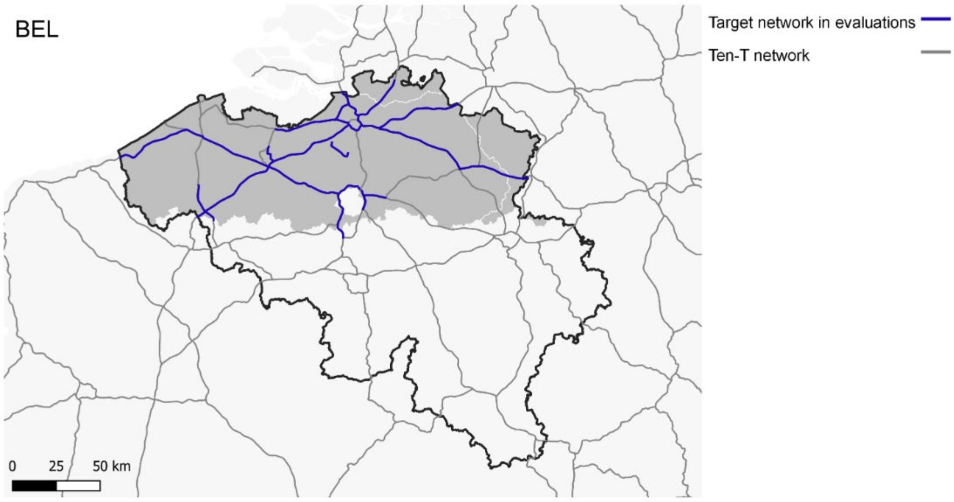

Figure 9. ERS target network in Flanders. Source: Own Illustration based on Aronietis und Thierry 2021 (University of Antwerp, 2021). Ten-T network data by European Commission - DG MOVE -TENtec Information System (2022)

3.3.8. United Kingdom Great Britain and Northern Ireland

The UK government has set a target of only zero-emission heavy-duty vehicles being registered by 2040.

In this context, electrification by means of ERS (including overhead contact line) is being pursued as an option and is being investigated in several studies (Nicolaides et al. 2018; Department for Transport (DfT) 2021; Ainalis et al. 2020). The target network would cover about two-thirds of the national mileage of heavy-duty vehicles, with the first expansion stage covering about one-third. These priority routes would focus primarily on the south of the United Kingdom, connecting the capital London with major cities, industrial nodes, and international connections.

It is true that the United Kingdom is of lesser importance for infrastructure development in the EU due to its exit from the EU and its peripheral location in Europe. In view of its economic importance and its pioneering role in the implementation of climate protection technologies, the developments on ERS are nevertheless considered relevant for a possible overall network of ERS in Europe.

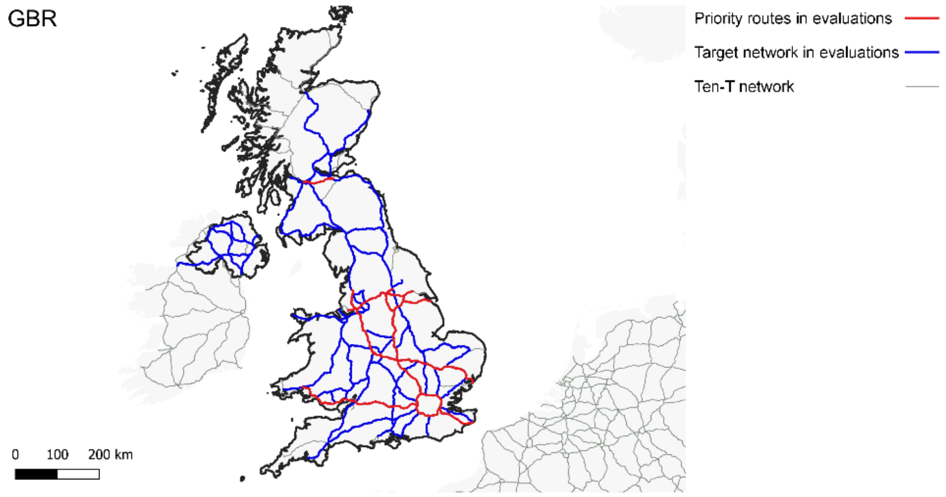

Figure 10. ERS target network and potential priority routes and partial networks in Great Britain. Source: Own Illustration based on Ainalis et al. 2020 (SRF. The Center For Sustainable Road Freight). Ten-T network data by European Commission - DG MOVE -TENtec Information System (2022)

3.4. Possible European ERS target network

3.4.1. Bottom-up approach based on available country studies

As the preceding analyses have shown, there are several studies available at the level of European countries on a possible national ERS expansion. This is not yet the case for the development of a European ERS network. However, despite their different approaches, important insights can be drawn from these studies for the possible development of a European ERS target network.

As a common feature of the national considerations, it can be stated that the routes preferred in the longer term refer exclusively to long-distance roads, with traffic volume being the decisive criterion for route selection. Accordingly, there is a high degree of overlap with the TEN-T core network and the approach also corresponds with the AFIR's spatial reference framework for alternative energy supply infrastructure. Insofar as different expansion stages are addressed at the national level, connections between important freight transfer points, such as seaports and important industrial centers, are frequently mentioned for early expansion. One main reason is likely to be that such routes could already open relevant freight traffic flows between these transhipment points even without a branched European ERS network and would be suitable for the use of ERS trucks on such commuting routes.

It is striking that especially smaller EU member states with a high share of international freight transports (e.g. Netherlands and Austria) point out the importance of similar activities in neighbouring countries (e.g. Germany), as for them an early integration into a European ERS network would be of particular importance. On the other hand, studies for e.g. Germany show that domestic traffic could also already provide a high utilization of an ERS infrastructure on important routes and that international expansion is only considered in further steps. Other influencing factors, mainly dealing with possible difficulties in ERS construction, are mainly addressed in Austria. The challenging spatial conditions (topography, civil engineering infrastructure) are an obvious explanation for this.

The lack of a European perspective in the national studies to date is understandable in view of the lack of anchoring of the technology in central European regulations (above all AFIR) and in the standardization of the infrastructure. However, for the longer-term use of ERS in European long-distance transport, an infrastructure network along the most important freight corridors is the central precondition. Based on the available country studies and considering additional background information on traffic volumes as well as important international connections, the network shown in Figure 11 results.. This network, which is the result of bottom-up analyses, includes priority routes for those countries that have already shown preliminary work (see previous section) and interest in the technology, as well as a longer-term target network. The combination of the results of the country studies already indicates a relatively consistent network of international ERS corridors and a large overlap with the TEN-T core network.

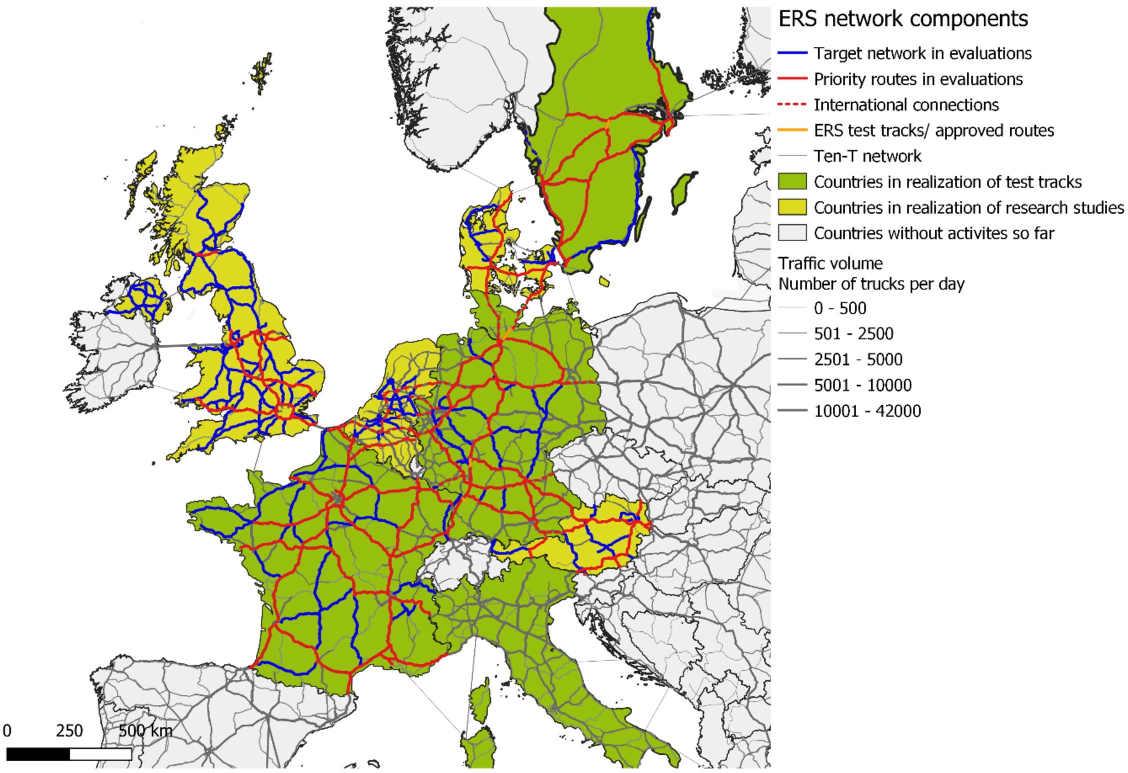

Figure 11. ERS on European route network based on national ERS studies. Source: Own Illustration based on: Speth et al. (2022). Traffic volume database by Fraunhofer ISI. Ten-T network database source European Commission - DG Move -TENtec Information System (2022)

3.4.2. Top-down approach for EU-wide expansion in several stages

In addition to the bottom-up analysis of national ERS plans (see previous section), a top-down analysis can provide complementary important indications for significant international corridors that are suitable for early electrification. In this case, particular importance is attached to cross-border traffic, and other EU countries that have not yet carried out any practical ERS activities or studies on possible infrastructure development, but show great interest in this technology (e.g. Italy), are included in the analysis.

The basis to analyse the main road segments in Europe is the synthetic road freight data published by Speth et al. (2022b). Figure 12 shows simulated HDV traffic intensity on the main European roads based on Eurostat consistent OD matrices and shortest time routing (cf. Speth et al. 2022b); actual traffic count and routing can deviate but long-haul trucks are usually captured well based on shortest travel time. The comparison with the national ERS plans confirms that the national studies show a high level of agreement with the trunk roads with the highest traffic volumes. Important international connections to neighbouring countries such as Italy, Poland, Spain, Switzerland and the Czech Republic that are mentioned in national ERS studies are confirmed by the analysis of international traffic data.

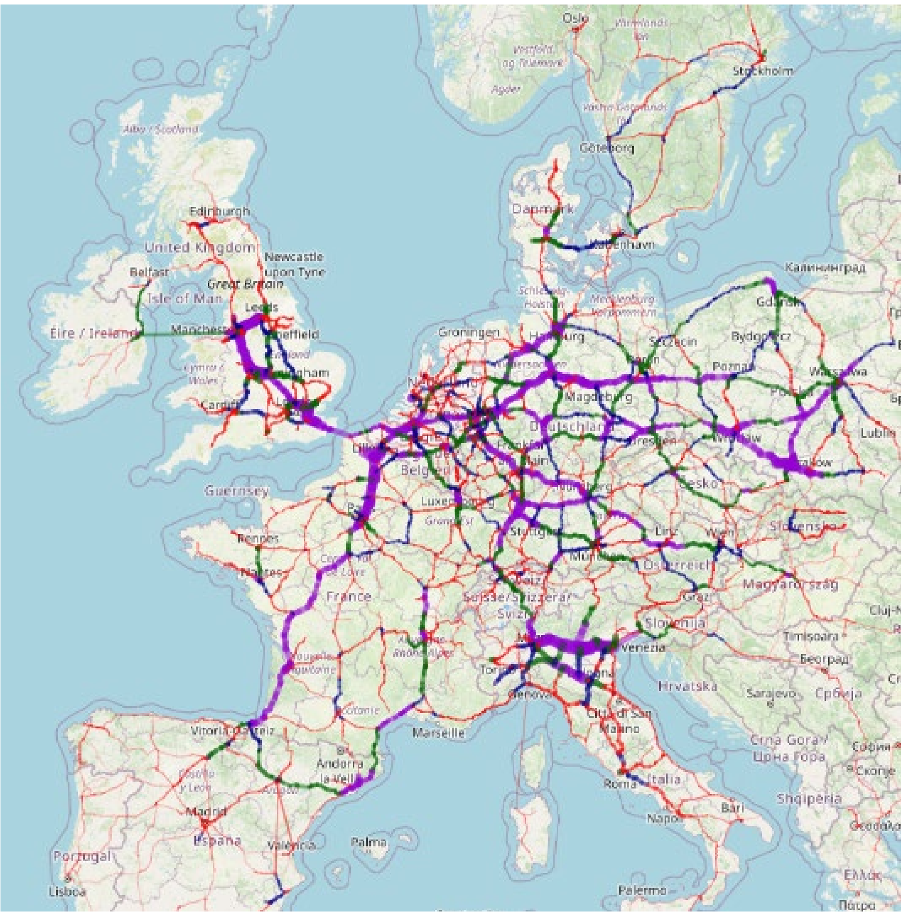

Figure 12. HDV traffic intensity on the main European roads. Own illustration based on (Speth et al. 2022b). violet: top 10 % of mostly used roads, i.e., top 10 % of number of HDV per day per road segment) in dark blue: top 10 – 20 %; dark green: top 20 – 30 %; red: remaining roads in red; width of the lines: number of trucks per day per road segments.

The idea of a fully European ERS network now is to include important national roads from existing ERS feasibility studies (see previous section), add important roads in other countries and add connecting road segments. Based on the European road transport data and the existing national ERS studies, the following European routes could form a blueprint for a European ERS rollout (see Figure 13). More specifically, we focus on the top 10 %, top 20 %, and top 30 % of the European road freight network as the first (green), second (yellow), and third stage (orange) of ERS network expansion. However, using this as only criterion for expansion would lead to several unconnected ERS stretches across Europe. Thus, we manually add connecting road segments and give countries with already advanced ERS discussion and political backing a priority in an ERS network expansion. The proposed network comprehends about 12,000 km of the European road network.[1] Of course, the assignment to stages and the exact routes are a first sketch here and should see further in-depth analysis and detailed studies. A further extension of such a network could follow the national roll-out studies and the mostly used roads. This map is a first attempt to stimulate further European discussion and to provide a first basis for a joint European planning process and negotiations about best routes and European rollout. Local or national interests can lead to different routes and need to be discussed with various stakeholders.

[1] Stage 1, in total approx. 4,800 km: Antwerp to Poznan, approx. 1,000 km; Duisburg to Vienna, approx. 960 km; Rotterdam to Paris to San Sebastian, approx. 1,160 km; Hamburg to Milan, approx. 1,150 km; Venice to Milan to Bologna, approx. 500 km; Stage 2, in total approx. 4,800 km: Leeds to Liverpool to Dover, approx. 600 km; Stockholm to Gothenburg to Hamburg (via Fehmarn Belt), approx. 1,100 km; Frankfurt to Krakow, approx. 980 km; Paris to Lyon to Barcelona, approx. 1,150 km; Vienna to Budapest, approx. 250 km; Hamburg to Bremen □ Duisburg, approx. 380 km; Karlsruhe to Munich, approx. 300 km;
Stage 3: Gap closure, approx. 2,500 km: Leeds to London, 330 km; Bologna to Rome, 380 km; San Sebastian to Zaragoza to Barcelona, Mannheim to Nuremberg, Poznan to Warsaw to Krakow, Stockholm to Malmö direct, and closing further small gaps in the Netherlands, the Ruhr area and areas.

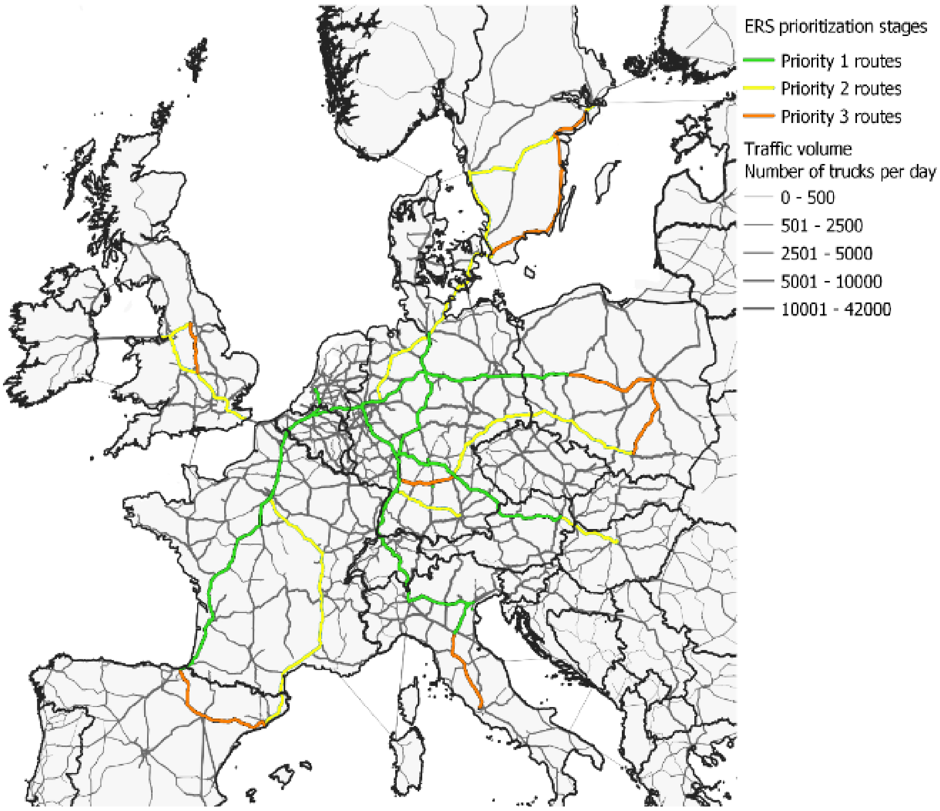

Figure 13. Potential EU-wide extension stages of ERS in Europe. Own illustration based on (Speth et al. 2022b)

4. Selected case studies as examples of early realization

As described in the previous section, activities regarding ERS in Europe are currently being carried out mainly by individual member states, which have conducted feasibility studies on possible ERS application in their respective national road freight context. From today's perspective, a decision at European level on coordinated Europe-wide ERS expansion is unlikely in the short to medium term. Rather, it is to be expected that individual states or regions could initiate locally limited ERS networks on their own, which could serve as nuclei of a large-scale (and in perspective transnational) ERS rollout later on. A similar process was observed with the electrification of the railroads in the last century. Nevertheless, a number of sincere lessons in terms of interoperability should not be ignored when reflecting the history of integration of the European railway system (Salander 2019):

- European Integration and cross-border operations are simplified, when technical core features (e. g. power supply voltage, frequency and mechanical properties) are compatible.
- European technical standardisation is a good means of harmonising technical features (Staub und Lehmann 2022).
- Subsequent harmonisation of operation and control technologies can pose long implementation times and thus require conscious decision making regarding their ultimate necessity.

Hence, it is of great importance to secure interoperability between different nuclei at an early stage. This includes securing uniform interfaces via appropriate standardization processes and contracts on the application of standards. Joint cross-border pilot projects can also play an important role. They can help identify and solve practical challenges of international interfaces (technical, legal) and possible deadlocks related to industrial policy. In addition, they can become international "flagship projects" and subsequently promote decidedly European ERS planning.

Two possible cross-border ERS pilots are outlined below as examples. The objective of these examples is to estimate some basic technical and economic parameters of international ERS pilots in terms of magnitude. A more detailed consideration of route suitability, usage patterns, and infrastructure costs is not possible within the scope of this discussion paper. More detailed studies on this would be essential for feasibility studies of specific international corridors.

Based on the pilot projects for ERS announced in Germany, it is assumed that a cross-border ERS pilot could have a route length of about 100 km. Furthermore, assumptions are made for the investment costs per ERS-km and some other economic variables, which can be found in Table 1.

Table 1: Economic assumptions for the exemplary pilots in terms of ERS infrastructure

ERS installation cost	3,000,000 €/km
Part of invest financed by loan	50 %
Interest rate	3.5 %
Life time	20 a

A significant market ramp-up of battery-powered electric trucks is expected in the coming years; according to a scenario of the ICCT for European truck traffic (Ragon et al. 2022), about 7 % zero-emission trucks could be in the fleet in 2030, and in 2040 with 79 % already a large part of all trucks. These are assumed here as the possible user base for an ERS pilot: If the use of ERS is sufficiently attractive, some of these vehicles could be equipped with pantographs for dynamic charging on the cross-border pilot routes.

A study (Jöhrens et al. currently unpublished) has already been conducted on possible criteria for the suitability of international ERS pilots as part of the CollERS project. Regarding the selection of meaningful first pilot routes and country combinations, the following criteria should be particularly considered:

- High number of potential vehicles using ERS. This means that routes with high traffic volumes should be selected and, especially for the initial phase, the involvement of anchor users should be ensured who regularly have high transport volumes along the ERS route.
- Strategic congruence of the countries involved. This includes, for example, agreeing on one ERS technology for the pilot project and dealing with industrial policy issues.
- Fiscal and regulatory frameworks that make ERS use attractive on both sides of the border.

The analysis of the total cost of ownership (TCO) conducted for various truck drive technologies in several European countries in Andersson et al. (2023) revealed a particularly large full cost advantage of electric drives in Austria. This country also describes itself as a "second mover" and would like to align its ERS-related activities on the German expansion plans. An Austrian study estimated the hurdles for the development of ERS on various sections of the Austrian highway network (Figure 14.). According to this study, both the German A3 (border crossing at Passau) and the A93 (border crossing at Kiefersfelden) could be considered for a cross-border pilot with Germany. Traffic volumes are significantly higher in the first case (approx. 15,000 trucks/day). In addition, truck traffic in the Inn valley as well as via the Brenner route is discussed rather critically overall and is planned to be shifted to rail to a large extent in the long term. Therefore, the A3 (Germany) or A8 (Austria) with border crossing near Passau is used as an example.

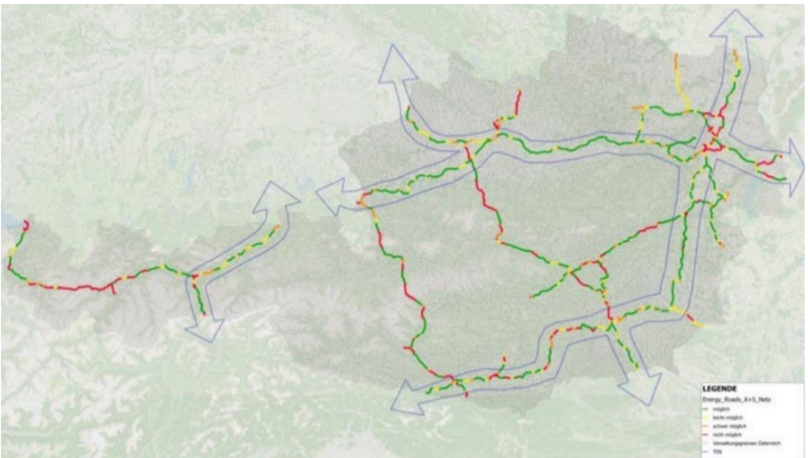

Figure 14. Assessment of the suitability of individual sections of the Austrian highway network for the installation of ERS; green = no limitations, yellow: some limitations, orange: serious limitations, red = almost impossible. Source: Austrian Energy Agency 2022).

Table 2 shows the parameters of the exemplary Austrian-German ERS pilot. For the two reference years considered (2030 and 2040) with different fleet penetration of electric trucks, two different assumptions are made in each case for the share of ERS-capable trucks among electric trucks (10 % and 50 %). Depending on this, it is shown which vehicle-kilometre-based costs for the infrastructure result when the annuated investment costs are applied to the mileage of ERS-capable vehicles on the ERS infrastructure. A comparison with the expected full cost advantage of ERS vehicles over diesel vehicles (based on the country-specific TCO calculations performed in Andersson et al. (2023)[2]) shows that the infrastructure costs are still significantly higher than the savings of electric trucks over diesel vehicles at the use intensities conceivable for 2030. For 2040, however, this looks different: Here, ERS vehicles could still have lower costs per kilometer than diesel vehicles even in case of full infrastructure cost allocation onto the vehicle operators, if fleet penetration of ERS vehicles is sufficiently high. Note that the ERS installation costs will in reality depend on the capacity of the ERS, which is neglected here for the sake of simplicity.

Table 2: Overview of exemplary ERS pilot Germany-Austria

Route	Deggendorf --> A3 --> border crossing Suben --> A8 --> Wels			
Distance	67 km (Germany) + 58 km (Austria) = 125 km (total)			
Annuity for ERS infrastructure	9.4 million €			
Mean traffic intensity[3]	15,000 trucks per day (both directions)			
Reference year	2030		2040	
Assumed share of zero-emission trucks[4]	7 %		79 %	
Assumed share of ERS vehicles in ZEV	10 %	50 %	10 %	50 %
Daily passages of ERS vehicles.	105	525	1,185	5,925
Costs for ERS infrastructure per vehicle-km	5.72 €/v-km	1.14 €/v-km	0.50 €/v-km	0.10 €/v-km
TCO advantage ERS-BEV vs. diesel	0.44 – 0.49 €/v-km			

With regard to cross-border truck traffic flows with Germany, the Netherlands also has good prerequisites in principle for an international ERS pilot, and there have already been several studies (Movares 2020; van Ommeren et al. 2022) on the economic viability of and network development for ERS in the Netherlands. By far the highest traffic volume is observed on the route between Eindhoven and Duisburg with about 16,000 daily truck passages. This route also connects to the national pilot route between Eindhoven and Amsterdam considered in Decisio et al. (2022) and carries a significant share of international traffic to Belgium. It therefore appears suitable in principle for a cross-border pilot and is selected here as a second example.

The parameters of this second example are shown in Table 3. Since the traffic volume on the selected section is like the previous example, the infrastructure costs per vehicle-km on the ERS are similarly

[2] In deviation from the results shown there, an ERS vehicle with a battery range of approx. 500 km was assumed here for the cost comparison, since the vehicles are assumed not to have access to ERS infrastructure nationwide yet and thus mainly have to charge stationary, which results in a rather high required range.

[3] Traffic volume is based on Speth et al. (2022b) annual data was converted to daily figures using the number of 250 working days per year.

[4] Ragon et al. 2022.

high. However, the TCO advantage of ERS vehicles over diesel vehicles is significantly lower than in the first example because the cost components determined by the national framework (energy costs, tolls) differ significantly in Austria and the Netherlands. The expected willingness to pay for ERS use thus tends to be lower than in the first example.

Table 3: Overview of exemplary ERS pilot Netherlands-Germany

Route	Eindhoven --> A67 --> Venlo --> A40 --> Kreuz Moers (near Duisburg)			
Distance	69 km (Netherlands) + 28 km (Germany) = 97 km (total)			
Annuity for ERS infrastructure	7.3 million €			
Mean traffic intensity	16,000 trucks per day (both directions)			
Reference year	2030		2040	
Assumed share of zero-emission trucks	7 %		79 %	
Assumed share of ERS vehicles in ZEV	10 %	50 %	10 %	50 %
Daily passages of ERS vehicles.	112	560	1,264	6,320
Costs for ERS infrastructure per vehicle km	5.36 €/km	1.08 €/km	0.48 €/km	0.10 €/km
TCO advantage ERS-BEV vs. diesel	0.34 – 0.39 €/v-km			

These examples can only provide a rough picture in terms of magnitude. A more detailed analysis of local conditions would allow for adjusted cost estimates, and the prevailing usage profiles on the ERS routes are important input variables for the design of the ERS (e.g., to estimate at which power vehicles along the ERS would reasonably charge). In an introductory phase, shorter ERS sections would also be conceivable, for example, depending on the permitted vehicle-side charging power and vehicle configurations operating there.

Whether a decision will be made in favour of transnational ERS pilots is likely to only partly depend on cost considerations. As discussed in more detail in the following section, national strategies and national road freight planning processes are likely to be ultimately decisive for the development of national ERS trunks as pre-requisite for international connections. If the decision is made to implement a cross-border ERS route, the fiscal framework conditions between the countries should be coordinated as far as possible to enable a predictably economical operation of ERS vehicles on both sides of the border. This also includes a coordinated funding model for the ERS infrastructure investment costs, for example via toll revenues. Finally, such international infrastructure projects can also be facilitated through industrial policy cooperation.

5. Implementation of ERS under different national planning regulations

As stated in the second discussion paper from the CollERS2 project (Anderson et al. 2022), the AFIR and TEN-T provide a suitable framework for regulating the European roll-out of Electric Road Systems (ERS) in European law, insofar as it is politically desired. First steps in this direction are the definition of ERS together with a standardisation mandate in the proposal for a new AFIR presented by the Commission in 2021. Further steps as suggested in the second discussion paper would be required, to facilitate a European roll-out. But what if such an update of AFIR, TEN-T and some other European legislation as suggested in the second discussion paper would provide a suitable European legal framework for the roll-out of ERS corridors as outlined in the previous sections? In this paragraph we give an overview what national steps, bilateral and European coordination would be required to implement ERS under different national planning regulations in this case.

Since the introduction of the Trans-European Networks (TEN-T) as a guiding principle of EU transport policy, there has been a great deal of experience with the implementation of transnational infrastructure projects in the transport sector. In principle, all TEN-T projects show that the backbone is initially national projects that only require special coordination in the cross-border area. This cross-border coordination results in the basic planning steps and subtasks shown in Table 4 for the creation of a coherent European infrastructure. For the construction of an ERS, the individual steps can be briefly described as follows.

In any case, a national selection decision on the national network and the cross-border section is the starting point for the implementation of an ERS expansion, be it that a pilot corridor to a TEN-T line or a network of transport corridors for electrification are selected first. The responsibility for this selection usually lies with the national governments and is based on different national decision-making procedures (benefit-cost assessments, achievement of national and European targets, environmental and spatial impact assessments with variant selection etc.). Finally, it is often necessary to involve national parliaments in the selection decision, but in any case, in the closely related financing decision. However, such a national system decision on the electrification of road freight transport – whether grid-bound or stationary – must be made timely to achieve the ambitious and pressing national and European climate protection goals and is ultimately independent of the realisation of European corridors.

Once the national decision on the establishment of large-scale ERS corridors has been made, international agreements on the interconnection of the respective national network elements must be made on this basis. The subject of such agreements is primarily the determination of the technology to be implemented as well as the corresponding transfer points, including the surrounding road sections. Other questions that usually must be clarified in an international treaty are the scope of the project and the implementation periods, the project ownership (if necessary, in a transnational company) as well as questions of financing and risk sharing. Examples of such – technically much more demanding – international treaties can be found in the Brenner Base Tunnel or the fixed Fehmarn Belt rail/road-link. These system decisions and clarifications must also be made in principle in any case. The compulsory European standardisation and harmonisation of ERS, as emanating from the proposal for a new AFIR, can have an accelerating effect here.

Another essential element is the harmonisation of national planning procedures for the establishment of the legal requirements for construction. First, a planning authority must be determined. In Germany, researchers (Boltze et al. 2021; Kryl und Trimpop 2021) and planning authorities involved in the FESH (eHighway.SH 2023), ELISA[5], and eWayBW (ewayBW 2020) pilot projects have so far agreed that the catenary infrastructure, including the utilities and substations, are part of the road on which it is being built. This is evidently also true for other ERS, as the connection with the road is even closer. This would mean that planning, construction and financing would lie with the national authorities responsible for road construction. The extent to which concessionaires for road sections would be affected here depends on the contracts with the authorities. At present, the view of ERS as part of the road is shared by researchers from other Member States to the extent that the question has been dealt with at all. However, it cannot be ruled out that ERS may be viewed from the perspective of energy law, primarily from the point of view of the energy supply network (Hartwig 2016). Since the simultaneous application of the regulation for roads and electricity grids to ERS can lead to significant contradictions, all Member State will either remove ERS from the regulation for roads or for electricity grids. The first could be the chosen variant if a private operator and/or no financing of ERS via the toll is favoured by the Member State. In case only electricity grid regulation applies to ERS it would be the responsibility of the private operators to present a concept with which "their" ERS fit into the road space and the corresponding planning processes. Building on this, ERS could then in turn be included in road planning, but as private infrastructure under different circumstances. Already here a common approach should be taken, either at European level or by treaty between the states participating in a corridor. Differences of opinion at such a fundamental point, would also lead to ERS systems in the areas of planning, accounting, operation and financing that would be difficult to reconcile.

Once there is agreement on the affiliation of the ERS to the road planning area, the sectoral planning must be coordinated. In Germany, this is usually exclusively road planning since the connection of ERS to a medium-voltage grid does not trigger a planning requirement on the grid side. In other Member States, the legal situation is likely to be comparable, so that cross-border coordination will be necessary, primarily between the road planning authorities. If an extensive expansion of the electricity supply grid becomes necessary, especially at the border, additional coordination requirements between the actors in grid operation and planning may be added; however, this should be the exception.

Nevertheless, and as described before, ERS should not be understood as an independent technical solution or alternative. This is of utmost importance especially for the estimation, allocation, and securing of sufficient electric power supplies (including generation and distribution) in the public supply networks. In a full or largely electric road freight system the final outlet in terms of stationary or dynamic charging infrastructures is of lower importance than a clear concept of the overall power demand of the road freight sector and its consequences for the supply networks. Research into that field has begun but would require a further discussion paper on its own.

About a corridor selected for electrification, it is now necessary to investigate and determine which sections of the motorway should be electrified, as continuous electrification is not required for dynamic charging at ERS (Hacker et al. 2020a). The selection of the preferable variant only makes sense

[5] ELISA - eHighway Hesse, https://ehighway.hessen.de/projekt

in conjunction with an overview of the technical implementation together with considerations of the grid connection/supply routes and a cost estimate of the variants derived from this. In Germany, however, all the steps mentioned above are also part of the necessary preliminary planning of the planning procedure, the results of which are summarised in a preliminary planning document of the road authority (Voruntersuchung) (BMVBS 2012). This planning stage also includes the general preliminary environmental impact assessment, which may currently be required to a greater extent under existing legislation for the construction of ERS (Boltze et al. 2021).

Preliminary planning is followed by a planning and approval procedure in all Member States, but this can vary greatly in detail. In general, the negative impact of the motorway on the residents will not be increased by the attachment/installation of ERS, and negative environmental effects from the installation are only to be expected in individual cases. If the selection of variants in the preliminary investigation already avoids a complicated guidance of the ERS (it is always possible to dispense with ERS in tunnels, at exits and entrances, at motorway junctions, etc.), the technical complexity of the planning will also be limited. For this reason, there will often be the option of choosing simplified planning procedures, often without public participation and environmental impact assessment (EIA), and clarifying most essential issues in advance with the authorities and stakeholders to be involved. However, this will not always be the case, and the requirements for a complete planning process with public participation and, if necessary, cross-border EIA can be complex and involve very different requirements in the participating states. Here, too, early coordination and coordination in bilateral agreements appear to be necessary. The requirements for the equipment of motorways, some of which vary greatly from one Member State to another, can pose an additional challenge, especially for technical planning. On the other hand, the already advanced standardisation of some ERS is a positive prerequisite for the cross-border interoperability of ERS.

Finally, the construction phase is also an important joint task of international projects. Starting with the implementation planning, which forms the basis for the Europe-wide tender for the construction work to be awarded, through coordinated construction supervision to the acceptance of construction or commissioning approval, numerous tasks in cross-border projects must be jointly coordinated and harmonized. Nevertheless, the timing of these tasks can be based on the realisation of comparable national projects such as the electrification of railway lines.

Table 4. Planning systems of motorways for Germany, the Netherlands and Austria.

	GERMANY	NETHERLANDS	AUSTRIA
National decision making	Federal Ministry of Transport / German Bundestag	Ministry of Infrastructure and Water Management / Parliament (House of Representatives)	Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology
Central plan	Requirements Act (Bedarfsplan as part of the Fernstraßenausbauge-setz) based on the Federal Transport Infrastructure Plan (BVWP) > parliamentary law	"Structural vision infrastructure and space" (SIVR) as well as "Multi-annual programme Infrastructure, Space and Transport (MIRT) > parliamentary decision	ASFINAG expansion plan
Possible planning agency	Federal motorway company	Ministry of Infrastructure and Water Management	ASFINAG
Corridor/variant/ preliminary investigations	If necessary, spatial planning procedures with EIA and public participation	Structural vision and concept route decree with plan EIA and public participation > parliamentary participation	Preliminary investigation, feasibility, and pre-selection of variants; If applicable, EIA and route determination procedure with public participation
Building permit	If necessary, planning approval procedure with EIA and public participation	Route decree procedure ("Tracébesluiten") with EIA and public participation	Approval procedures and preparatory measures for construction, if necessary incl. EIA with public participation
Possible operator	Federal motorway company (Autobahn GmbH)	?	ASFINAG

The above overview shows the comparison of the planning systems of motorways for the countries Germany, the Netherlands and Austria. The main planning levels, planning procedures and decision-making steps are generally easily comparable, so that even joint cross-border planning procedures can be integrated relatively easily into national planning processes. However, while in Germany and Austria national motorway companies can be considered both as planning agencies and as potential operators, in the Netherlands this is still at the level of the national Ministry of Transport.

6. Synthesis and Perspectives

The market ramp-up of alternatively fueled trucks in European long-distance transport requires the European development of alternative energy supply infrastructure. The TEN-T network provides important guidance given its major importance for European road freight transport. Several European countries that directly border each other have explored the development of a national ERS network in recent years. Sweden and Germany have already tested the technology on public roads. The analyses of national ERS plans conducted here show that, in the long term, the most heavily used routes of the core network are relevant for the development of ERS routes. Thus, there is a high degree of consistency with the route network addressed by the AFIR. From both a bottom-up analysis of the country studies and a top-down analysis of traffic volumes, a relatively consistent picture of a target network and initial expansion corridors emerges. About pan-European decarbonised road freight transport, important expansion corridors can be outlined for different expansion stages. These represent important north-south and east-west connections in European road freight transport and are concentrated in Central Europe.

In an early market phase without a larger ERS network, point-to-point ERS connections between important freight handling points that can already guarantee high utilization are of great importance for development. In this context, the first transnational corridors could be realized at an early stage and take on a "flagship function" in the European context. As already discussed in the second Discussion Paper of the CollERS 2 project (Anderson et al. 2022), the AFIR and the TEN-T network provide the appropriate framework for a European coordination of ERS development. At the same time, national and bi-national initiatives can provide important impetus for technology dissemination and experience from other cross-border transport infrastructure projects (e.g., Brenner Base Tunnel or the fixed Fehmarn Belt rail/road-link) can be built upon. The exemplary analyses carried out in the context of this paper show for first cross-border corridors between Germany and Austria and the Netherlands, which national planning level would be involved for the implementation and would have to coordinate. When selecting cross-border corridors with high traffic volumes, the examples show that with an increasing share of electric trucks, it is possible to operate ERS trucks economically compared to diesel trucks and that the infrastructure costs can be refinanced by the users.

The corridor analyzes discussed in this paper were able to show a consistent target network for ERS and important cross-border corridors that could be realized in several implementation stages. This allowed the discussion of the second CollERS paper to continue and a reference to possible ERS corridors to be established.

For the further development of ERS, the area of tension between a desirable, pan-European coordination of expansion and standardization on the one hand and the incremental further development of technology and infrastructure on the other hand remains. The possibly resulting strategies were earlier discussed in a qualitative manner (Hartwig et al. 2020). The analyzes discussed in this paper attempt to provide more detailed view on these approaches to an expansion strategy with a focus on individual countries and actual transport flows. On the one hand, the derived target network can serve as a background for the European coordination of the ERS expansion. The corridors shown for early implementation and the discussion of the planning aspects in the case of bilateral implementation offer starting points for a less centrally coordinated approach of the ERS network expansion.

Finally, a European ERS extension strategy will need to consider the following aspects in a non linear and mutually interlinked manner:

- Stronger incorporation of ERS and static charging infrastructures in the respective European regulations AFIR and TEN-T framework and their future editions.
- International flagship projects based on joint (technical, economic, organisational) feasibility studies to prove possibilities for seamless integration of national and international activities along selected TEN-T corridors with high truck volumes.
- Continuing efforts in technical standardisation (ERS supply interfaces) and harmonisation of related processes in the respective European institutions, e. g. CENELEC.
- Variety of different deployments for decarbonised road freight services involving stationary and – possibly – different ERS technologies on highways and in shuttle applications focusing primarily on national transport demands.

A joint European approach regarding an integrated ERS core network would have the highest effect in terms of reducing transport related greenhouse gas emissions. Nevertheless, with the current state of observant European regulation and heterogeneous national activities a joint approach is not be expected in the near future. It is even questionable whether such a joint activity should be pushed for, as the related discussions would be very time consuming and may have the effect of even delaying national initiatives. Thus, ERS will likely evolve and mature further as (integral) part of national activities, as outlined in the country profiles. International projects along TEN-T corridors would serve as “flagship projects” enforcing interoperability by limiting technical varieties. Assuming the success of such flagship projects they could stimulate a market driven pull for a joint European approach. This would then ultimately pave the way for a full electric European road freight network that synergistically combines ERS and stationary charging.

7. Acknowledgements

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