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PERSPECTIVE

The possible future of electric road systems in Europe—time to decide and act

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Abstract

Electrification of road transport is crucial to limit global warming. Battery electric vehicles with stationary charging infrastructure have received considerable attention in the scientific literature for both cars and trucks, while dynamic charging via electric road systems (ERS) has received much less attention and their future role in low-carbon road transport is uncertain. Here, we envision three potential scenarios for the future of ERS in European low-carbon transport. We sketch a potential European ERS network and discuss the political, technological, and market steps needed to realize these. We argue that existing field trials, tests, and research projects have collected sufficient evidence to make the next step: Decide and act. Decision-makers will never have perfect information about all aspects of ERS or competing technologies, but the urgency of the climate crisis requires a commitment one way or the other. A clear decision with respect to ERS would send a clear directive and would help focus time, effort, and money on the necessary infrastructure and policies to implement ambitious GHG abatement targets in road transport.

1. Introduction

Electrification of road transport is crucial to limit global warming in accordance with the Paris Agreement (Axsen *et al* 2020, IEA 2023). Among the different technologies for decarbonisation, direct use of electricity is most likely to play the largest role (Plötz *et al* 2022, ITF 2022, Noll *et al* 2022). Battery electric vehicles (BEVs) with stationary charging infrastructure have received considerable attention in the scientific literature for both cars and trucks, while dynamic charging has received much less attention (Shoman *et al* 2022). 'Stationary charging' refers to charging vehicles while parked at charging stations, while 'dynamic charging' refers to charging the vehicle while in motion. So-called Electric Road Systems (ERS) for dynamic charging can rely on either overhead catenary lines or conductive or inductive ground level power supply. ERS is often motivated as technology to decarbonise long distance heavy-duty vehicles (HDVs) which are considered the most challenging segment for direct electrification and where stationary charging faces significant obstacles.

If ERS is to play an important role in road freight transport any time soon, we need to move quickly beyond research and field trials. This paper discusses possible future scenarios for ERS, highlights actions needed, and underscores key choices to be made, and suggests avenues for future research. We argue that a decision about ERS needs to be taken soon to create clarity for industry and society. Without making an explicit choice, some of the scenarios could still manifest but the future would remain uncertain. A lack of coordination also leaves a greater possibility of wasted resources, in terms of money, material, and time, We argue that the most important choices are:

- Should ERS be kept on the table as a viable technology pathway?
- Which criteria should be used to decide on a large-scale rollout of ERS?

- Given public support, where should ERS be built (and how much)?
- Which ERS technology should be chosen?
- How to organise financing and include ERS in regulations?

Stationary charging infrastructure is already included today in several national and supranational policies, e.g. in the Alternative Fuels Infrastructure Regulation (AFIR) in Europe (EC 2023: Regulation (EU) 2023/1804) or the Federal Highway Administration in the US (US Federal Register (2023)). Dynamic charging, on the other hand, has only received scant attention in selected national roadmaps and policies. An International Transport Forum (ITF) study recently addressed this policy discrepancy and suggested that policy should avoid closing the door to ERS and should start targeted studies and further pilot tests to better understand their viability (ITF 2022). A Swedish study concluded that a mix of stationary and dynamic charging could be advantageous (Rogstadius 2022). Passenger cars drive shorter daily distances than HDVs and stationary charging could thus be sufficient to a larger extent. ERS have, however, also been discussed as a potential solution for reducing battery sizes in passenger cars (Shoman *et al* 2022).

Research and tests have demonstrated the feasibility of dynamic charging with ERS (e.g. Haddad *et al* 2019, Konstantinou and Gkritza 2021, Trinko *et al* 2022, Konstantinou *et al* 2023) for the US and for European countries, including Austria (Link *et al* 2023), the Netherlands (Decisio 2022), France (Ministry of Transport 2021), Germany (Wietschel *et al* 2019), Sweden (Trafikverket 2021), and the UK (Nicolaides *et al* 2018, Ainalis *et al* 2020, Department for Transport 2021). In addition, the total cost of ownership (TCO) is expected to be similar for BEV and ERS and significantly lower than for hydrogen (ITF 2022, Noll *et al* 2022, Plötz 2022, Ainalis *et al* 2023, Andersson *et al* 2023). Research results emphasise that ERS can play a role in decarbonizing trucks, but studies also find that planning needs to step up in terms of deployment strategy (e.g. corridor choice), regulation, and choice of technology (Scherrer 2023).

Several key techno-economic aspects are still under development but the many tests and studies have led to the following picture. (1) Standardisation: Several operating versions of ERS exist today and technical specifications are currently being developed on the interaction between pantograph and overhead lines on electrified roads as well as for Current Collectors for ground-level feeding system on road vehicles in operation both for the European Union and internationally (see Andersson *et al* 2022 for more Details). (2) Roll-out times: There are currently little estimate how long a large scale construction of ERS might take. From the engineering side, overhead line solutions benefit from large experience of railroad electrification with no or little fundamental problems (bridges and tunnels are difficult but can be left out in many cases—see Link *et al* 2023 for a case study). As such planning and approval times are important. There are currently little estimates on the time to build ERS but a comparison to railroad electrification indicates that several thousand km of ERS construction will take several years or up to one decade (depending on the network length). (3) Road service: Little changes in general road service operation are expected. Depending on the type of ERS (in road or catenary), large road service vehicles have to avoid contact with the poles. Generally, oversight of the electrical equipment would be a new tasks for road administration and the world road association PIARC has looked deeper into this, see PIARC (2023). (4) ERS Lifetime: similar to railroad infrastructure, ERS lifetime of at least 20–30 years is expected (PIARC 2023). (5) Innovation cycles: For ERS itself, the infrastructure technology is long established for overhead line catenary with no significant innovations expected and used in many environments for in-road ERS (but not many decades). As such, the ERS build today can be expected to be still useful for many years. Further innovation can, however, be expected on the vehicle side, e.g. with the pantograph, but this no problem, as vehicle lifetimes are much shorter than infrastructure lifetimes. (6) Investment and operation costs: Literature estimates of the ERS invests range between EUR 1.1–1.65 million per kilometre and direction (ITF 2022). About 2% of invest are expected as operational costs per year (see Wietschel *et al* 2017). In addition, a first tender in Sweden has shown has the specific bids depend on the details of the technology requirements. In terms of financing, options being discussed are state ownership as part of the road or public private partnerships, see Andersson *et al* (2022).

In the reminder of this piece, we present three potential future scenarios for ERS, sketch a potential European ERS network to initiate the discussion around a potential network, and discuss strategies to choose among different ERS technologies.

2. Three potential scenarios for ERS

Based on the described challenges and potential pathway decisions, we envision three potential scenarios for the future of ERS in low-carbon transport, and discuss the political, technological, and market steps needed to realize these. The scenarios are built on our joint expertise gained over years of involvement in field trials, policy consultancy, infrastructure decision-making, and research within the realm of ERS. The first scenario

Table 1. Outline of three potential scenarios for ERS.

Scenario	ERS Now	ERS Revival	ERS Niche
Description	Rapid and large-scale deployment of ERS along international corridors	Further technical development and standardisation prior to a large-scale roll-out	ERS only in specific niches such as logistics centres, ports, or mines
Advantages	- ERS contributes to rapid transition to low carbon road transport - Smaller batteries in vehicles	- More time to solve remaining issues - More clarity about role of MCS	- Cross-border coordination less necessary - A few specialised vehicles are sufficient
Disadvantages & Challenges	- Selection of technology done under greater uncertainty - Some policymakers and many vehicle manufacturers not convinced - Risk for technological lock-in effects	- Potentially time lost for electrification - A major, but late, ERS expansion might imply an oversupply of MCS and result in stranded MCS assets	- Larger batteries needed in vehicles - More space needed for MCS close to highways - Niches possibly too small for ERS commercialization
Technological steps	- Fast standardisation - Fast technology decision	- Further field trials & improvement of ERS	- Development of MCS - Adaption of ERS for the respective niches
Policy steps	- National and supranational commitments as soon as possible (e.g. inclusion in AFIR revision and national policies with specific roll-out targets) - Fast track funding	- Include in AFIR revision and national BET infrastructure plans	- Continue focus on MCSs

'ERS now' (see table 1 for a summary) envisions a strong political commitment for ERS to play a key role in the decarbonisation of road transport as soon as possible. It is characterised by a joint commitment of many political actors (e.g. EU member states) and a coordinated political action to (1) choose an ERS standard, (2) rapidly build ERSs, and (3) implement accompanying policies to ensure sufficient vehicle model availability. Although this scenario exhibits higher risk (choosing ERS as a technology under uncertainty) it underscores the urgency of meeting current decarbonisation goals. This scenario could see significant opposition from several vehicle manufacturers that currently focus on megawatt charging for BEVs and hydrogen; as such, these actors may be less willing to proactively develop a third infrastructure.

The second scenario 'ERS revival' describes a vision of further testing, research, and development to keep the path for ERS open as a potential future solution. It would allow for more time to work on remaining questions in a stepwise manner over the next 5–10 years (e.g. how to bill users, how to develop different ERS standards, etc). During this time, regulation and policy documents could be developed in order to support a larger roll-out. From a demand perspective, logistics operators may favour having an additional charging alternative for their BEVs—in particular one that does not require a stop. Further, limited availability of truck parking spaces in Europe may entice additional support from vehicle manufacturers. In this scenario ERS would still play a key role in low-carbon road freight, but a delayed introduction, on top of a megawatt charging systems (MCS, i.e. very fast stationary charging) ecosystem, could reduce the cost-effectiveness of an ERS. In addition, starting with MCS implies certain path dependence: an existing MCS network reduces the number of ERS users and makes ERS less cost-efficient.

The third scenario 'ERS Niche' describes a future that lacks a large-scale connected network of ERS. Instead, road transport electrification would be dominated by stationary charging. ERS could, however, play a role in certain niches, such as trucks in transit from mines and ports, or logistic centres. In this case, batteries in LDV and HDV would become larger than they would need to be, relative to other scenarios where ERS plays a larger role. Public policy would rely on MCS for HDVs as well as slower overnight charging for HDVs and different power levels of stationary charging for LDVs. In this case, the ERS network would be much smaller and should match well with traffic in short but fixed relations.

3. What a large ERS network in Europe could look like

An optimal ERS network could either be built on individual road segments with some vehicles only travelling back and forth (as in scenario 'ERS niche'), or along all major highways of a region, country, or continent (as in scenarios 'ERS now' and 'ERS revival'). A local small scale ERS can be built, operated, and used by a limited number of actors without extensive coordination effort. For example, fixed shuttle line trips by trucks on highway corridors can reach up to 1000 trucks per day in Germany (Hacker *et al* 2022), which can be compared to several thousand trucks per day on all major German highways. However, larger social gains can be achieved when ERS is deployed in larger settings, such as regions or countries. But this requires political commitment and investment decisions by regional, national, or super-national governments, which in turn requires coordination about which ERS corridors are most important.

Even in a large-scale roll-out, the entire road network would not be equipped with ERS; rather, the focus would be on major roads that make up about one third of the highway network. Vehicles would use their on-board batteries to travel between destinations that are found off the highway and the ERS network. The design of a larger ERS network is complex as it should be customized to fit a given geography, road network and local HDV traffic. Customization requires that the most important road segments in terms of daily traffic are identified, that these segments are connected to enable long-distance travel, that local stakeholder views are integrated, and that local factors are considered (e.g. bridges, tunnels, energy grid, etc). For the case of Europe, this requires a long and integrated planning process. Such an analysis has been done in several national case studies and results in a typical recommendation of about one third of the highway network to be equipped with ERS. This recommendation results from an optimization of two factors. On the one hand, an infrastructure should be highly used to reduce the costs per users, which implies that only the most highly utilised part of the road or highway network should get ERS. On the other hand, for an infrastructure to be useful to a wider group of users, some broader geographical coverage is needed. The compromise of both is, depending on the specific assumptions in a cost-benefit calculation, around 20%–40%—or roughly one third—of the highway network.

As a first idea and to illustrate a potential outcome, figure 1 shows the main HDV transport corridors in Europe and potential ERS network. The map is based on synthetic road traffic data (Speth *et al* 2022) and highlights in blue the top 30% of European highways in terms of HDV per day. Broad yellow lines suggest a potential European ERS network that covers the main north-south and east-west transport corridors, as well as major ports, and integrates current front runners such as Sweden, France, and Germany. The suggested ERS networks in figure 1 are an illustration to support further discussion, rather than the result of a complex planning process. The total main highway network in Europe encompasses about 100 000 km, while the suggested potential ERS network would cover about 12 000 km.

4. Which choices among different ERS solutions will be necessary?

A choice between the ERS solutions is most relevant for the scenarios of 'ERS now' and 'ERS revival' as they require international connections for a full rollout of the technology. Significant effort has been put into testing the different ERS technologies and discussing on what basis the choice of technology should be made (see PIARC (2023) as well as Andersson *et al* (2023) for overview). Three technologies are available: inductive embedded coils, conductive rail, and conductive overhead catenary lines. Each of these technologies have pros and cons and, naturally, different proponents.

In the past, many shippers changed trucks at the border. This would have made coordinating the choice of ERS technology unnecessary since the consumer argument for choosing the same technology all over Europe disappears. However, this is not the case anymore. From a technological perspective, it is possible to combine several technologies on the same vehicle (relatively minor obstacles for combining inductive with conductive technologies exist, but these are likely to be overcome). The manufacturers see it as unlikely that there will be a business case that includes several different technologies on the same vehicle.

We consequently have a challenge if we want the choice of technology to be coordinated such that:

1. The network effect of ERS is fulfilled: users should be able to make use of the whole system.
2. There is a competitive market for the production of ERS technology, which stimulates innovation.

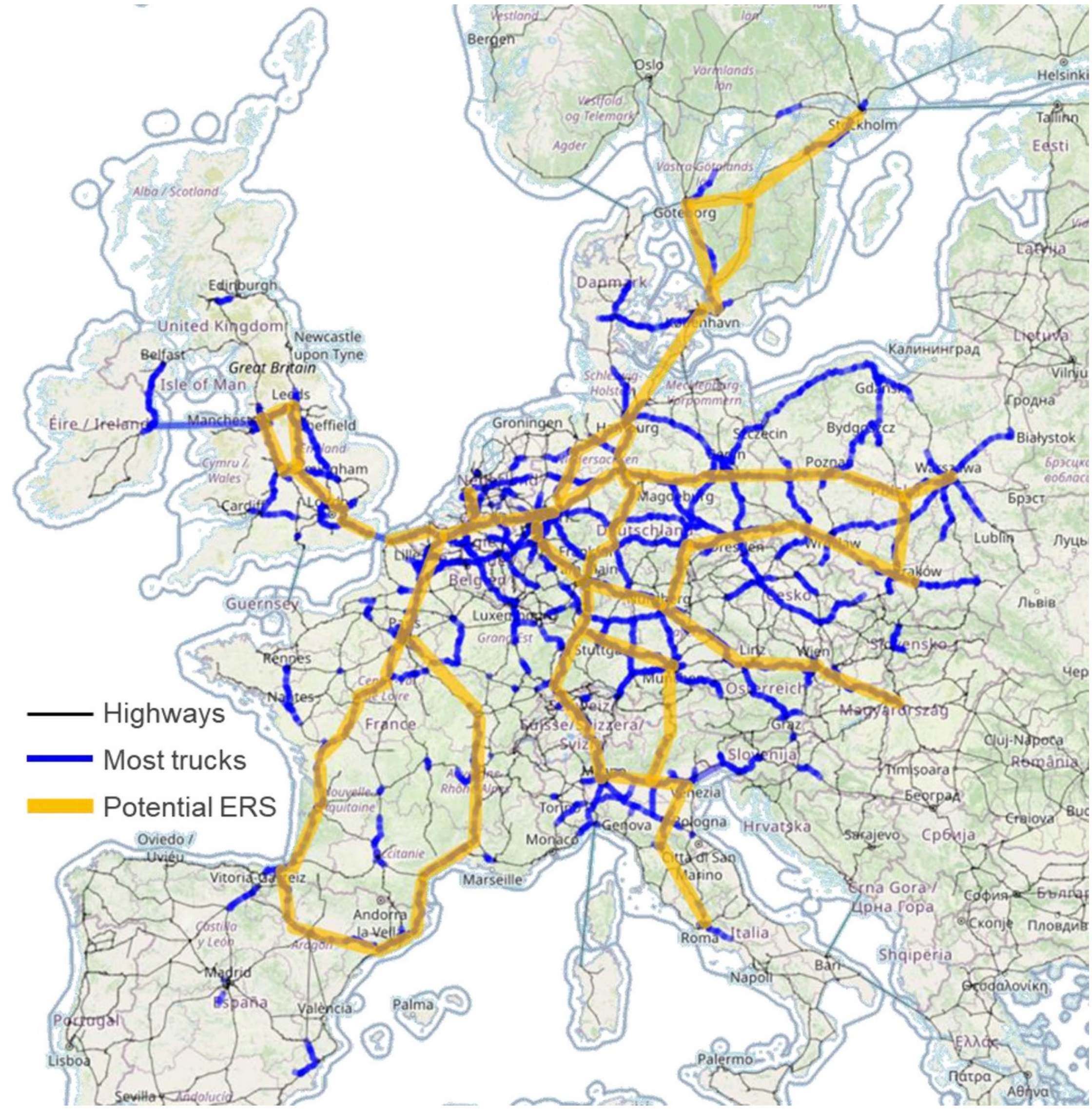

Figure 1. Main HDV transport corridors in Europe, including a potential ERS network that could be relevant for the two scenarios with large scale ERS roll-out. The map shows the main road network (thin black lines) with the most HDV travelled road segments (top 30% in HDV per day) highlighted in thick blue. The overlay in yellow suggests a potential ERS network covering and connecting most important HDV routes. Source: own illustration based on synthetic HDV road transport data from Speth *et al* (2022).

It is important to remember that ERS consists of several subsystems: electricity supply, road, power transfer to vehicles, daily road operation and vehicles. Some of those subsystems may be decided to be the same all over Europe, and some not. This will require more research.

ERS manufacturers focus on developing and rolling out their own product, which suggests that coordination across one or several ERS technologies will have to involve political decision-making. Policy makers have a few options: technology-neutral tendering, stakeholder involvement, or formulating criteria to be met for a decision. In the 'ERS now' scenario, which would have to be initiated before a revision of the AFIR at the EU level, individual countries would have to either make decisions on their own (if they are large enough to trust that others will follow) or coordinate with other countries. In the 'ERS revival' scenario, this coordination could take longer and happen at the EU level through policy revision and standardization processes that already include both government and industry representatives.

5. Financing and regulating

Each of the three potential scenarios imply a different approach for financing and regulation. The scenarios 'ERS now' and 'ERS revival' require large-scale deployment of ERS and, most likely, government intervention in the form of policies that reduce uncertainty for industry. The scenario 'Niche ERS' does not rely on government intervention or support to the same extent. Therefore, the focus below is on the first two scenarios.

Initiatives and incentives for ERS could come from three angles: regional and national governments, supranational entities like the European Union, and the market (private actors). Currently, national governments and private actors are the driving forces but a large-scale deployment of ERS across borders would require active intervention by the EU. If the EU takes up the initiative and offers financial incentives for ERS along the TEN-T, then national governments are likely to begin their roll-out in these areas. If the EU remains passive, national governments are more likely to respond to the interests of local carriers and small-scale solutions.

The EU could prioritise ERS in an AFIR revision by putting it on equal footing with efforts to build out infrastructure for stationary charging and hydrogen. One option would be to count ERS as a replacement for infrastructure targets of other technologies, which would imply a stronger competition between the different infrastructures. AFIR could also point out requirements of ERS along certain routes, as outlined in figure 1 above. Further, the EU could provide funding incentives for the deployment of ERS, as with other infrastructures along the TEN-T. By 2028 the new multiannual financial framework within the EU will be set and the budget and goals of EU's Connecting Europe Facility (CEF) funding instrument will have been negotiated (Council of the European Union 2020). CEF is the EU's funding instrument for completing the TEN-T corridors and today it partially funds the infrastructure for alternative fuels but excludes ERS.

6. Recommendations

Zero emission vehicles powered by ERS have been successfully tested in several countries, but their centralised character requires a clear political decision on their future role in low carbon transport. This role could be larger or smaller. We consider all three scenarios possible future developments based on the existing research and conclude that existing field trials, tests, and research projects have collected sufficient evidence to make the next step: Decide and act. As we have shown in our scenarios, the realization of ERS at a large scale requires fast and concerted action—a path that is much more unlikely without security provided to industry and society from the policy side. If, on the other hand, niche applications are favoured, resources for larger tests could be saved by making a decision early on rather than using this scenario as a fall-back option if other efforts fail. Decision-makers will never have the luxury of perfect information about all aspects of ERS, or competing technologies, but the urgency of the climate crisis argues for decisive and quick action. We urge policy and decision makers to commit one way or the other: choose one of the three potential scenarios described above and send a clear and unambiguous message about what will be supported and why.

We believe that a policy decision or joint public-private decision with respect to one of the three ERS scenarios outlined here would contribute by sending a clearer directive, which in turn would help focus time, effort, and money on the necessary infrastructure and policies to implement ambitious GHG abatement targets in road transport. Given the difficulty of making policy decisions under uncertainty, we urge policy makers to define evaluation criteria for assessing the low-carbon truck infrastructure alternatives—e.g. maturity, costs, scalability & deployment speed, as well as carbon intensity—and to set a time frame for the technological decision (ITF 2023). Technological uncertainty or technology openness can no longer be used as an excuse for inaction. Thus, deciding for some infrastructure now while specifically keeping other options open re-evaluate the decision in a few years.

As is the case for most developing technologies, there are two alternative paths when choosing ERS technology: (1) a passive path that follows a first mover without striving for compatibility and (2) an active path where a decision is made on the European level. Agreeing on a European level might be difficult, but it brings the most benefits for climate and accessibility. This active choice necessitates a transition from evaluating and researching ERS technologies to determining how the choice should be made.

Since ERS requires transnational agreements on corridors, a European discussion about where to build needs to take place. The map in figure 1 suggests a potential ERS network in Europe and could serve as a starting point for this discussion.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.1016/j.dib.2021.107786.

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References

Ainalis D T, Thorne C and Cebon D 2020 Decarbonising the UK's long-haul road freight at minimum economic cost *Technical Report CUED/C-SRF/TR17. Hg. v. SRF* (The Center for Sustainable Road Freight)

Ainalis D, Thorne C and Cebon D 2023 Technoeconomic comparison of an electric road system and hydrogen for decarbonising the UK's long-haul road freight *Res. Trans. Bus. Manage.* **48** 100914

Andersson M, Gather M, Johansson E and Lehmann M 2022 Regulating Electric Road Systems inEurope - How can a deployment of ERS be facilitated? A discussion paper from the CollERS2 project (available at: https://electric-road-systems.eu/e-r-systems-wAssets/docs/publications/CollERS-2-Discussion-paper-2-Regulatory-issues.pdf)

Andersson M, Johansson E, Jöhrens J and Mottschall M 2023 Opportunities for ERS in road freight economics. A discussion paper from the CollERS2 project (CollERS2—Swedish German research collaboration on electric road systems) (available at: https://electric-road-systems.eu/e-rsystems-wAssets/docs/publications/CollERS-2-Discussion-paper-3-Opportunities-for-electric-roadsystems-in-road-freight-economics.pdf)

Axsen J, Plötz P and Wolinetz M 2020 *Nat. Clim. Change* **10** 809–18

Council of the European Union 2020 Council regulation (EU, Euratom) 2020/2093 of 17 December 2020 laying down the multiannual financial framework for the years 2021–2027 *Document 32020R2093* (available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.LI.2020.433.01.0011.01.ENG)

Decisio 2022 *Cost-effectiveness Analysis Electric Road Systems (ERS) for the Netherlands* (Commissioned by the Ministry of Infrastructure and Water Management)

Department for Transport (DfT) (eds) 2021 Decarbonising Transport. A Better, Greener Britain (available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1009448/decarbonising-transport-a-better-greener-britain.pdf)

EC (European Commission) 2023 Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU (available at: https://eur-lex.europa.eu/eli/reg/2023/1804/oj)

Hacker F, Jöhrens J, Speth D and Wallace R 2022 Mögliche Ausbauschritte für eine Oberleitungsinfrastruktur für den Straßengüterverkehr in Deutschland. Eine kriterienbasierte Analyse *Hintergrundpapier im Rahmen des Projekts BOLD (Begleitforschung Oberleitungs-Lkw in Deutschland)* (Öko-Institut, ifeu, Fraunhofer ISI) (available at: www.oeko.de/fileadmin/oekodoc/BOLD-Oberleitungsinfrastruktur-Deutschland.pdf)

Haddad D, Konstantinou T, Prasad A, Hua Z, Aliprantis D, Gkritza K and Pekarek S 2019 Data-driven design and assessment of dynamic wireless charging systems *2019 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW)* (IEEE) pp 59–64

International Energy Agency (IEA) 2023 Global EV outlook (available at: www.iea.org/reports/global-ev-outlook-2023)

ITF 2022 Decarbonising Europe's trucks: how to minimise cost uncertainty *International Transport Forum Policy Papers, No. 107* (OECD Publishing)

ITF 2023 *Supporting the Deployment of Low-Carbon Trucks* Forthcoming (OECD Publishing)

Konstantinou T, Gkartzonikas C and Gkritza K 2023 Public acceptance of electric roadways: the case of Los Angeles, California *Int. J. Sustain. Transp.* **17** 77–101

Konstantinou T and Gkritza K 2021 A multi-criteria decision-making approach for a statewide deployment of dynamic wireless charging for electric vehicles *Adv. Transp. Stud.* **53** 5–22

Link C, Rohrer M, Schopf V, Schwarz M, Lackner B, Koppelhuber F, Medicus E, Scherounigg E and Schimany H-K 2023 EnergyRoads—Dynamisches elektrisches Laden im hochrangigen Straßennetz als Option für die Dekarbonisierung des Schwerverkehrs in Österreich *Endbericht. Wien*

Ministry of Transport 2021 Electric road system. Decarbonizing road freight transport through ERS, issues and strategy WG1 report: interest in solutions and conditions for success *WG 1 of Transport Infrastructure Directorate of the Ministry of Transport*

Nicolaides D, Cebon D and Miles J 2018 Prospects for electrification of road freight (available at: https://api.repository.cam.ac.uk/server/api/core/bitstreams/1d11698f-4050-4781-ba0f-5bd8a5eef8c8/content)

Noll B, Del Val S, Schmidt T S and Steffen B 2022 Analyzing the competitiveness of low-carbon drive-technologies in road-freight: a total cost of ownership analysis in Europe *Appl. Energy* **306** 118079

PIARC 2023 Electric road systems—a route to net zero—technical report (available at: www.piarc.org/en/order-library/42690-en-Electric%20Road%20Systems%20%E2%80%93%20A%20Route%20toNet%20Zero%20-%20Technical%20Report)

Plötz P 2022 Hydrogen technology is unlikely to play a major role in sustainable road transport *Nat. Electron.* **5** 8–10

Rogstadius J 2022 Interaktionseffekter mellan batterielektriska lastbilar, elvägar och statisk laddinfrastruktur (eng. interaction effects between battery electric trucks, electric road systems and static charging infrastructure) *RISE Rapport 2022* p 110

Scherrer A 2023 The end of the road for dynamic charging? Conflicting interests, institutions, and ideas in infrastructure politics for heavy-duty vehicles in Europe *Int. Sustainability Transitions Conf. 2023* (*Utrecht*)

Shoman W, Karlsson S and Yeh S 2022 Benefits of an electric road system for battery electric vehicles *World Electr. Veh. J.* **13** 197

Speth D, Sauter V, Plötz P and Signer T 2022 Synthetic European road freight transport flow data *Data Brief* **40** 107786

Trafikverket 2021 *Regeringsuppdrag—Analysera förutsättningar och planer för en utbyggnad av elvägar* (Publikation) p 13

Trinko D, Horesh N, Zane R, Song Z, Kamineni A, Konstantinou T, Gkritza K, Quinn C, Bradley T H and Quinn J C 2022 Economic feasibility of in-motion wireless power transfer in a high-density traffic corridor *ETransportation* **11** 100154

US Federal Register 2023 National electric vehicle infrastructure standards and requirements. A rule by the federal highway administration on 02/28/2023 (available at: www.federalregister.gov/documents/2023/02/28/2023-03500/national-electric-vehicle-infrastructure-standards-and-requirements)

Wietschel M, Gnann T, Kühn A, Plötz P, Moll C, Speth C and Mader S 2017 Machbarkeitsstudie zur Ermittlung der Potentiale des Hybrid-Oberleitungs-Lkw. Studie im Rahmen der WissenschaftlichenBeratung des BMVI zur Mobilitäts- und Kraftstoffstrategie (available at: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2017/MKS_Machbarkeitsstudie_Hybrid-Oberleitungs_Lkw_Bericht_2017.pdf)

Wietschel M, Gnann T, Plötz P and Doll C 2019 Electric trolley trucks—a techno-economic assessment for Germany *World Electr. Veh. J.* **10** 86