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Summary

Global warming urges the world to largely decrease carbon emissions and be fossil-free by the mid of the century. The transport sector is especially challenging with growing transport demand worldwide, especially for goods transport. Here, one promising solution are overhead catenary trucks (OC-trucks) powered by overhead lines. This technology has been tested and analysed in three field trials and several more research projects within the funding programme Erneuerbar Mobil (engl.: Renewably mobile) by the German Federal Ministry for the Economy and Climate protection. The project BOLD (Begleitforschung Oberleitungs-Lkw in Deutschland, engl.: Accompanying research for overhead catenary trucks in Germany) aimed at bringing the project partners of these research projects together and discuss and challenge their joint findings in expert panels and stakeholder dialogues. Several results have been published earlier (see www.isi.fraunhofer.de/bold), yet this final report contains new and additional findings in from the 3.5 year lasting project phase until April 2023.

The mood in society around catenary trucks remains critical and is influenced by a lack of public information, high perceived costs, comparisons with alternative technologies and problems in the operational phases

For the social acceptance of the OC system, three acceptance dimensions are distinguished: socio-political acceptance (general social climate with regard to the object of acceptance), community acceptance (reactions of those locally affected by the construction of a certain infrastructure) and market acceptance (acceptance of the market actors, i.e. suppliers and demanders, but also intermediaries such as network operators). To analyse the social acceptance of the OC system, the results from the accompanying research in the field trials were compiled along the dimensions of social acceptance and an international literature review as well as a media analysis of German regional and national newspapers on the technology were conducted.

The analyses on *community acceptance* have shown **many reservations towards the technology** as well as towards the field test in local residents and local political actors - this applies in particular to *eWayBW*. In both projects, *eWayBW* and *FESH*, the social acceptance of the technology and the field tests suffered from a low number of trucks visible on the test tracks. Similarly, in both projects, local actors and residents wish for more information about what is happening in the project at the moment. However, when it comes to the acceptance of road users, ELISA studies showed that the infrastructure has hardly any effects on driving behaviour and there are hardly any acceptance barriers in this group. In the early stages of field testing, it can be seen that the construction phase in some field trials was problematic from the point of view of local residents and road users, who feared traffic problems. These fears have not been confirmed in most cases in the operational phase (with the exception of *eWayBW*, where some complained about traffic disruptions during the construction phase) and many respondents reported that the catenary masts have no impact on driving performance.

In terms of *market acceptance,* a **positive attitude** towards catenary trucks and infrastructure **in the energy sector** as a whole can be observed. When it comes to the perspective of the **logistics** sector, at the beginning of the field trials it was noted that non-participating haulage companies had a **wait-and-see attitude** as to how the technology would cope with real-life operations. This attitude did not change over the duration of the field trials. Haulage companies participating in the ELISA project are satisfied with the OC-trucks although the truck operation requires higher attention by the drivers and in some cases there is a higher effort for route planning. From the management's point of view, the OC truck is currently particularly suitable for regional transports. The integration potential changes with the expansion of the overhead line infrastructure.

For the dimension of *socio-political acceptance*, results of the **media analysis** revealed that, compared to the first edition of this media analysis, sentiments have become more polarised. The shares of both **articles reporting positive and negative sentiments have increased**. In the second edition of the media analysis, impacts on traffic and the motivations for the field trials appeared more frequently compared to round 1. Costs for the construction of the infrastructure are frequently discussed as well as comparisons with related technologies and rail - both in the construction and the operational phase. Results from the field tests show

that these comparisons with related technologies also play a role in discussions around the technology. In addition, visual impacts of the technology are discussed in the field trials. A look at the development over time shows that delays in the construction phase sometimes lead to a more critical view of the costs and the technology than at the beginning of the field tests.

International actors wait for Germany's decision while trucks manufacturers currently consider OC-trucks in niches at most

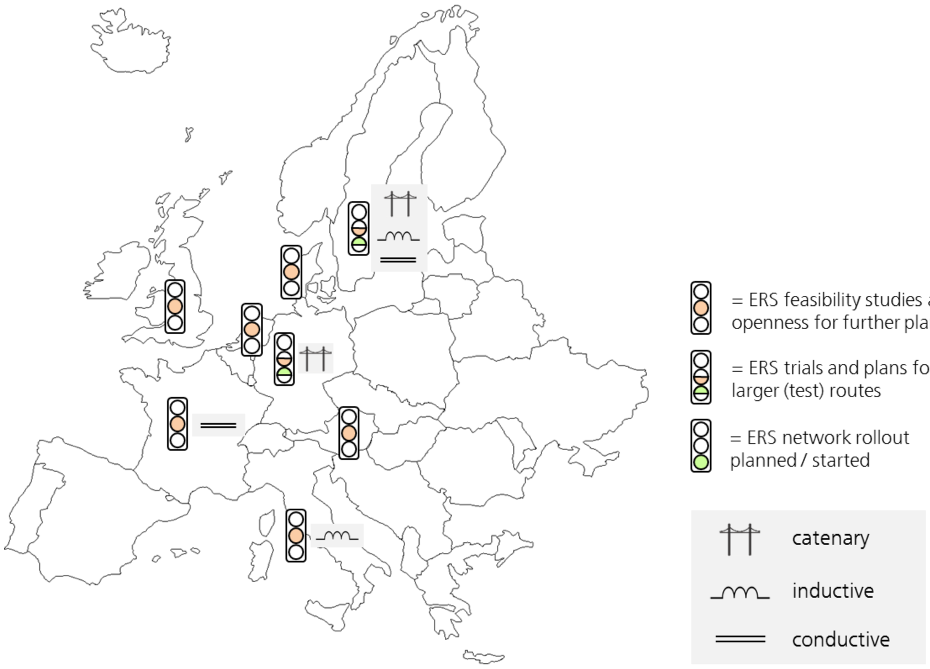
To identify potential social barriers for OC-trucks and ERS in general that go beyond the direct acceptance of the technology, the actor and policy landscape concerned with the technology was analysed. The results show that the actor network in support of ERS in Europe has grown substantially when comparing the period before 2018 and until 2020. However, the growth of the network has only happened in specific actor functions and for different ERS technologies: **interest by multiple European governments**, for example in France, Italy, Austria, and the Netherland has grown in this time frame, including but also for other ERS technologies besides OC-trucks, such as electric rails or in-road inductive coils. Furthermore, more actors have become involved through the local implementation of ERS in the field trials but no additional diversification in the provision of OC-trucks from the vehicle and infrastructure manufacturing side has taken place. This means that the potential implementation and resilience of the system is dependent on the motivations of these few manufacturing actors as bottlenecks in the system. The support of additional countries could support the technology, depending on the degree of heterogeneity in the solutions supported, and was further looked at, as were the perspectives of vehicle manufacturers.

Perspectives of the interviewed vehicle manufacturers proved to be heterogeneous, pointing towards current or potential future support but also indicating barriers to OC-trucks and ERS more generally. While some of the activities superseded the time frame of the analysis, all OEMs have become in some way involved in technology trials on ERS but with different foci and different levels of support, as their individual statements prior or in parallel to these trials show. Publicly, **Daimler Truck has been the most dismissive of OC-trucks**. They have become involved in the field trial project in Baden-Württemberg with a focus on comparing their battery electric truck with the OC truck by Scania. **Scania**, on the other hand, **has been the most positive OEM on ERS** and has provided the vehicles for multiple field trials in Sweden and Germany. They can be expected to be a supporting actor in the potential rollout of an OC truck system across Europe. Nevertheless, their total company strategy shows that their main focus is on battery electric trucks and stationary charging. Other OEMs voiced a neutral to observant stance towards OC-trucks and have become involved to different degrees: Volvo has withdrawn from early involvement, IVECO has engaged in trials with inductive coils, and DAF in a recent development project with OC-trucks. MAN, related to Scania through Traton, and Renault Trucks, as a brand of Volvo Trucks, have not become involved separately and voiced a slightly critical stance towards OC-trucks in the interviews.

The analysis of perspectives in the countries that have actively engaged with ERS so far, provided more detailed insights into the growing actor coalition identified through the actor network analysis. For OC-trucks, the analysis revealed **Germany as a key governmental player** to which second mover countries have looked for orientation. Sweden was also seen as an important role model due to their trial projects for multiple ERS technologies but as a less central decision maker to a potential rollout of an ERS system because of their smaller and less central geographical position. Due to the country's size and growing involvement in ERS technologies, **France** was also considered a pivotal context but with **a potential barrier for OC-trucks** due to their greater focus on electric rails. The self-identified **second mover countries for ERS Austria, Denmark, Great Britain, Italy, and the Netherlands** considered barriers to the technology to not originate from their own countries but to potentially persist in the future if key countries like Germany would not make a clear government commitment towards the technology and if the coordination on ERS across countries would not succeed, i.e., if actors in favour of ERS do not successfully coordinate and push in the same direction. All interviewed countries point out the critical role played by EU decisions for the decarbonisation of trucks and the corresponding infrastructure. At the **EU level** itself, however, interviews show that **ERS have not played a central role in policy discussions**. Many EU policymakers remain uninformed or indifferent about the technology and national policymakers have decided to not lobby for ERS at the EU level at the studied point in time. With the consequential dependence of ERS, specifically OC-trucks, on only one key lobbying industry actor, interests towards stationary charging and hydrogen infrastructure have dominated the discussions and have led to ERS only playing a minor role in a footnote to the most recent AFIR policy.

Overall, the analysis reveals that on the socio-political side, the success of OC-trucks and ERS in general is perceived by involved actors to hinge on few key decisions that mark critical bottlenecks for the future development of the technology. **Decisions about innovation clusters in Germany, the European coordination behind one ERS technology, and policy decisions at the EU level are all seen as key developments deciding the future of the technology.** As much as the technological readiness for a larger rollout, **decisions by industry and policymakers will therefore decide whether an ERS system can succeed** and capitalise on its environmental benefits or whether other infrastructures will be supported instead.

Figure 1: ERS activities in Europe until 2022 and technology focus.



Direct electrification has the best climate balance and OC-trucks the lowest overall environmental impacts.

To make a sound assessment of the potential contribution of OC-trucks towards the mid-term reduction of greenhouse gas emissions, technical, environmental and field test data have been evaluated within the working groups of the BOLD project. For a comprehensive picture, however, also other alternative technologies have been considered in a comparative life-cycle assessment, namely Battery Electric Vehicles (BEVs), Fuel Cell Electric Vehicles (FCEV) and the use of Power-to-Liquid (PtL) fuels. The analysis covers the whole life cycle of the vehicles themselves, from manufacturing and fuel/ electricity production to the use phase (including maintenance) and the end-of-life (including battery recycling). Infrastructure for energy production is included due to the significance for renewable energies (e.g. solar power) for which impacts only originate from infrastructure.

The results show that **direct electric concepts**, whether with stationary charging of batteries or dynamic supply via overhead lines, will provide alternatives for large areas of road freight transport that are technically feasible and whose climate balance is **advantageous even in the short term** within a national framework. Here, OC-BEV have the advantage of direct electricity use combined with a significantly smaller battery compared to BEV-trucks. This not only results in **slightly higher greenhouse gas savings, but also significantly reduces other environmental impacts compared to BEV-trucks**, e.g. acidification and eutrophication. So, while BEV trucks reduce greenhouse gas emissions, but significantly increase other environmental impacts, only minor adverse effects can be attributed to OC-trucks. At least in terms of greenhouse gas savings, the infrastructure for energy transfer (i.e., catenary lines, charging stations) only has a small impact on the total results.

Concepts with **direct use of electricity** should therefore be pursued as a matter of **priority** and only supplemented where their use is limited for technical or economic reasons. Among the concepts with direct use of electricity, **reduction of battery capacity should be a secondary goal** in order to reduce adverse effect in other impact categories.

Infrastructure setup is the main among several actions required for a successful development of OC-trucks

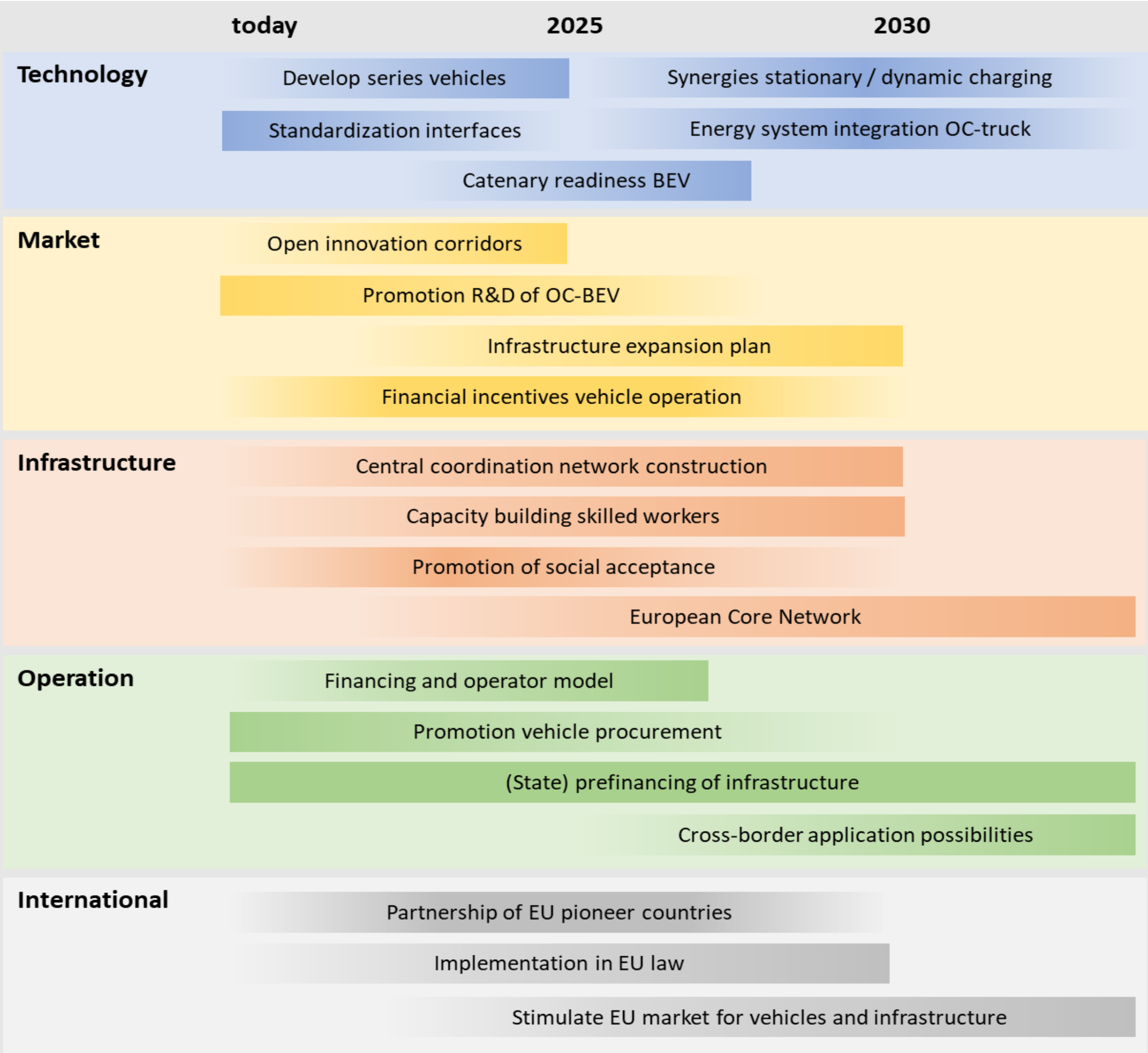
The **construction of an overhead catenary infrastructure** to meet demand is the **key challenge for the use of OC-trucks**. In Europe, a few test tracks of a few kilometres in length are available for testing to date. Economic analyses show that OC-trucks could already be more economical for users than diesel trucks in the next few years. In the network development phase, the infrastructure costs cannot be passed on to the early users, but in the longer term the infrastructure can be refinanced by the users if the network is used to a greater extent.

In **Germany, the target network** is the core network of highways with a length of around **4,000 kilometre**s, which is characterised by particularly high utilisation by trucks and great importance for long-distance road freight traffic. While in the early phase, routes with a high commuting share between important freight handling points are of particular relevance, highways with a high share of long-distance traffic and international connections will gain in importance in the future.

The development of high-performance charging points for **battery-electric long-distance trucks** shows a certain **competition** to the overhead catenary system, but both systems have strengths and weaknesses in different market phases. While **stationary** charging points represent the **more flexible** system, especially in the early market phase, the **overhead catenary** system can, in perspective, reduce the pressure on the construction of charging stations and create synergies through the possibility of **dynamic charging**.

For the **successful further development of the overhead catenary system** and its market ramp-up**, activities in several fields of action are required in the coming years**. The technology of the vehicle and infrastructure must be further developed to series production readiness and the standardisation of central interfaces must be advanced. A market for OC vehicles must be created that includes several manufacturers as producers and meets a demand. To gain broad acceptance among users, an operating model for the overhead catenary infrastructure is required that ensures technically feasible and economically attractive operation of vehicles. Infrastructure expansion beyond pilot trials must be achieved, thus creating planning security for users. European coordination of infrastructure development should be sought at an early stage.

Figure 2: Action required for successful introduction of OC-trucks.



Source: Own illustration (Mottschall et al. 2023).

1 Introduction and aim of the project

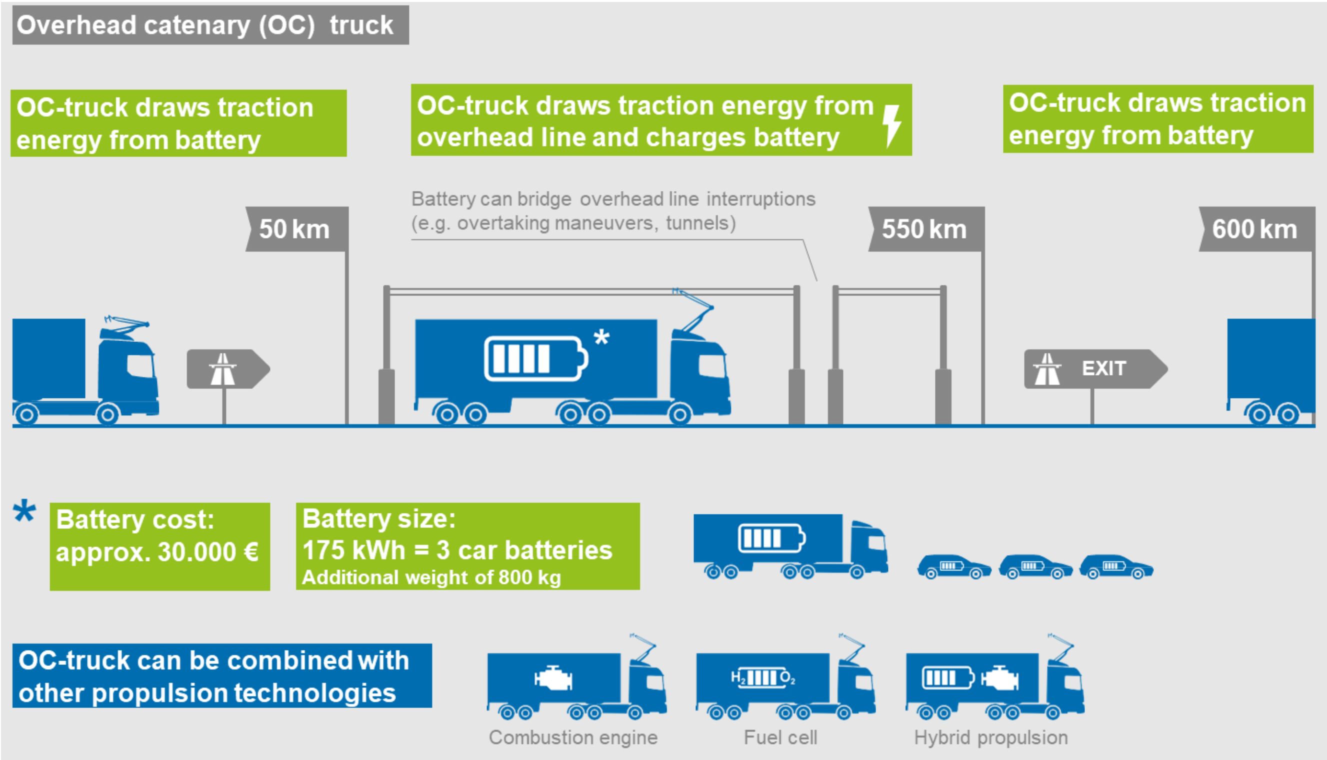
Climate change and global warming are some of the biggest challenges of our times. To reduce global warming, most countries of the world agreed to largely reduce their carbon emissions in the next decades in the Paris Agreement. The transport sector is responsible for almost 25% of global carbon emissions and almost half stems from heavy-duty transport (Rose 2020). While goods transport is still increasing worldwide, several technical solutions are tested for carbon neutrality around the world. Apart from the well-known battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and fuel cell electric vehicles (FCEV), a new technology system is being tested in several countries - the so called electric road systems (ERS).

ERS use electricity for traction that they receive from in-road inductive coils, electric rails or an overhead catenary line. An overhead catenary (OC) truck is a truck that is driven by an electric motor and receives its traction energy from an electric overhead line. When travelling away from the overhead line, two options are possible: Firstly, the overhead catenary truck can carry a battery as an energy storage device, so that journeys of several hundred kilometres without an overhead line are possible. This would be a pure battery vehicle, an OC-BEV. The battery could be recharged both while driving under the overhead line and in a depot. On the other hand, the OC truck could carry an additional combustion engine to provide propulsion on routes without overhead lines. This would be a hybrid overhead line truck (OC-HEV - *hybrid electric vehicle*) analogous to a plug-in hybrid vehicle for passenger cars. Both variants are currently under discussion and are developed by individual truck manufacturers for small-series production. With limited electric range beyond electrified routes, the size and weight of the battery can be severely limited (see Figure 1). In principle, other concepts, such as the fuel cell, are also suitable as a supplementary drive system in the future.

A decisive factor for the use of OC-trucks is the construction of overhead line infrastructure on roads. This would have to be built on a significant scale for the introduction and meaningful use of overhead catenary trucks. To ensure that as many vehicles as possible can use this infrastructure, the overhead contact line should be set up on roads with heavy traffic, i.e. primarily on highways. Of course, this also applies for other infrastructures e.g. hydrogen or static electric charging station as well.

An important advantage of overhead catenary trucks is the high efficiency of the electric drive combined with a central infrastructure that would be highly utilised in the long term. The central challenge of an overhead line system, however, is the necessary construction of the overhead line infrastructure. The high efficiency in operation implies that much less energy needs to be provided for truck traffic compared to today. In addition, the operating costs of electric drives are significantly lower than those of internal combustion engine systems.

Figure 3: Principle of the overhead catenary (OC) truck



Source: (Göckeler et al. 2020a)

In Germany, three pilot projects for with OC truck test tracks have been built and been operated since 2018: the project *ELISA* on A5 close to Frankfurt airport, *FESH* on A1 between the port of Lübeck and Hamburg and *eWayBW* on B462 in the Black Forest close to Rastatt. And many more projects cover different aspects like legal aspects (*AMELIE-RED, ESOB-RKI*), energy provision (*DevKopSys, enERSyn*), the technology (*OL-Lkw, AMELIE-TED, ELONSO*), the market potential in different phases (*StratON, StratES, Roadmap OH-Lkw, My eRoads, CollERS2*) which have been funded first by the Federal Ministry for the Environment and now by the Federal Ministry for the Economy and Climate Protection (BMWK) in the funding programme "Erneuerbar Mobil" (engl.: Renewably mobile, www.erneuerbar-mobil.de).

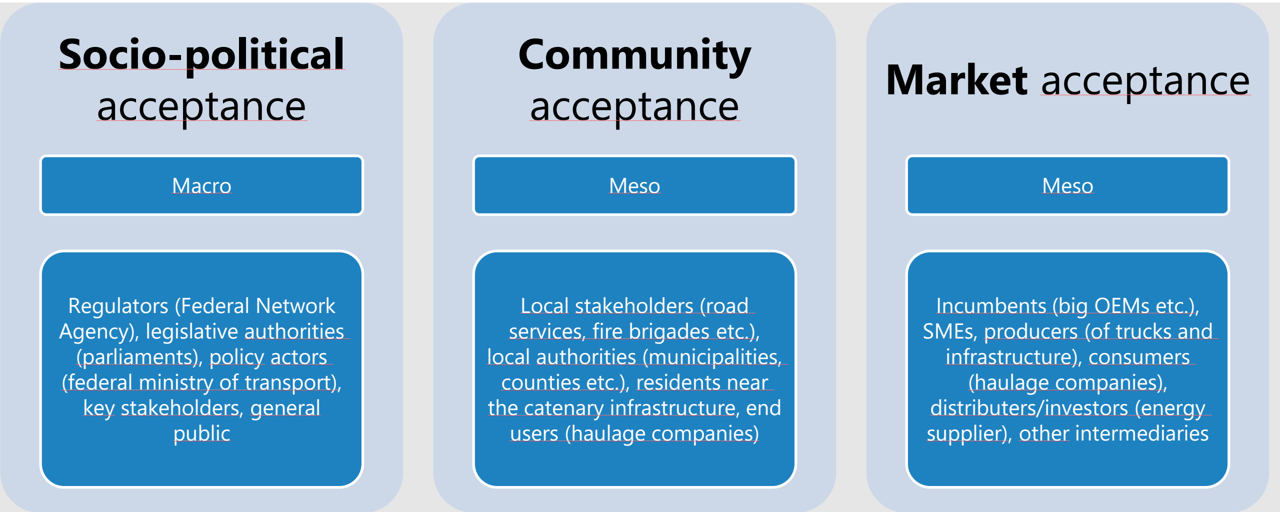
The project *BOLD* (Begleitforschung Oberleitungs-Lkw in Deutschland, engl.: Accompanying research for overhead catenary trucks in Germany) aimed to bring together the different research partners and institutions and to discuss and promote their findings in expert panels and stakeholder meetings. Several results of these workshops and several interim results have been published in policy briefs and background papers, but also in presentations and protocols of the meetings (all available online at: www.isi.fraunhofer.de/bold). In this final report, we summarise these previously published results and present new findings from our research on OC-trucks. The report will follow the work package structure and present results from the analyses on social acceptance of OC-trucks and infrastructure (Section 2), the actor and context analysis (Section 3), the environmental evaluation (Section 4) and the political implications (Section 5). A summary of the report is to be found at the very front.

2 Social acceptance of catenary trucks and infrastructure

This section presents results on the social acceptance of catenary trucks and infrastructure based on analyses in the German field tests and an additional literature and media analysis. The concept of acceptance can be defined as follows: "a favourable or positive response (including attitude, intention, behaviour and - where appropriate - use) relating to a proposed or in situ technology or socio-technical system, by members of a given social unit (country or region, community or town and household, organisation)" (Upham et al. 2015). In this respect, acceptance can manifest itself at different levels (from attitude to behaviour or use), refer to different objects (technology vs. socio-technical system) and manifest itself in different subjects of acceptance (from the individual to households and organisations to populations of a country).

The concept of social acceptance also distinguishes between different acceptance dimensions (Wüstenhagen et al. 2007): socio-political acceptance (general social climate with regard to the object of acceptance), community acceptance (reactions of those locally affected by the construction of a certain infrastructure) and market acceptance (acceptance of the market actors, i.e. suppliers and demanders, but also intermediaries such as network operators). For catenary trucks and infrastructure, the levels (macro, meso, micro) and respective actors are assigned to the different acceptance dimensions (Figure 4).

Figure 4: Social acceptance of catenary trucks and infrastructure (Gordon et al. 2022; Wüstenhagen et al. 2007)



In the following, the results from the accompanying research in the field trials are presented, compiled along the three dimensions of social acceptance. This is followed by a presentation of the additional analyses carried out as part of the BOLD project: an international literature review of scientific articles and grey literature on the social acceptance of catenary trucks and infrastructure and a media analysis of German regional and national newspapers on the technology.

2.1 Results from the accompanying scientific research in the field trials

The three German field trials conduct surveys on social acceptance of the OC system in their respective accompanying scientific research. The results of these studies are compiled and compared for the overall accompanying research as part of BOLD. Interim and project reports of the individual projects and other written material, such as presentations, are used as sources. Table 1 provides an overview of the sources considered for this report as well as the acceptance subjects (persons or groups who have an attitude or stance towards the OC system as an acceptance object) and acceptance dimensions addressed therein.

Table 1: Sources used from the field trials.

Field trial	Type of source	Objective of the study and actors considered	Adressed dimensions of social acceptance	Methods
ELISA	Conference contribution (Wauri and Boltze 2019)	Acceptance of road users	Community acceptance	Survey, n=65
	Journal paper (Hein et al. 2023)	Acceptance of actors in the energy economy	Market acceptance	Survey, n=81
	Presentation (Linke 3/14/2023)	Acceptance of representatives of haulage companies and truck drivers	Market acceptance	Surveys and (group)interviews
	Presentation (Schöpp, Wauri 10/14/2021)	Acceptance of road users	Community acceptance	Survey, n=306
	Presentation (Schöpp, Wauri 10/14/2021)	Behaviour of road users	Community acceptance	Measurement of the driving behaviour of road users before (August 2017) and after infrastructure construction (August 2020)
FESH	Project report (unpublished) (Kryl and Trimpop 2020)	Phase 1[1]: Acceptance of different actors part of or affected by *FESH* project	Socio-political acceptance, community acceptance	Guideline-based interviews, n=15. Target groups: motorway maintenance, emergency service, salvage company, local politics, haulage company, haulage association, nature protection, authority, network operator, police, truck manufacturer, truck driver, fire brigade
		Acceptance of visitors of various events	Socio-political acceptance, community acceptance	Survey, n=29
		Phase 2[2]:	Socio-political acceptance,	Guideline-based interviews, n=18.

[1] Phase 1=infrastructure development.

[2] Phase 2 and 3=operation.

	Project report (unpublished) (Kryl and Trimpop 2020)	Acceptance of different actors part of or affected by *FESH* project	community acceptance	Target groups: motorway maintenance, emergency service, salvage company, local politics, haulage company, haulage association, nature protection, authority, network operator, police, truck manufacturer, truck drivers, fire brigade
		Acceptance of the population	Socio-political acceptance, community acceptance	Online survey, n=121 Target group: respondents not affected by the project (n=22), residents of the field test track (n=34), regular users of the section of the test track (n=75), respondents affected due to other reasons (n=29) (multiple answers possible)
	Project report (unpublished) (Kryl 2023)	Phase 3: Acceptance of different actors part of or affected by *FESH* project	Socio-political acceptance, community acceptance	Guideline-based interviews, n=20. Target groups: motorway maintenance, emergency service, salvage company, local politics, haulage company, haulage association, nature protection, authority, network operator, police, truck manufacturer, truck drivers, fire brigade
eWayBW	Project report (unpublished)	Acceptance of local residents of test track	Socio-political acceptance, community acceptance	Qualitative content analysis of citizen enquiries, n=83
	Interim report (unpublished) (Wietschel et al. 2020)	Acceptance of haulage industry (haulage companies, haulage association),	Market acceptance	(Group-)interviews), n=2
	Interim report (unpublished) (Wietschel et al. 2020) Conference contribution (Scherrer und Burghard 2019)	Media coverage on catenary trucks in Germany	Socio-political acceptance	media analysis, n=74 newspaper articles

	Master's thesis (Breuer 2023)	Acceptance of local residents of technology and test track	Community acceptance, socio-political acceptance*	Focus groups, n=25
	Project meeting presentation (unpublished) (Burghard et al. 9/27/2022)	Acceptance of (local) political actors	Community acceptance, socio-political acceptance*	Guideline-based interviews, n=5

Note: grey: already described in report and policy brief 2020.
* This dimension of acceptance played a subordinate role in the work.

In the following, the collected results from the accompanying research of the three field trials are summarised along the three dimensions of social acceptance: socio-political, community and market acceptance. Only those results that were obtained in the last two years are presented here. For a detailed description of previous project results we refer to Burghard and Scherrer (2020b).

Five key take-aways on social acceptance can be derived from these previous analyses for the time frame 2018-2020.

1. Costs for the construction of the infrastructure are frequently discussed in the construction phase or the start of the operational phase in the three field trials - both in the media coverage and in the field trials.
2. Comparisons are often made with related technologies or reference is made to them. In particular, rail is mentioned here, but also battery-electric trucks.
3. While the environmental impacts of OC systems tend to be portrayed positively in the media, the mood among local actors and in the media in the field trial regions is more critical.
4. The analyses of acceptance in the market show that haulage companies in the field trials accept the technology if the continuation of previous operating procedures and attractive overall operating costs can be guaranteed. Haulage companies that are not yet active in the field trials currently show a rather wait-and-see attitude.
5. A lack of local acceptance can pose a further challenge to the diffusion of the technology. For example, (potential) negative consequences of the technology, such as presumed traffic congestion due to the construction of the infrastructure, are in some cases discussed more intensively in the field test regions than positive effects. In the *eWayBW* project, questions of local acceptance are particularly virulent due to the proximity of the field trial to settlements.

2.1.1 Results from the field trials on socio-political acceptance

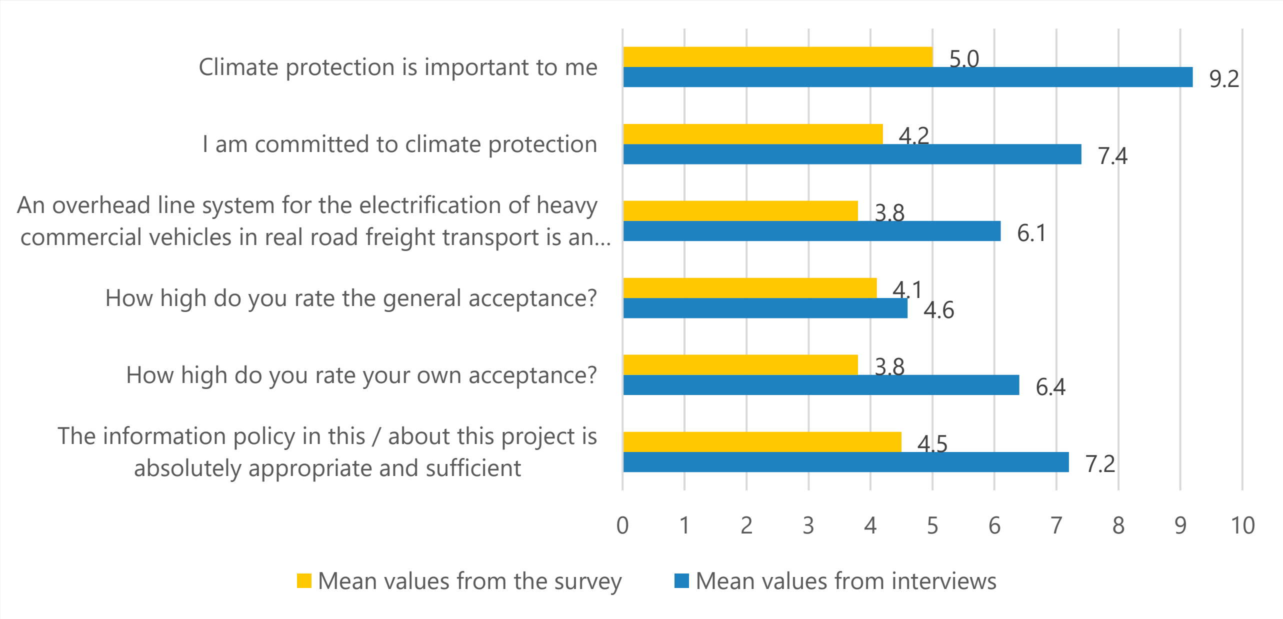
In the online survey in the *FESH* project in phase 2, four groups that differ in terms of how they are affected by the eHighway were identified: respondents not affected by the project, residents of the test track, regular users of the section of the test track and respondents affected due to other reasons. In addition, in phase 2, interviews with actors affected or part of *FESH* were conducted. In the survey and in the interviews, topics of local as well as socio-political acceptance are addressed. In this section, consequently, *FESH* results on socio-political acceptance topics are presented; the next section presents a summary of *FESH* results relating to community acceptance.

In the online survey, 55% of the respondents stated they are positive about the technology, 35% are ambivalent and 10% are negative. In the survey and the interviews, reasons were given for these evaluations. Concerns about costs, never seeing catenary-trucks in regular route use, impacts on residents, preference for rail or H2, dangers and doubts about correct behaviour in case of accidents, international connectivity as well as questioning the purpose of the field trial were given as reasons for rejection and discord. Medium acceptance values were explained by a poor cost-benefit ratio, negative visual effects and negative effects on the local environment, planning security for industry, high burden on roads and their maintenance. Respondents with a high acceptance named a positive evaluation of the accompanying research, opportunities for freight transport companies nearby, positive research results to date and climate protection as reasons for their positive rating.

When it comes to the evaluation of the *FESH* project and overhead line technology in phase 2 of the survey, the values for all items were significantly lower than in phase 1. The lowest values were given for respondents' own acceptance and the perceived importance of the overhead line system. However, it has to be taken into account that participants in phase 1 were recruited at events, some of which had an affinity for technology. Respondents in phase 2 were recruited online, i.e. the survey reached a larger variety of groups.

Comparing the evaluation of the *FESH* project and overhead line technology between the interviews (interviews with actors affected or part of *FESH*) and the survey in phase 2, it can be seen that the mean values in all questions in the survey are significantly lower than in the interviews (Figure 5).

Figure 5: Evaluation of the *FESH* project and overhead line technology: comparison between interview and survey results (Kryl and Trimpop 2020, own translation).



1=does not apply at all/very low; 10=applies fully / very high

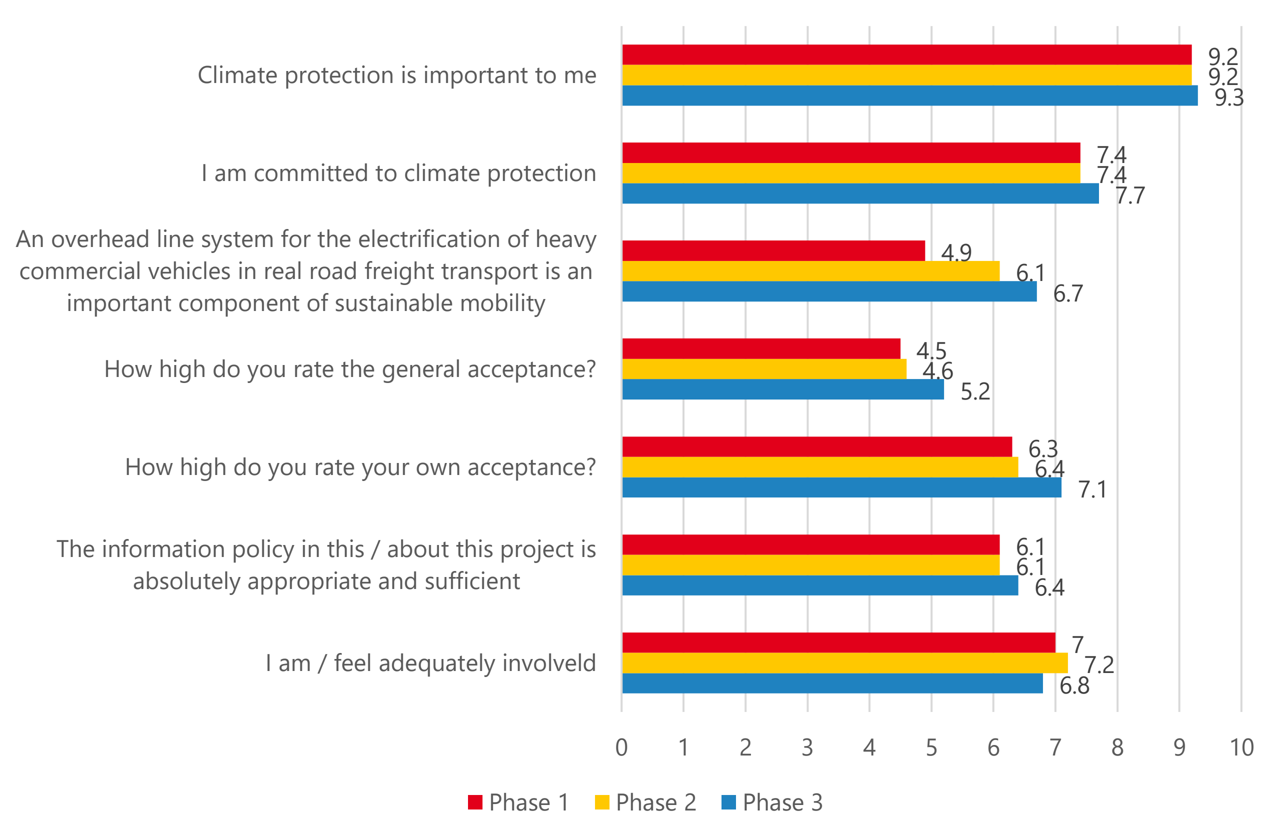
The interviews and the survey also asked about success factors and barriers for overhead catenary technology. The respondents in the survey and the interviewees consider economic efficiency, a sufficient number of catenary trucks and acceptance by the population to be the most important factors for the success of the OC system. As possible reasons for a failure of the OC system, the interviewees and respondents above all mention a lack of economic efficiency, a lack of catenary trucks on the test tracks and a lack of political will.

2.1.2 Results from the field trials on community acceptance

A survey and a monitoring of traffic behaviour of road users in the *ELISA* project reveal no difference in the behaviour between truck and car drivers before and after the construction of the OC (Schöpp, Wauri 10/14/2021). That is, no loss of travel time of heavy vehicles is detected; average distance of light and heavy vehicles as well as average speed of light and heavy vehicles remain unchanged. However, the low number of catenary trucks on the route so far has to be taken into account. The survey found that the OC infrastructure causes fears among some drivers (e.g. legibility of signs, interference with rescue operations). This applies especially for respondents from other regions. On the other hand, almost 50% of the respondents express no fears. The respondents report no adjustment of driving behaviour (e.g. no change in lane changes, safety distance or speed) (Schöpp, Wauri 10/14/2021).

As part of the *FESH* project, interviews with actors affected or part of *FESH* were conducted. The interviews in phase 2 (Kryl and Trimpop 2020) and phase 3 (Kryl 2023) reveal that the attitude towards the overhead line system ("An overhead line system for the electrification of heavy trucks in real road freight transport is an important component of sustainable mobility.") has improved between phases 1, 2 and 3 (Figure 6). The assessments of general and own acceptance ("How high do you rate your own acceptance?", "How high do you rate the general acceptance?") were slightly better on average in phase 3 compared to phases 1 and 2. The interviewed stakeholders assessed their own acceptance of the project as significantly higher than general acceptance (Figure 6).

Figure 6: Acceptance averages from interviews in the *FESH* project (Kryl 2023, own translation).



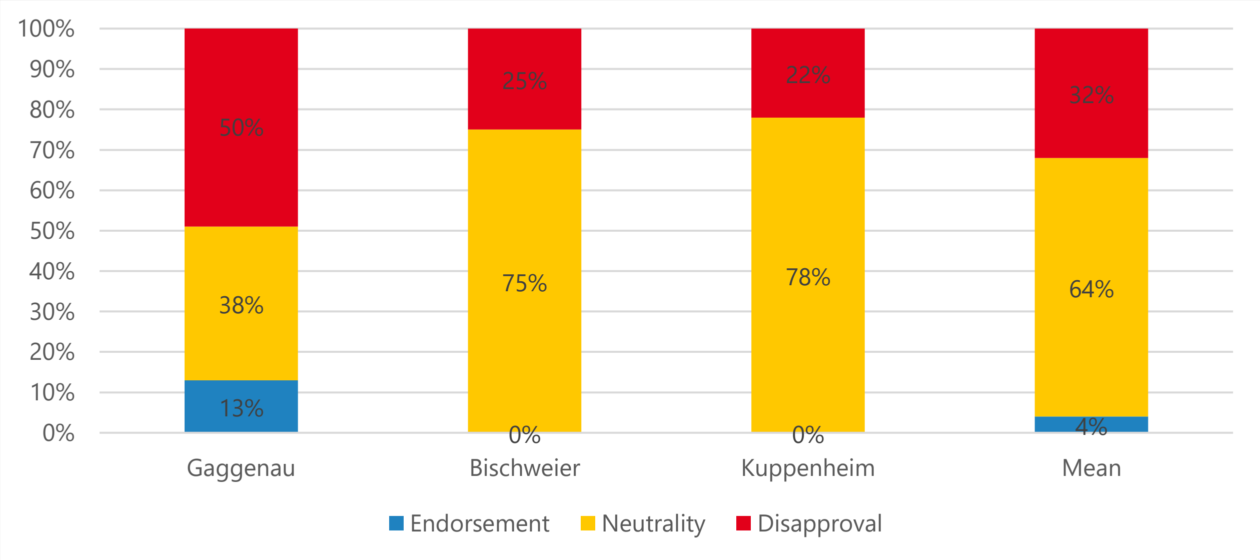
1=does not apply at all/very low; 10=applies fully / very high

Furthermore, in the interviews, the information policy receives medium scores in all phases (Figure 6). That is, the population should be more involved, because many people seem to be very interested in learning more about the technology, also in comparison to alternative technologies. When asked from which sources information about the OC system was obtained, interviewees most frequently cited the local and regional press as well as regional television. Most of them judged the press coverage as neutral and balanced (Kryl 2023). The satisfaction with the progress, however, suffers from the low number of catenary-trucks on the test track and technical problems. The respondents advise to get local politics more on board, e.g. through information evenings, creating better exchange with R&D or with the manufacturer, e.g. regarding maintenance or technology and to inform more quickly about problems at project management level to find solutions and compromises (Kryl and Trimpop 2020).

The *FESH* survey differentiates between different actor groups. When it comes to the evaluation of the *FESH* project and overhead line technology, all acceptance values are in the lower middle range. Motorway users and non-affected people show the lowest, firefighters and residents the highest values for the general evaluation of the catenary system and their own acceptance of the system. When it comes to the evaluation of the information policy in the project, residents and regular users of the electrified road consider the information policy to be less adequate - members of the fire brigade and non-affected people rate the information policy better on average (Kryl and Trimpop 2020).

Focus groups with local residents as part of the *ewayBW* project (in three villages in the immediate vicinity of the field trial) point to a neutral to negative attitude towards the technology and the project (Figure 7).

Figure 7: **Evaluation of the project *eWayBW* and the OC technology (before the start of the focus groups). Note: The *eWayBW* project and the OC technology were assessed identically**



Initially predominantly neutral attitudes developed negatively in the course of the focus groups due to the dynamics of the discussion. Main points of criticism of the technology are the perception of hardly any environmental benefits and little acceptance among stakeholders overall. In addition, it is perceived as outdated, inefficient, prone to failure, not aesthetically pleasing and uneconomical as the following quotes illustrate:

> *„What is this nonsense about old technology? It is an ancient technology, with tram technology actually."*

> *„It's a monstrous hideousness compared to railway catenary masts."*

Main criticisms of the project is a perceived lack of involvement of the local population, high costs, poor planning and project implementation, lack of visibility of truck traffic and an unclear purpose of the project. The following quotes illustrate this opinion:

> *„There is a lack of information, now they drive. [...] You don't see anything, you don't hear anything. The truck probably also has a flat tyre and is parked somewhere."*

> *„I was neutral at the beginning, but today I would say: no. Quite simply because everything that was promised has not happened and there is no end in sight. There were so many mistakes made regarding planning, preparation and construction."*

As can be seen in the last quote, some participants reported that their attitudes had worsened compared to the start of the project (Burghard et al. 9/27/2022; Breuer 2023).

Interviews with (local) political actors in the *eWayBW project* refer to a general disinterest among the population towards the project. As a reason, interviewees point to other topics that have become more virulent in the municipalities in the meantime. However, in terms of the attitude towards the project on the local level, there are different perceptions among interview partners: Representatives of the municipalities perceive a predominantly negative attitude on the local level, i.e. protests among the local population and a lack of support from local politics. Representatives at the state level, however, perceive a mixed local acceptance, i.e. a "loud minority" with a negative attitude, but also many positive voices (Burghard et al. 9/27/2022).

2.1.3 Results from the field trials on market acceptance

An expert survey with actors in the energy economy as part of the *ELISA* project points to an overall positive attitude towards the OC technology in this group. Three quarters of the respondents stated they have a positive attitude towards the technology. In addition, half of the respondents saw catenary trucks and infrastructure as a viable technology for their business field; only a quarter perceived them as not sustainable. A further expansion of the overhead line system in Germany was supported by over 70% of the respondents, only 6.5% were against it. The potential of catenary trucks for sustainable road-based heavy goods transport was rated positively and more positively compared to alternative technologies. However, complex approval processes for the implementation of the overhead line system represented a criticality that needs to be emphasised from the point of view of the respondents (Hein et al. 2023).

A study from the *ELISA project* with surveys and interviews with representatives of haulage companies found that drivers are satisfied with OC-trucks (Linke 3/14/2023). In more detail, the operation of the OC truck requires a higher attention by the driver; however, the use of the pantograph is not perceived as a nuisance. In addition, drivers feel safe during the use of the pantograph. Transport planners in the surveyed companies stated that the effort for route planning has increased or remained the same due to the OC-trucks. Finally, the management showed medium to high satisfaction with the OC-trucks over time. The satisfaction in particular is influenced by the vehicle availability. From the management's point of view, the OC truck is currently particularly suitable for regional transports. The integration potential changes with the expansion of the overhead line infrastructure.

2.2 Literature analysis

A literature review was conducted to identify (scientific) literature (journal publications and grey literature) on the social acceptance of the OC technology. In this task, we explicitly searched for further results on the topic of social acceptance of overhead line technology that do not stem from the German field trials (these are described in section 2.1).

Therefore, an initial research via Google was conducted and keywords for the search were identified (in German and English). Afterwards, we performed a search in Scopus, using the identified keywords, for the years 2021 and 2022 (for a summary of older scientific studies on social acceptance of the OC technology we refer to Burghard & Scherrer, 2020). In addition, Google Scholar was searched with the same keywords in order to identify grey literature. The research was completed at the end of December 2022.

The keywords used are combinations of all technology-related and social science related keywords:

- Technology-related keywords (all search terms were linked with the OR operator):
    - catenary (truck) / Oberleitung
    - OR overhead line

  AND

- Social science related keywords (all search terms were linked with the OR operator):
    - actors / Akteure
    - OR stakeholder
    - OR acceptance / Akzeptanz
    - OR social (science) / sozial (-wissenschaftlich)
    - OR politics/political / Politik/politisch
    - OR law / Gesetz
    - OR rules/regulations/policies / Regeln
    - OR opinion / Meinung

The results of existing studies on social acceptance of catenary trucks and infrastructure are described below.

As part of the StratEs project, Göckeler et al. (2020b) conducted a standardised online survey of 250 companies in 2021 with the aim of analysing the acceptance by users in the logistics industry, e.g. perceived potentials, reservations and necessary framework conditions. Hence, this work can be assigned to the dimension of market acceptance. Results of the survey show that the potential for hydrogen-powered trucks is assessed more positively compared to that of battery-electric and overhead catenary trucks. Central necessities for the use of alternative drives in the transport industry from the user perspective are operational reliability, suitability of the vehicles for the tour requirements and an area-wide energy supply infrastructure. When it comes to purchase decisions, reliability and proven track record of the vehicle models is the most important criterion, followed by total cost of ownership (TCO).

In summary, there is still hardly any empirical research on the acceptance of OC systems apart from research from field trials in Germany. The only scientific publication stems from the UK, in which different factors for the diffusion of inductive charging systems were identified via stakeholder engagement (Gadgil et al. 2022). As this technology is not the focus of BOLD, this study is not summarised here.

2.3 Media analysis

A media analysis was carried out to analyse whether and in what form certain groups of actors take a position on overhead lines with regard to the projects and field trials. For this purpose, articles from German regional and national media dealing with overhead line trucks and infrastructure were systematically collected and evaluated. The media analysis was conducted in two rounds: (1) January 2015 - May 2020 and (2) June 2020 - September 2022. In this section, the focus is on results from the second round. Key results from the first round, however, will be displayed here to draw comparisons. For further information and results on the first round we refer to Burghard and Scherrer (2020).

2.3.1 Method

For the media analysis, we searched newspaper articles via a keyword search in the newspaper database LexisNexis. We considered both regional and national newspapers for the time since the first round of the media analysis was conducted and carried out the analysis in autumn 2022. Regional newspapers not indexed in LexisNexis were contacted and archival research commissioned, as for Badische Neueste Nachrichten, or we gained direct access to the archives via a short-term subscription, as in the case of Lübecker Nachrichten and Hamburger Abendblatt.

2.3.1.1 Data sources

We included articles from the following national newspapers:

- Frankfurter Allgemeine Zeitung incl. online edition
- Süddeutsche Zeitung incl. regional and online editions
- Die WELT incl. WELT am Sonntag
- Handelsblatt incl. online edition
- Die Tageszeitung (taz)
- Die Zeit
- Spiegel incl. online edition
- Bild incl. regional and online editions

Additionally, we included articles from two regional newspapers from each region of the three ERS field trials in Germany (*ewayBW*: Southern Germany, Baden-Württemberg; ELISA: Frankfurt / Rhine-Main region; *FESH*: Northern Germany, near Hamburg)

- *eWayBW*: Badische Neueste Nachrichten and Schwarzwälder Bote
- *ELISA*: Darmstädter Echo and Frankfurter Neue Presse incl. regional and online editions
- *FESH*: Lübecker Nachrichten and Hamburger Abendblatt.

The research was conducted on September 9th and 22nd, 2022 (including articles that were published on or before Sept 6th, 2022) with the following search terms (in German):

- Oberleitungs-Lkw (catenary trucks)
- HO-Lkw (hybrid catenary trucks)
- OH-Lkw (catenary hybrid trucks)
- Hybrid-Lkw (hybrid trucks)
- oberleitungsgebundener Lkw (catenary trucks)
- e-Lkw (electric trucks)
- eHighway (electric highway)

Additionally, we included search terms consisting of the three field trials' project names:

- *eWayBW*
- *ELISA* - Elektrifizierter, innovativer Schwerverkehr auf Autobahnen (electrified, innovative heavy duty traffic on highways)
- *FESH* - Feldversuch eHighway an der BAB A1 in Schleswig-Holstein (field trial electric highway on the federal highway A1 in Schleswig-Holstein)

All search terms were linked with the OR operator.[3]

2.3.2 Data base

We identified a total of 152 relevant newspaper articles. Table 2 displays the distribution of articles across the six regional and eight national media outlets.

Table 2: Number of articles per newspaper.

	Newspaper	**Number of articles**
Regional newspapers	Badische Neueste Nachrichten (BNN)	101
	Schwarzwälder Bote	7
	Lübecker Nachrichten (LN)	3
	Hamburger Abendblatt	13
	Frankfurter Neue Presse	1
	Darmstädter Echo	5
	Total regional	**130**

[3] The research in Schwarzwälder Bote included the search term AND NOT @elkw to exclude all articles referencing the e-mail address of a local church organisation.

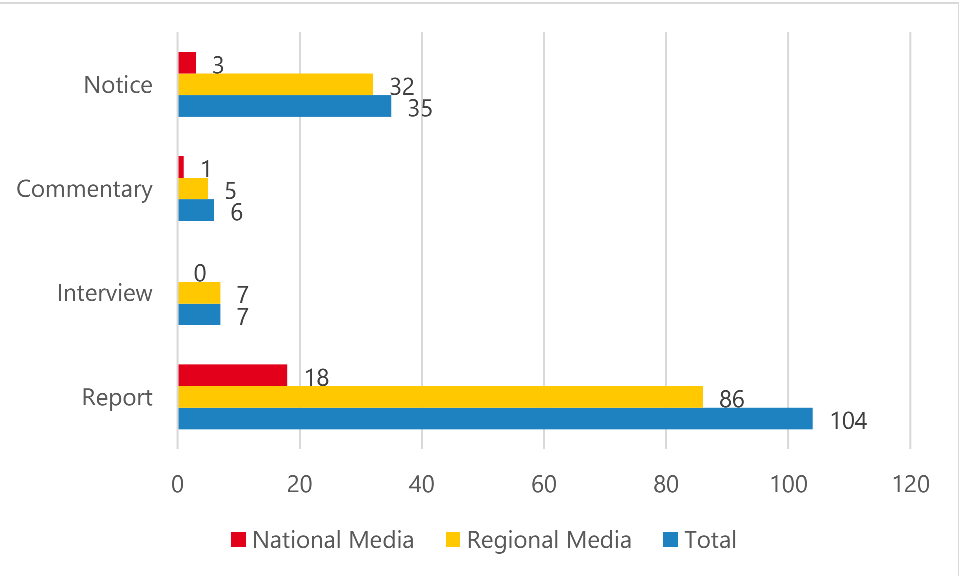
National newspapers	Frankfurter Allgemeine Zeitung (FAZ)	7
	Handelsblatt	4
	BILD	9
	Der Spiegel	0
	Süddeutsche Zeitung (SZ)	1
	Die Tageszeitung (taz)	0
	Die Welt	1
	Die Zeit	0
	Total national	**22**
	Grand total	**152**

Similar to the first edition of this media analysis, regional newspapers reported considerably more often about the three field trials for catenary trucks than the national newspapers. In this round, BNN is especially noteworthy as they published by far the most articles on the topic (101 articles).

Number of articles per article type

Figure 8 displays the different types of articles for regional and national media. The data shows that reports are the most common article type in both regional and national media. Reports contain detailed background information about electric highway systems and the specific field trials. The second-most common article type is the notice, which usually gives updates on the field trials in a very short and concise way, e.g., when there are traffic restrictions due to building or maintenance work. While there were a number of notices published in regional newspapers, only three were published in national media. A total of six commentaries were identified, and regional newspapers published seven interviews during the time considered in this analysis. These two article types played next to no role in national media. This distribution of article types is similar to the distribution in the first round of the media analysis.

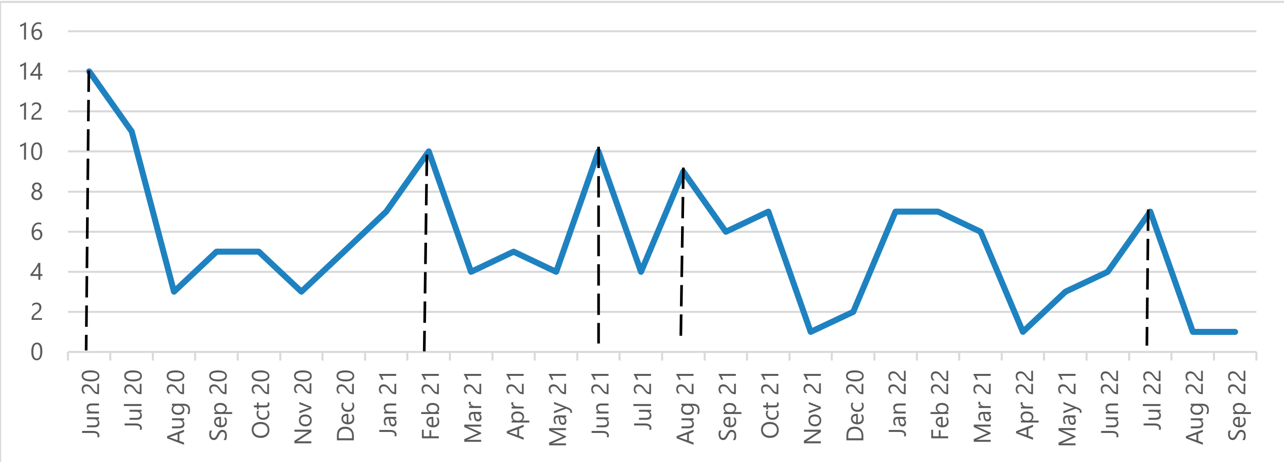
Figure 8: Number of articles per article type.



The analysed articles over time

During the time considered in this analysis (Jun 2020 - Sept 2022), Figure 9 displays a continuous decline in the number of articles per month. The number varies between 14 articles in June 2020 and one article each in November 2021, as well as March, August, and September 2022. A few peaks can be identified. The first peak appears right before the field trial *ELISA* went into full operation, and just before building work started for the field trial *eWayBW*. The second peak in February 2021 is related to increased reporting in the run-up to the election of the Baden-Württemberg regional parliament. During that time, the field trial *eWayBW* was a prominent topic in many parties' campaigns. A third peak can be seen in June 2021, right before *eWayBW*'s system went into operation on June 28th, 2021. A smaller fourth peak in August 2021 is related to the planned extension of the field trial *ELISA*. Lastly, in July 2022, the extension of *ELISA* was yet again a popular topic in the media, as well as the challenges surrounding the field trial *eWayBW*.

Figure 9: Number of articles over time. The dashed lines represent the peaks



2.3.2.1 Data analysis

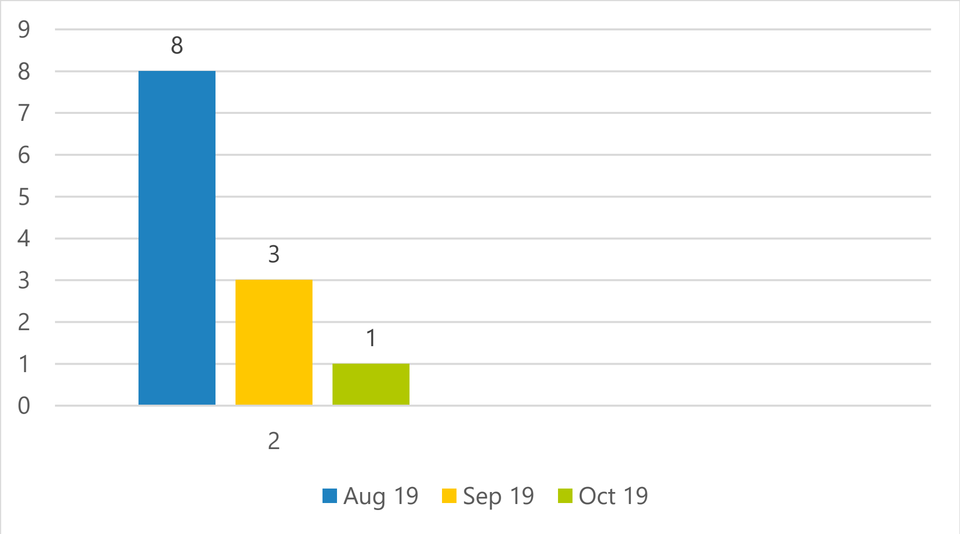
As in the first round, the software MaxQDA was used to analyse the newspaper articles in more detail. The evaluation of the opinions of individual actors as well as the authors in the articles was carried out via a content analysis according to (Mayring 2015). The results are presented at the document level, i.e. it is shown in how many of the newspaper articles a certain code, i.e. a certain topic, occurs.

2.3.3 Results of the media analysis

Sentiments

Compared to the first edition of this media analysis, the sentiments have become more polarised. While 9% of the articles in regional media and 18% of articles in national media reported (rather) negative sentiments in the first edition, this time we observe 23% and 24%, respectively. The share of articles reporting positive sentiments has increased as well. In the first edition, we recorded ten percent each of regional and national articles. This time, as Figure 3 displays, 23% of regional and 14% of national articles report positive sentiments. Consequently, articles with neutral sentiments are slightly less frequent (53% in regional and 64% in national articles) in this edition than in the previous one (82% and 72%, respectively).

Figure 10: Sentiments in the analysed articles (June 2020 – September 2022).



Code frequencies

Figure 11 and Figure 12 display the frequencies of different topics in regional (N=130) and national (N=22) articles. Both figures only display codes with a frequency of ten percent or more.

In the regional articles, topics with a concrete regional reference (e.g., current project status, project and trial descriptions, traffic impacts, motivation for field trials) were most prevalent. Apart from these regionally important topics, the regional articles reported most often about the costs and financing of the infrastructure, alternative technologies, ecological aspects, as well as technology acceptance on different levels. Here, we can see a difference compared to the first edition of the media analysis, when knowledge transfer, ecology and innovativeness / future relevance were the most important topics after costs and financing.

In the national articles, regionally relevant topics only play a minor role, but project and trial descriptions as well as the motivations for conducting the field trials are still relevant topics. Infrastructure costs and financing play an important role in the national articles as well. Additionally, national articles often contain descriptions of electric road systems as a technology, discussions about alternative propulsion technologies such as hydrogen or batteries, as well as a broader perspective on the German ERS field trials with their preliminary results and implications for a nationwide catenary network. Contrary to the first edition of this media analysis, the national articles in this analysis neither report on ecology (the most important topic at the time), nor on the trucks' economic efficiency. Instead, new topics emerged both in the national as well as the regional newspapers, such as preliminary results from the field trials or first descriptions of the plans around so-called innovation clusters with which ERS are envisioned to be scaled throughout Germany.

Figure 11: Frequency of codes in regional newspapers (for codes with frequencies of more than 10%).

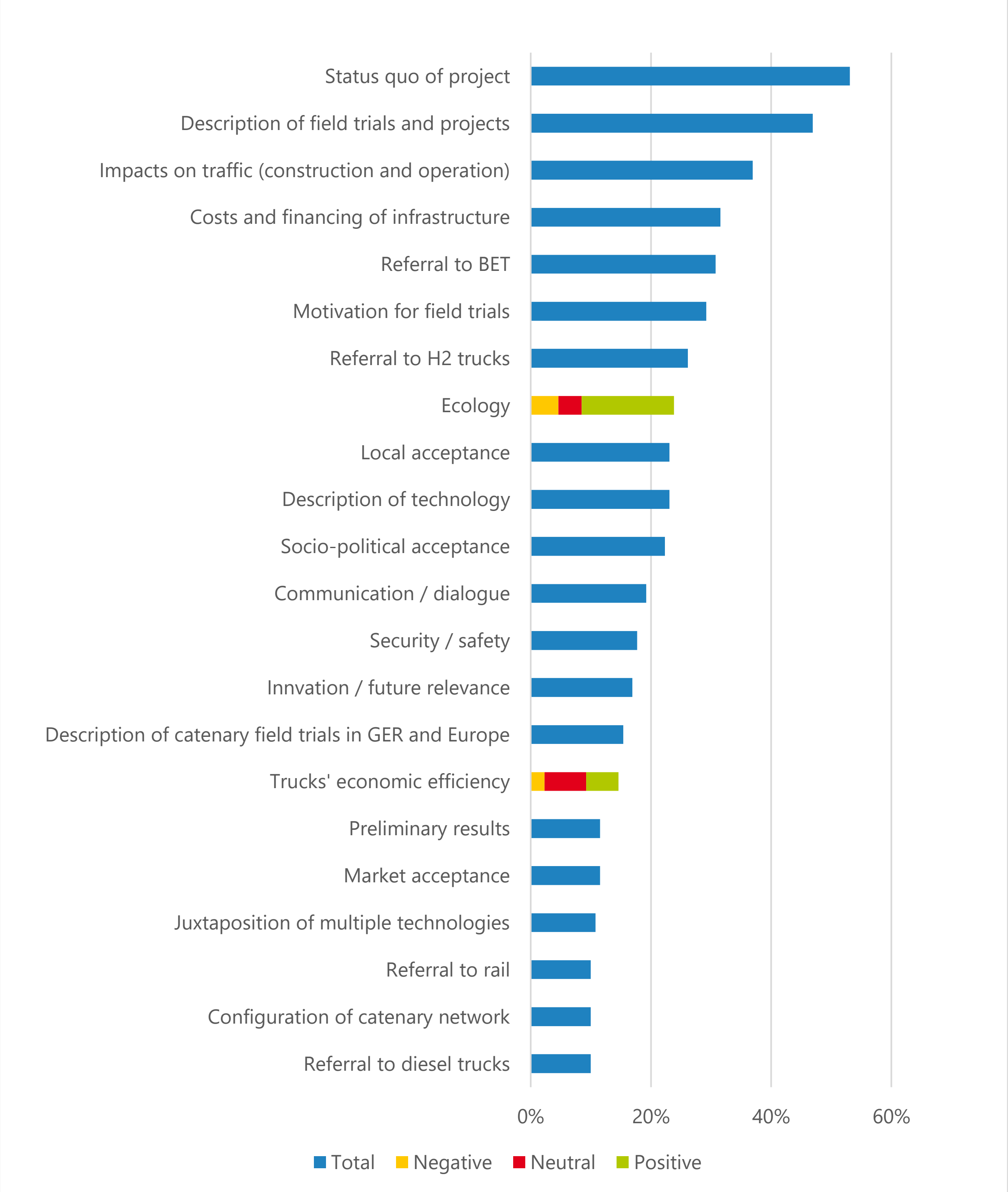


Figure 12: Frequency of codes in national newspapers (for codes with frequencies of more than 10%).

Figure 13: Comparison of code frequencies between round 1 (2020) and round 2 (2022) for codes with frequencies of more than 10% in round 2.

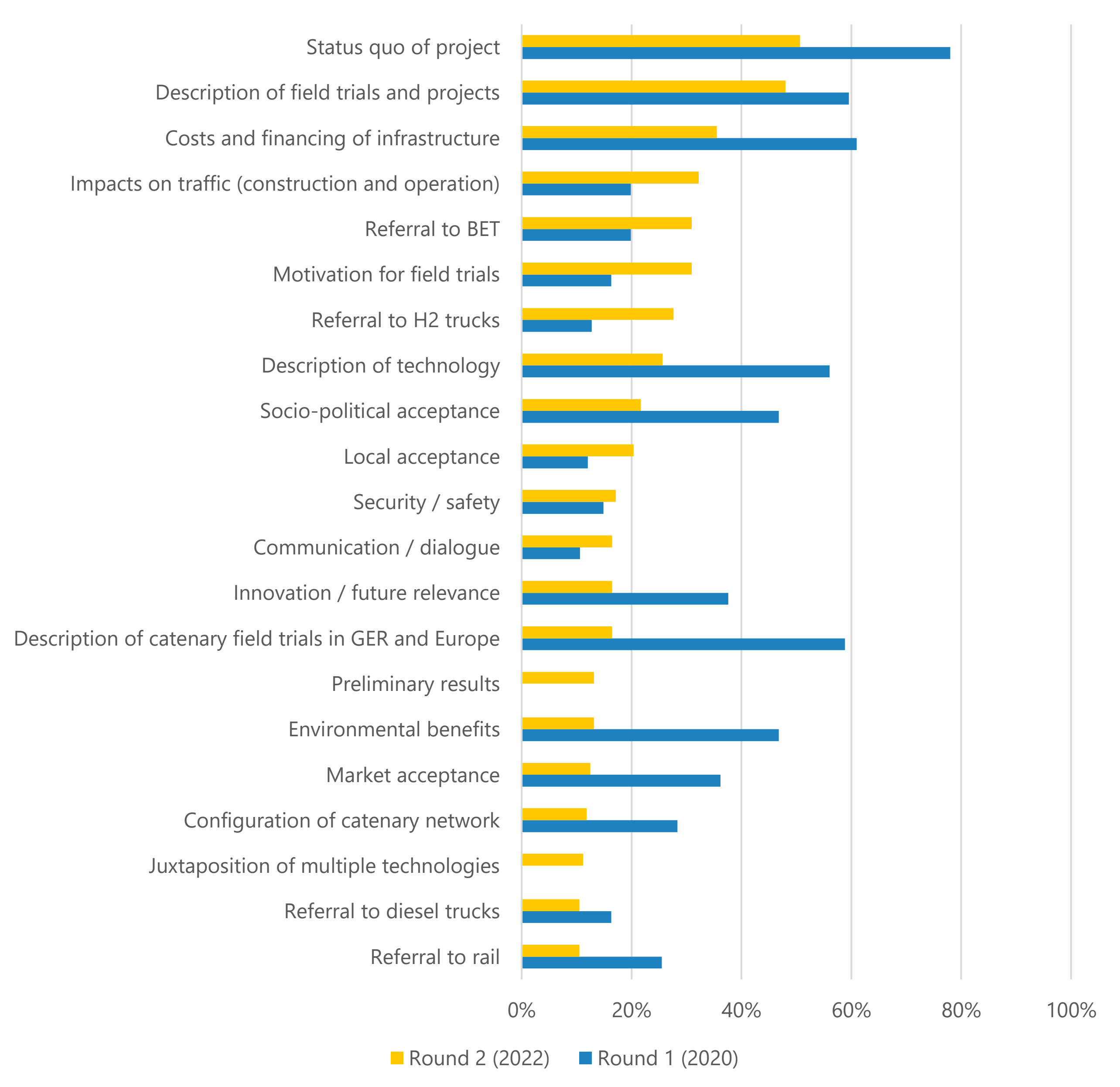


Figure 13 displays the frequencies of codes that appeared in more than ten percent of the analysed articles of round 2 in a comparison between rounds 1 and 2. It can be seen that impacts on traffic, the motivations for the field trials, as well as the referral to H2 trucks and battery-electric vehicles as alternative solutions appeared more frequently in round 2 compared to round 1. Contrarily, project-specific topics such as status quo, costs and financing, and descriptions of the field trials, as well as descriptions of the technology and aspects of acceptance appeared less frequently in round 2 compared to round 1. Similarly, we observe a reduction in referrals to railway technologies and diesel trucks and a simultaneous spike in referrals to other alternative truck technologies, such as battery electric and hydrogen trucks.

2.4 Summary of key results, discussion and further research needs

2.4.1 Key results on social acceptance

A key focus of the social scientific studies in the field trials lies on local acceptance, i.e. most of the studies deal with community acceptance. Socio-political acceptance is often included in studies that mainly focus on local acceptance. This is because the perception of the technology itself and the perception of its implementation on site are often inseparable in practice. The media analysis in BOLD allows to check to what extent the media conveys a certain image of the technology. Less research has been done so far on market acceptance in the field trials, with the exception of research around the project *ELISA*.

Most studies involve people who are affected by or are part of the field trials, such as road users, residents, local political actors or operational stakeholders. An exception is the survey from ELISA, which included stakeholders from the energy sector who are not affected by ELISA.

The analyses on *community acceptance* have shown many reservations towards the technology as well as towards the field test in local residents and local political actors - this applies in particular to *eWayBW*. In both projects, *eWayBW* and *FESH*, the social acceptance of the technology and the field tests suffers from a low number of trucks visible on the test tracks. Similarly, in both projects, local actors and residents wish for more information about what is happening in the project at the moment. However, when it comes to the acceptance of road users, ELISA studies showed that the infrastructure has hardly any effects on driving behaviour and there are hardly any acceptance barriers in this group.

With constantly compiling and comparing results from acceptance studies in the individual field trials and the accompanying research projects, the development of acceptance over the respective project periods can be tracked and compared. In the early stages of field testing it can be seen that the construction phase in some field trials was problematic from the point of view of local residents and road users, who feared traffic problems. These fears have not been confirmed in most cases in the operational phase (with the exception of *eWayBW*, where some complained about traffic disruptions during the construction phase) and many respondents report that the catenary masts have no impact on driving performance.

In terms of *market acceptance*, a positive attitude towards catenary trucks and infrastructure in the energy sector as a whole can be observed. When it comes to the perspective of the logistics sector, at the beginning of the field trials it was noted that non-participating haulage companies had a wait-and-see attitude as to how the technology would cope with real-life operations. This attitude did not change over the duration of the field trials. Haulage companies participating in the ELISA project are satisfied with the OC-trucks although the truck operation requires higher attention by the drivers and in some cases there is a higher effort for route planning. From the management's point of view, the OC truck is currently particularly suitable for regional transports. The integration potential changes with the expansion of the overhead line infrastructure.

For the dimension of *socio-political acceptance*, results of the media analysis revealed that, compared to the first edition of this media analysis, sentiments have become more polarised. The shares of both articles reporting positive and negative sentiments have increased. In the second edition of the media analysis, impacts on traffic and the motivations for the field trials appeared more frequently compared to round 1. Costs for the construction of the infrastructure are frequently discussed as well as comparisons with related technologies and rail - both in the construction and the operational phase. Results from the field tests show that these comparisons with related technologies also play a role in discussions around the technology. In addition, costs of the technology (costs for the set-up of infrastructure as well as economic efficiency) and visual impacts of the technology are discussed in the field trials. A look at the development over time shows that delays in the construction phase sometimes lead to a more critical view of the costs and the technology than at the beginning of the field tests.

2.4.2 Discussion

As became particularly apparent in the focus groups in *eWayBW*, the acceptance of the respective field trial and the acceptance of the OC technology can often not be completely separated from each other. People who are affected by the field trials or who experience them directly form an opinion about the technology through these experiences. Negative evaluations of a certain project can thus eventually lead to a critical evaluation of the entire technology.

Differences can be observed between the three field trials when it comes to social acceptance. That is, in *eWayBW* we note more critical voices from local residents, as the field trial is closer to the settlements than the other two trials. In addition, the test track is located next to a Daimler plant – Daimler has made negative public statements about the technology. This might have affected the reactions of the local residents in a negative way. In *ELISA,* it was possible to survey many road users who drive along the test route in everyday life and thus to obtain comprehensive results on acceptance from the point of view of this group. Both in *FESH* and *eWayBW,* a desire for more public participation becomes apparent; but not in *ELISA*. These differences can be attributed to the different design of the field tests (e.g. motorway vs. federal road, proximity to settlements). On the other hand, they may also be partly due to the different designs of the surveys and studies in the different field tests, i.e. the different studies have different thematic foci (e.g. a focus on the evaluation of public relations work in *eWayBW*) and different methodological approaches (e.g. a more qualitative approach in *eWayBW* versus a more quantitative approach in ELISA and *FESH*). In addition, there may be differences between the field trials with regard to the design of public relations, i.e. how much local stakeholders have been informed about the status of the project.

Discussion foci developed on the basis of the media analysis are used as a content-analytical grid for the individual results on the social acceptance of the OC system. Table 3 summarises central discussion foci covered in the analyses in the field tests and as part of BOLD. Here, the costs of the infrastructure construction are a persistently important topic, both in the media and in the empirical studies in the field trials. This may possibly be due to the high visibility of the infrastructure. The environmental impact and the comparison with alternative technologies as well as the impact on traffic also play an important role in both periods of time - in media as well as in the field trials. This shows that the technology is evaluated from different perspectives - environment, economy and technology.

Other topics that have not changed in importance over time, but which are discussed somewhat less than the topics mentioned above, are the economic efficiency of trucks, social acceptance and citizen participation. This means that information and involvement of the public is important throughout the entire duration of the project.

Issues that have become less important over time in media are security, knowledge building, innovation, noise emissions, health and electricity production. Perhaps the field tests have shown that the technology is safe. In addition, over the long project durations, innovativeness and knowledge gain play a minor role. Noise emissions possibly have not been shown to play a major role.

Table 3: Central discussion foci in the results on the social acceptance of the OC system

Central discussion foci		
	2018-2020	**2020-2022**
Environmental impact	MA ++, *eWayBW*, *FESH*	MA +, *eWayBW*, *FESH*
Cost of the overhead network	MA ++, *eWayBW*	MA ++, *eWayBW*, *FESH*
Security	MA +, *ELISA*	MA 0, ELISA, *eWayBW*
Competing / related technologies	MA +, *eWayBW*	MA ++, *eWayBW*, *FESH*
Knowledge building	MA ++	MA -

Innovation/future relevance	MA ++	MA 0
Impacts on traffic	MA +, *eWayBW*	MA ++, *eWayBW*
Economic efficiency of trucks	MA 0, *eWayBW*	MA 0, *eWayBW*
Noise emissions	MA +	MA 0
Design of overhead network	MA ++	MA +
Health	MA 0	MA -
Electricity production	MA +	MA 0
Citizen participation	MA 0, *eWayBW*, *FESH*	MA 0, *eWayBW*, *FESH*
Social acceptance	MA +	MA +

MA = Media analysis:
MA ++ Among five most discussed topics
MA + Among ten most discussed topics
MA 0 Not among ten most discussed topics
MA - not discussed
Results of field trials: The field trials in which this topic is critically discussed are listed here.
Note: Results of field trials cannot be fully compared with each other, as they use different target groups and methodological approaches.

2.4.3 Research gaps and further research needs

The field trials have been relatively comprehensive in investigating different stakeholders and their acceptance of catenary trucks and infrastructure. The BOLD media analysis additionally allows to trace the image of the technology that is conveyed in the media. This means that the acceptance research on OC technology is already covering multiple actor groups and acceptance dimensions and that there is little need for further research.

An additional acceptance survey that includes actors involved in all three field trials and using the same methodology would allow direct comparisons between the field trials in terms of social acceptance. This would allow to work out the effects of the different designs of the field trials on social acceptance.

In order to get a more comprehensive view of the acceptance of the general population or car drivers, a nationwide survey could be conducted. Descriptive texts and visualisations could be used to familiarise the respondents with the technology.

2.5 Recommendations for the design of further overhead line infrastructure projects

Based on the results from the field tests and the media and literature analysis, recommendations are derived for each acceptance dimension and/or for specific groups of actors. Some recommendations have been developed in the policy brief und related background paper published in the first year of BOLD (Burghard and Scherrer 2020b). These recommendations are taken up here again and mirrored with current findings.

In the *socio-political acceptance* dimension, we recommend to politicians and the media to develop positive narratives for the technology in order to counter acceptance reservations in the general population and to achieve a better image in society as a whole. The comparisons between OC and similar technologies, such as rail transport, must be addressed in communication. The parallel funding of rail with separate funding pots as well as the comparatively moderate costs of catenary infrastructure in relation to the total budget for road construction represent only two examples here. One possible solution can be a clear common narrative that differentiates catenary trucks from visually similar technologies and makes the systemic advantages easily accessible. In addition, it is important to make the strategy for promoting future freight transport modes transparent to the public (Kryl and Trimpop 2020).

For the dimension of *market acceptance*, we recommend that haulage companies provide trainings for drivers and adapt operating procedures when using route-specific catenary trucks. Political instruments should provide planning security, so that technology development and marketing are supported by more companies in the future. One way of doing this is to integrate the technology into funding measures beyond field trials and into overarching strategies for road freight transport. A recent example is the "Overall Concept for Climate-Friendly Commercial Vehicles" (2020) by the German Ministry for Digital and Transport (Federal Ministry of Transport and Digital Infrastructure 2020).

With regard to *local acceptance*, recommendations relating to the implementation of the technology on-site are derived. That is, the following recommendations are aimed at project managers who are responsible for the construction of overhead line infrastructure as well as professionals responsible for the operation of the system. In addition, the recommendations are directed at those responsible for press and communication in the projects. Communication and public participation in the field trials should specifically address important reservations of local stakeholders. Positive (local) environmental effects and reduced noise emissions must be communicated more strongly so that this important advantage of the technology can be played out. Furthermore, it is essential to inform the public about important steps in the project at an early stage and on a regular basis. Because there is little experience with public participation measures due to the novelty of the technology, experience from related projects, such as wind turbines, could be used and the public relations work could be evaluated cyclically and adapted if necessary. Finally, the visibility of catenary trucks on the routes should also be increased so that road users can see that the technology works (Kryl and Trimpop 2020).

3 Actor perspectives on catenary truck systems

This work package set out to characterise the actor system around catenary trucks and overhead lines in Germany and beyond. Both an overarching view at the actor system as a whole (Section 3.1) as well as individual perspectives of different actors (Section 3.2) formed part of the analysis. The acquired knowledge from both parts of the analysis is laid out in the following.

3.1 Actor and context analysis

3.1.1 Actor system analysis

To analyse the actor system around catenary trucks and overhead lines, a comparative assessment of the developments over time is most informative. As one key process for the successful development of technological innovation systems (TIS), the literature on this framework puts forward growing supportive actor coalitions as a direct connection or enabler for the legitimation of a technological innovation (Scherrer et al. 2020). Additionally, a systematic view at actor networks can provide information on strong and weak links and the overall connectedness between the actors active around catenary trucks and overhead lines. For this reason, a media and publication analysis was carried out to identify the relevant actors on OC, their characteristics (actor analysis), and their relationships (actor network analysis).

The results presented in the earlier working paper on actors and acceptance published in BOLD (Burghard and Scherrer 2020a, 2020b) show two key take-aways from the actor (network) analysis for the time frame until 2020: The actor analyses show that the number of actors in the R&D and industry sectors in particular has grown significantly when comparing the periods 2013 - 03/2018 and 04/2018 - 2020. Especially in sales and operations, as well as in freight forwarding and in the trade/industry category, additional actors have been identified. On the production side, i.e., vehicle manufacturing and infrastructure, there has been little change. This reflects the current situation, which is mainly focused on field trials in Germany.

The actor network has become denser in the period under consideration and actors are more directly connected. This growth can be explained, among other things, by the field trials that started in Germany in the second observation period. The start of the field trials adds actors to the network who are involved or affected locally in the construction and operation of the facilities as well as in other functions. The increased density of the network can be explained by the fact that actors who were identified for individual projects in the old network (2013-2018) have since collaborated and communicated in new formats. New formats were, for example, the more well-attended ERS conferences, regular networking meetings between the German research projects on OC systems, and a workshop with interested actors from different countries bordering Germany. The workshop and the conferences also explain the increasing internationalisation of the network.

3.1.2 Context analysis

The context of the actor system was captured by summarising the relevant policies for catenary trucks and overhead lines. This analysis served as an input for the more detailed stakeholder interviews and therefore remains focused on the developments before 2021. Some of these aspects may have changed up to now, yet the section serves to understand the status quo during the interviews.

3.1.2.1 Goal and methodology

The aim of the context analysis was to summarise the political and legal framework conditions surrounding catenary trucks in Germany. It was based on three interviews conducted in November and December 2020 with project representatives of *eWayBW*[4], ELISA[5] and AMELIE[6]. The results were supplemented by existing work and internet research. This section first summarises the supporting framework conditions and then discusses the identified challenges.

3.1.2.2 Enabling political and legal framework conditions

The motivation for the introduction of overhead catenary electric trucks (OC-trucks) is mainly driven by global and national climate protection targets. In the Paris Climate Agreement, the international community committed to achieving substantial decarbonisation of their economies by 2050. The German government aims to achieve greenhouse gas neutrality by 2045. For the transport sector, this means reducing greenhouse gas emissions to almost zero. This goal cannot be achieved by improving the efficiency of existing technologies alone, and OC-trucks offer an option with particularly efficient use of electricity and great potential for reducing greenhouse gas emissions.

These long-term climate protection targets are followed by more specific short-term targets until 2030, such as -55% total emissions at EU level and at least -48% of transport emissions in Germany. These require the timely introduction of alternative technologies in heavy goods transport. The national climate protection framework derived from these goals (e.g. climate protection programme, climate protection law) is therefore the central political driver of OC-trucks. These objectives are operationalised by law on two main levels:

- On the EU level, the CO_2 emission performance standards for new heavy-duty vehicles (EU) can be considered a central measure for reducing greenhouse gas emissions from road freight transport and thus a concrete legal driver for OC-trucks. Compared to 2019, the emissions of newly registered commercial vehicles are to be decrease by 15% by 2025 and by 30% by 2030[7]. Zero-emission vehicles can be counted multiple times towards the fleet average, up to a certain limit, which significantly increases the incentive for introducing electric trucks. As part of the CO_2 standard, the maximum weight for zero-emission vehicles has also been increased by up to 2 tons by EU Directive 2015/719 to compensate for potential payload disadvantages of trucks with large batteries. Furthermore, on the European level, the emissions legislation (Euro standards), the Clean Vehicles Directive with requirements for the share of zero-emission vehicles in public procurement, and the Renewable Energy Directive all promote the introduction of catenary trucks and other alternative technologies. The Directive on the Deployment of Alternative Fuels Infrastructure (AFID) as well as the draft Regulation on the Deployment of Alternative Fuels Infrastructure (AFIR) address infrastructure for alternative technologies such as battery-electric, natural gas, and hydrogen vehicles, but not yet for overhead-line trucks.
- At national level, various funding instruments are in force for trucks with alternative drive systems. For example, electric trucks in Germany are initially exempt from the truck toll for an unlimited period of time (BMVI 2020a). In addition, since August 2021, there has been a subsidy of 80% of the additional investment costs for heavy battery-electric, fuel cell, and overhead-line trucks. Furthermore, purely electric commercial vehicles, as well as passenger cars, are exempt from motor vehicle tax for up to 10 years[8] (Customs online 2020). According to the economic stimulus package for new registrations adopted by the German government in June 2020, the exemption is to be granted until 2025 (Bundesregierung 2020). In principle, OC-trucks could also profit from the above-mentioned benefits.

The political framework conditions at national level were also influenced, including the National Platform Future of Mobility. At the municipal level, there are also occasional temporary access restrictions for internal

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4 https://ewaybw.de/de/ewaybw/

5 https://www.mobileshessen2030.de/elisa

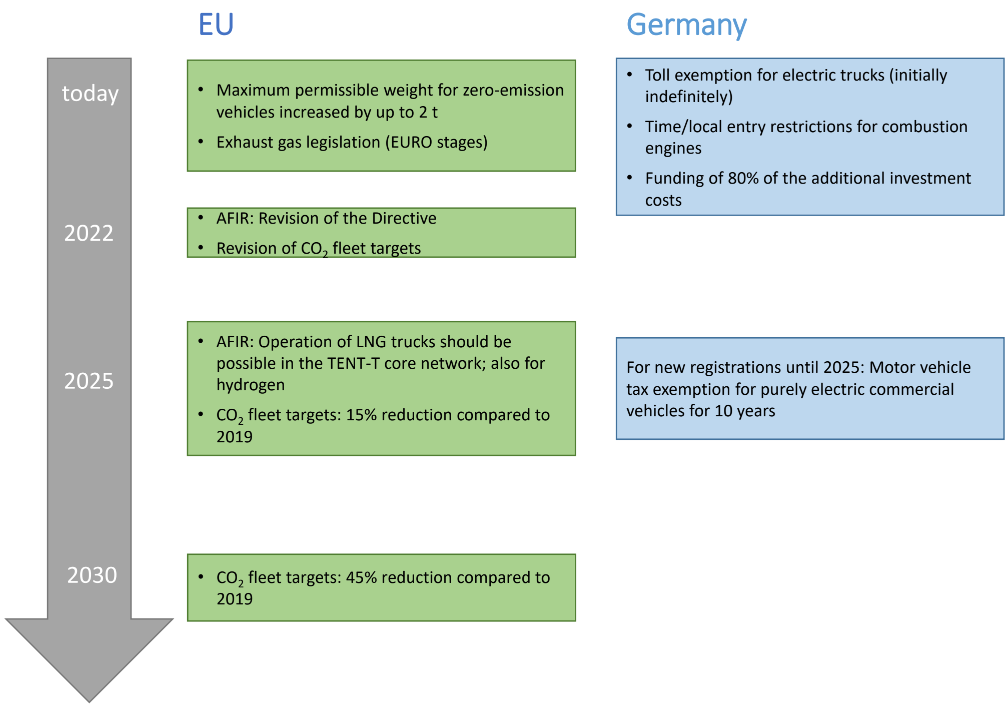
6 https://www.ikem.de/projekt/amelie/

7 In February 2023, a proposal for a more ambitious approach was published by the EU Commission. The proposal includes an expansion to other vehicle categories and a stronger reduction of fleet limits. By 2030, emissions should be reduced by 45% instead of 30%. Additionally, the proposal includes targets for 2035 (-65%) and 2040 (-90%). https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_763

8 https://www.klimafreundliche-nutzfahrzeuge.de/wp-content/uploads/2021/08/Foerderrichtlinie.pdf

combustion engine commercial vehicles, mainly for noise protection reasons. These local restrictions could provide significant incentives for the use of electric trucks and also benefit the use of pure electric OC-trucks.

Figure 14: Overview of selected regulations for catenary trucks



3.1.2.3 Political and legal challenges

Besides supportive framework conditions, a number of challenges and gaps in regulation could be identified. At the European level, there has been a lack of coordination of infrastructure development. In principle, a coordinated approach is provided in Directive 2014/94/EU (Development of Alternative Fuels Infrastructure - AFID), which is intended to standardise and accelerate infrastructure development across the EU. It obliges the member states to set national expansion targets in a so-called National Strategy Frameworks according to certain specifications. So far, however, there are only requirements for LNG and hydrogen infrastructure as well as charging infrastructure for passenger cars. A standard for loading capacities for trucks, as well as general specifications regarding an overhead catenary infrastructure, however, have not yet been integrated into the AFID[9]. This will be a decisive challenge for further infrastructure development. On the one hand, this involves the setting of preferred standards (Annex 3), which are set for car charging stations. In addition, the AFID contains volume targets and could therefore also provide for an ERS core network (TEN-T) or at least make recommendations for it.

Standardisation is a further challenge and will be a prerequisite for infrastructure development on a larger scale. SIEMENS is striving for standardisation within the framework of railway standards EN50119 (overhead lines for electric train operation), EN50122-1 (protective measures against electric shock), and IEC 62590 (general requirements for electric power converters), which are intended to also apply to OC in the future. The interaction between pantograph and overhead line is additionally intended to be standardised through CENELEC TC9x (Electrical and electronic applications for railways).

In addition, various legal challenges at national level have been identified. The main uncertainty here is the classification of overhead line infrastructure within the legal framework. The current legal assessment tends to

[9] The AFID has been replaced by the AFIR (Alternative Fuels Infrastructure Regulation). Again, this section contains the status quo until the end of 2021 as input for the interviews.

view the overhead lines as part of the highway (Hartwig 2020), but there is no final assessment yet. This is supported by the fact that ancillary operations (such as petrol stations) are already considered part of the motorway. However, this should be clarified in the "Federal Highway Act" (Bundesfernstraßengesetz = FStrG). This would imply a number of developments:

According to §90 FStrG, motorways are operated by the federal government and are therefore not in principle privatisable, which would then also apply to the overhead line infrastructure. At most, a functional privatisation, e.g. for maintenance, would be possible; externally, the overhead line infrastructure would remain to be part of the motorway.

As part of the motorway, the outer area of the motorway would be usable for the development of infrastructure under the Motorway Construction Directive (RAA).

According to the Road Charging Directive 1999/62/EC, no additional user charge can be levied on motorways apart from the toll. Network charges or other financing options for the infrastructure would therefore be eliminated, so the infrastructure would have to be financed through the federal budget and tolls.

One challenge in this context is the highly regulated energy industry law, which would require special regulations as private law. The electricity for traction is a private commodity that is delivered to ERS users via a public infrastructure. Excluding customers of certain providers from using this public infrastructure would not be compatible with the road usage law. Therefore, the motorway would have to be exempted from network regulation.

New mobility providers are seen as a possible solution. The infrastructure itself remains a natural monopoly in state hands, with competition existing only between mobility providers in the infrastructure: "*The ERS infrastructure is then used as a state infrastructure by the Autobahn GmbH, built as part of the road by the state from the federal budget and thus counterfinanced by the toll. For the benefit of ERS users, a competitive market for electricity with the best tariffs and tariff models should emerge. To achieve this, the roles of the infrastructure operator, the mobility provider and the toll system operator must be separated (unbundling) [...] It should be taken into account that ERS, like charging points for passenger cars, should not be subject to the grid regulation of energy industry law and therefore need their own regulation*" (Hartwig 2020).

Another challenge in this context is the lack of legally compliant meters, which currently do not allow billing based on the amount of electricity (kWh). Interim solutions such as tariff routes or similar would have to be applied temporarily. Legal regulations must therefore be introduced as soon as possible. Further energy industry framework conditions for the energy markets at the national level, such as the Energy Tax Act (EnergieStG), the Electricity Tax Act (StromStG), and the Biofuel Quota Act (BioKraftQuG) have an impact on catenary trucks; however, they are not fundamentally considered a hindrance or conducive to OC-trucks. They merely lead to differences in energy costs, mainly due to the level of levies for the respective energy carriers and the requirements for the share of renewable energies.

The specific construction of the infrastructure also involves a series of planning and implementation regulations, which, however, predominantly affect all larger construction projects. This initially concerns the tendering law (VOB Part A), which may require tendering in lots as construction progresses and is therefore dependent on standardisation. Additionally, issues such as environmental impact assessments in general, water protection areas, flood risk areas, landscape protection areas, and possibly compensation measures, noise assessments, and testing of electromagnetic compatibility must be considered in particular.

In the future, standardised rescue concepts or an adapted rescue card could be required and helpful in operation. (BMVI 2020b; Customs online 2020; Bundesregierung 2020; Hartwig 2020)

3.2 Stakeholder interviews with truck manufacturers and policymakers

Interviews with key actors in and beyond the German context were conducted to gather the views of different actors on ERS in general and on catenary systems, spanning different nations and governance levels from the national to supranational level. Additionally, interviews with truck manufacturers provided an industry perspective.

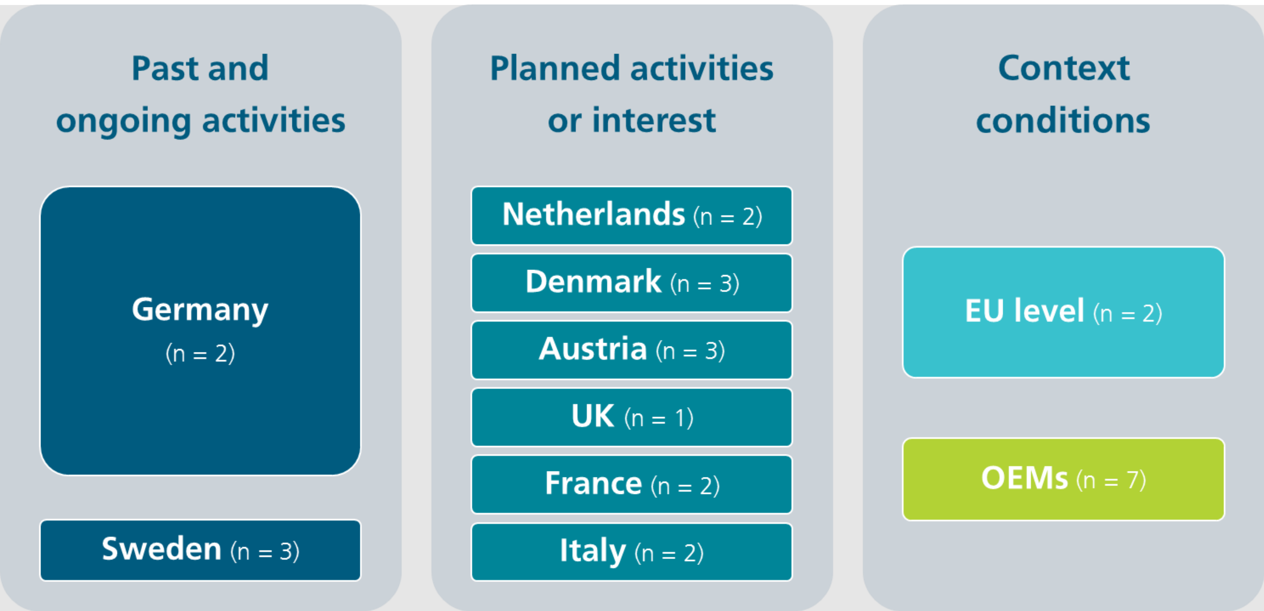
3.2.1 Methods

3.2.1.1 Data collection

Sampling and data base

To add to previous studies on catenary trucks around the field trials, the focus was placed on perspectives beyond the German context. In a total of eight countries, 2-3 interviews were carried out for each. This resulted in a total of five interviews in the two countries with previous and ongoing activities, i.e., ERS trials on public roads, 13 interviews in the six countries with planned activities or interest in ERS technologies, two interviews at the EU level, and seven interviews with OEMs (see Figure 15). In total, 27 actors were interviewed.

Figure 15: Overview of interview activities. Number of interviews for each focus area indicated in brackets.



This empirical data collection goes beyond the plan laid out in the initial project proposal. The choice for extending the data collection and analysis was made jointly with the project management agency to respond to the growing interest towards ERS in multiple European countries and consequently ensure a more complete picture of the most recent actor landscape around the technology. The sampling for relevant experts for the interviews was based on the actor analysis in WP2.1 and approached as a mix of convenience sampling and theory-led sampling. For the individual country perspectives, the aim was to focus on actors involved or close to policymaking and to include additional voices from industry where available and relevant. For the EU level, the focus was on policymakers and observing non-profit actors. Manufacturer interviews were limited to the largest truck manufacturers in Europe. Table 4 provides an overview of the actor types and number of experts interviewed in each category and information on the respective interviewer.

Table 4: Interviewed actor types and number of conducted interviews.

Country / INSTITUTION	Interview ID	Actor type (n=number of interviewees per organisation)	Interviewer ID
Austria	AUT-1	Federal ministry (n=1)	A
	AUT-2	Government agency (n=1)	A
	AUT-3	Publicly owned infrastructure corporation (n=1)	A
	AUT-4	Research association (n=1)	A
Denmark	DEN-1	Government agency (n=1)	A
	DEN-2	Trade association (n=1)	A
	DEN-3	Infrastructure developer (n=2)	A
France	FRA-1	Government agency (n=1) University (n=1) Consulting firm (n=1)	B
	FRA-2	Infrastructure producer (n=1)	B
Italy	ITA-1	Advisor to federal ministry (n=1)	C
	ITA-2	Motorway management company (n=1)	C
Netherlands	NED-1	Federal ministry (n=1)	A
	NED-2	Government agency (n=1)	A
Sweden	SWE-1	Government agency (n=1)	D
	SWE-2	Engineering and consulting firm (n=1)	D
UK	GBR-1	Government department (n=1)	A
-	OEM-1	Truck manufacturer (n=1)	A
-	OEM-2	Truck manufacturer (n=1)	A
-	OEM-3	Truck manufacturer (n=1)	A
-	OEM-4	Truck manufacturer (n=1)	A
-	OEM-5	Truck manufacturer (n=1)	A
-	OEM-6	Truck manufacturer (n=1)	A
-	OEM-7/SWE-3*	Truck manufacturer (n=1)	D
-	OEM-8	German industry association (n=1)	A
Germany	GER-1	Federal ministry (n=1)	A
	GER-2	Government agency (n=2)	A
EU	EU-1	Member of the European Parliament (n=1)	A
	EU-2	International environmental NGO (n=1)	A

*Manufacturer interview with focus on developments in the country beyond industry, utilising country questionnaire. Counted towards country interviews in Figure 2-1.

Implementation

Interviews were conducted online via MS Teams by four interviewers of the participating research institutions with a distinct semi-structured question list for each of the three categories (individual country; EU level; manufacturer). The interviews, except for those in Germany and Austria, were conducted in English and lasted between 26 and 120 minutes, with an average of 53 minutes.

Interview guideline

Questions for the three interview types were developed based on the following key categories: advantages and disadvantages of the technology, comparisons with competing technologies, general attitudes towards the technology, perceived acceptance by other actors and the general public, perceptions of the regulatory context, technologies, and the role of ERS in national plans to decarbonise heavy road transport. The interviews with manufacturers furthermore included questions about the general evaluation of ERS and catenary systems amongst the multiple available technologies to decarbonise heavy-duty road transport and questions on past developments in the firm's strategic perspective. Subquestions with prompts for potential answers were included in case the interviewees needed more specifications to answer the questions but overall, the sequence and follow-up questions were flexible to match the topic flow and particular focus of the individual expert interviews. This allowed interviewers to address unexpected themes brought up by interviewees and to allow for storytelling while still covering all relevant questions.

3.2.1.2 Data analysis

Interviews were recorded, summarised, and transcribed. For the analysis of the OEM interviews, transcriptions were used directly. For the analysis of the interviews in different European countries, a template was developed to summarise the answers to each interview question and collect key direct quotes. Summaries were then prepared as a first step by each interviewer and subsequently included in the main part of the analysis. The analysis of both the transcripts and the summaries was performed with a qualitative content analysis approach following Mayring (2014). Codes for the analysis were derived from the categories of interest at the outset of the study, such as the perceived advantages and disadvantages of ERS technologies, and supplemented by sub-codes based on the material, such as efficiency or resource demand. Additionally, points, which had not initially been covered by the question list, and themes linking multiple categories were added to the code list during the analysis. The final analysis was then performed in two ways. For codes including a large number of descriptive sub-codes, such as the aforementioned example of advantages and disadvantages, comparisons of magnitude were made. For codes including more qualitative sub-themes pointing to larger or overarching patterns in responses, segments were read again and jointly interpreted and summarised.

3.2.2 Results: OEM perspectives on ERS and catenary trucks

This section presents the results of the interviews with market leading truck manufacturers in Europe. It first summarises the activities, evaluations, and expectations of the manufacturers towards ERS and catenary trucks and points out similarities and differences between their perspectives. It then addresses the ways in which the manufacturers compare ERS and catenary trucks to other alternative fuel vehicle (AFV) technologies.

3.2.2.1 Activities and general technology evaluation

Before reporting on the anonymised results of our interviews, we first summarise the past activities of the truck manufacturers based on publicly available information. The majority of these activities focuses on catenary trucks, as OEMs have so far been involved in other ERS technologies, such as in-road inductive coils or electric rails, only to a very limited extent. Scania stands out from the group of truck manufacturers as the company with the most involvement in ERS through their provision of the catenary test vehicles for all past and present field trials (Sweden; *FESH*; ELISA; *eWayBW*). The manufacturer has been involved since the early days of research and development on catenary trucks and presents a generally positive attitude towards the technology. In its overall product portfolio and innovation strategy, however, catenary trucks are one out of many AFV technologies, with other technologies such as exclusively battery electric vehicles and biofuels occupying a more central place. Volvo, as the second Swedish manufacturer was initially interested in catenary solutions and its subsidiary Mack Trucks provided the diesel hybrid vehicles for an early technology trial in the US (Siemens AG 2017), but has since adjusted their stance and are no longer in direct support of the technology (Volvo Trucks 2020). DAF and IVECO have recently become involved in the topic of ERS: DAF as an associated partner in a research project by RWTH Aachen (BEE, BEV Goes eHighway) (Witham 2/15/2023) and IVECO as a participant in a research project on inductive driving in Italy, albeit with a bus ("Arena Del Futuro") (IVECO 2021). Daimler Truck has publicly criticised the catenary solution (Daimler Truck 2019, 2021; Magenheim 2021; Theile 2021) and the remaining manufacturers are observing ERS technologies with a critical interest.

The interviews support these publicly known positions and add further nuances to the support or criticism of the technologies. A clear lack of support becomes apparent in statements such as the following: „*We have lots* *of other projects but this topic not at all. I sometimes get the impression that my colleagues do not understand why Scania does that, when we joke around a little bit internally*." (OEM-5, interview, 2022)[10]

A more open stance but with preferences towards other AFV technologies can be found in quotes by two different manufacturers:

> *„We are not against anything per se. And as I said, I am sure we are looking at this. But the portfolio [is] fixed on [a different] path. I always say to our clients: buy what you want in terms of drive technology, as long as you buy it from us (laughs)." (OEM-4, interview, 2022); „For the truck manufacturers, I think, and I can spill the beans here, we are of course all looking at it. And it is of course interesting for us how this develops. But we definitely see the trend towards other technologies, where we can scale up quicker and where we do not see such a high maintenance effort*." (OEM-2, interview, 2022)

On the more positive side, one manufacturer summarises that, given a stronger political signal towards OC- systems, an adjustment of their vehicles would not provide a substantial technological hurdle: "*For us as manufacturers, that is not such a big change. So, you want to build an electric truck? Okay, that's something we're doing. [...] and if it is not possible, we just place in more batteries and everybody's happy again*." (OEM-3, interview, 2022). Another manufacturer points out that a clear pathway decision by governments could make them reconsider their current strategy: *„If the government decides to build overhead lines on all major highways, this would certainly change the perspective*." (OEM-6, interview, 2022). Overall, the results show that the positions by manufacturers besides Scania cannot be summarised under one homogeneous negative evaluation but range from a lack of support to an interested position with first research activities.

3.2.2.2 Detailed technology evaluation of catenary trucks and infrastructure

Manufacturers' more detailed evaluations of catenary trucks were collected by asking about perceived advantages and disadvantages of the technology but also came up in the answers to other questions throughout the interviews. The analysis of these factors shows that manufacturers refer to a list of technology attributes and context factors when laying out their evaluation. Additionally, they refer to other technology alternatives to contextualise their evaluation of catenary trucks, both amongst ERS and amongst the wider options for decarbonising truck transport. In the following, we will first present the advantages and disadvantages of ERS that were mentioned by the interviewed managers and then move on to present their expectations about important context factors and alternative technologies for the development of ERS.

Table 5: Evaluative attributes and context factors brought up by manufacturers towards catenary trucks and infrastructure.

Advantages or supportive factors	Disadvantages or challenges

• Efficiency
• Smaller batteries
  ○ Lower weight
  ○ Less raw materials = lower import dependency (industrial politics)
• Increasing technology competition for alternatives
• Less or no charging breaks necessary
• User acceptance (if cost-competitive)
	• Public acceptance
	• Aesthetics and perceived risks
	• Dependency on multiple actors
	  ○ Government support (integration in policies)
	  ○ Infrastructure provider(s)
	• Uncertainties and lack of a strong lobby
	• Restricted flexibility (build-up and usage)
	• User acceptance
	• Infrastructure build-up (minimum network)
	• Up-front investments
	• Unclear USP

[10] For all interviews referred to in brackets see Table 4.

	• Costs • Scalability • Lack in competition (risk for monopolisation) • Range off the highway • Standardisation • Loss in load volume • Unclear value on secondary vehicle market

The data (see Table 5) shows both technology attributes and context factors that manufacturers refer to when evaluating the technology. Overall, the statements about challenges considerably outweigh the statements about positive aspects as does the diversity of attributes and context factors.

On the positive side, technological and market factors dominate. Manufacturers consider the efficiency of the technology, as well as the possibility for having smaller batteries key advantages of the technology. The interviewed industry association also points to the possibility for dynamic charging and catenary trucks to increase the competition for other alternatives, such as battery electric vehicles, and the technology improvements that can be gained from such a competition. Respondents also point to the advantage of not needing charging breaks and the corresponding parking spots. Finally, some respondents do not see truck users as a barrier for the adoption to catenary trucks but consider them to be mostly focused on total cost of ownership (TCO) and manageable routines and accepting any technology that can fulfil these requirements.

For the challenges, governance and market factors are most prevalent. Here, manufacturers centrally discuss public acceptance, including the aesthetics of the technology and perceived risks, as challenges. Additionally, they point out the dependency of catenary solutions on multiple actors that users (and indirectly vehicle manufacturers) would consequently depend on: from governments that need to support the solution and integrate it into policies, to infrastructure providers that need to build the system and ensure its operation. As a more general factor, the respondents refer to the remaining uncertainties around the diffusion of the technology and the lack of a strong lobby. User acceptance comes up amongst the challenges more often than among the supportive factors and refers to manufacturers' doubts about the acceptance of catenary trucks by logistics companies. The minimal network that would be necessary to use a catenary truck over wider distances as well as the necessary up-front investments for building up the infrastructure are pointed out as additional challenges. To a smaller extent, manufacturers refer to costs, scalability, a lack in competition, possible ranges off the highway, standardisation, loss in load volume, and unclear values of the vehicles on the secondary market as further challenges.

3.2.2.3 Conditions for the success of OC truck systems

When asked about potential scenarios under which OC-trucks could succeed, manufacturers named thirteen factors in total. Most often, a Germany-wide or Europe-wide overhead catenary infrastructure network was stated as a necessity, followed by the requirement that catenary trucks would be fully electric rather than hybrid vehicles. More radically, some manufacturers only saw OC truck systems as a potential solution if other alternatives did not work, for example if there were problems with battery resources in the future or problems with the (construction and rollout of) stationary (fast) charging infrastructure. Clear government commitment and cost parity with diesel vehicles and/or other technology alternatives were named as additional conditions. Finally, and to a lesser extent, a universal and functioning billing system, the compatibility of multiple ERS systems, the availability of renewable energy, the compatibility with autonomous driving, an attractive overall offer for users, vehicle purchase subsidies, societal consensus on using this option, and a large pilot project were seen as conditions for the success of an OC truck system.

3.2.2.4 Comparisons with other alternatives and market development expectations

Manufacturers were asked three interview questions that led to answers comparing OC-trucks and infrastructure to other technologies: (1) advantages and disadvantages of ERS and OC-trucks, (2) whether and which other AFV technologies could contribute more to the decarbonisation of road freight than ERS, and (3) how they perceived the interaction between stationary and dynamic charging infrastructure.

Figure 16: Overview of technologies that manufacturers refer to when setting catenary trucks and infrastructure in context with technological alternatives. (BEV = battery electric vehicle; MCS = megawatt charging system; ERS = electric road systems; H2 = hydrogen; FCEV = fuel cell electric vehicle; H2-ICE = hydrogen internal combustion engine)

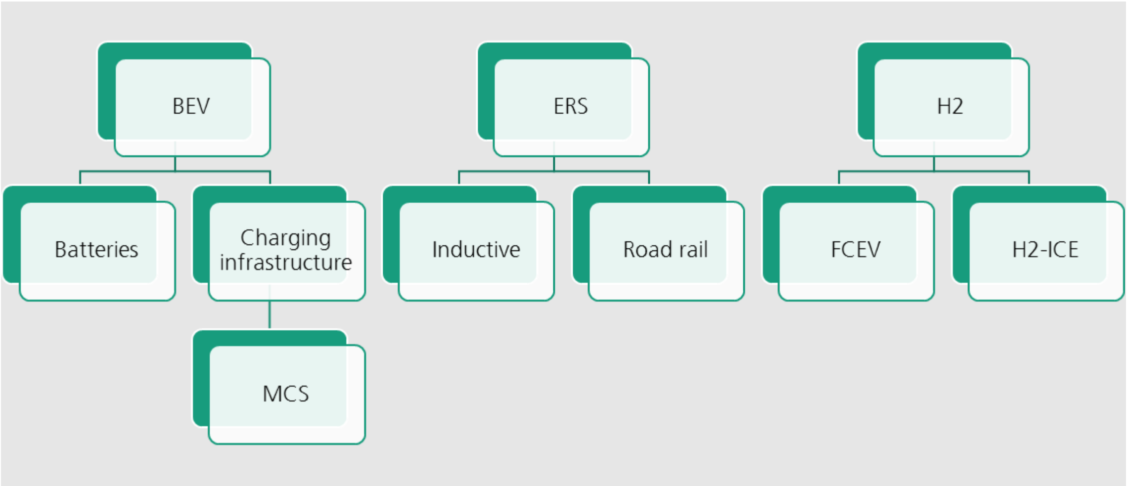


Figure 16 provides an overview of the technologies that interviewees referred to in comparison to OC-trucks and infrastructure. The most frequent comparisons were made with battery electric vehicles in general and with particular reference to stationary fast charging (MCS). One manufacturer pointed out that OC-trucks would not present a large technological difference to battery electric trucks (BETs), and thus no substantial hurdle in production. All other comparisons with BETs presented them as the superior solution in comparison to catenary trucks. Additionally, greater route independence of BETs and the flexibility of charging at rest points as in current routines with diesel trucks were named as advantages. Battery electric trucks were considered the *"most elegant solution"* (OEM-5, interview, 2022) as they would match diesel trucks in their appearance and were considered to be a sufficient option by themselves, not necessitating the addition of ERS. Finally, battery improvements and consequently growing ranges or lower weights of batteries were frequently mentioned as a potential threat to the business case of OC-trucks.

Comparisons based on charging infrastructure similarly pointed out one advantage of catenary infrastructure and multiple advantages of stationary infrastructure. On the positive side, catenary infrastructure was considered to lead to fewer issues with power requirement and electricity grid enhancements at parking areas compared to (fast) stationary charging and to be more efficient. On the negative side, stationary charging was considered to allow more independent developments at different, potentially decentral locations and at different construction speeds, whereas for catenary solutions, agreements would be necessary from the start. Additionally, it was pointed out that fast stationary charging would allow the same routines as with diesel trucks, with drivers taking 45-minute breaks and charging at a station. Finally, the already available experience and knowledge from stationary charging in the car segment was considered an advantage of stationary charging over catenary solutions.

To a smaller extent, interviewees also refer to inductive ERS solutions, rail transport, fuel cell electric vehicles, hydrogen combustion, and LNG as other alternatives. Comparisons with inductive solutions named aesthetics and the invisibility of the solution as an advantage over catenary systems. Comparisons with rail pointed to the challenges of maintaining such large-scale infrastructures. Comparisons with fuel cell vehicles pointed to a similar flexibility of the technology, independently of infrastructure on the road, as with BEV and comparisons with fuel combustion to the greater independence of such a solution from battery resources in comparison to electric solutions. Finally, LNG was mentioned as a solution that was more known by users, i.e. logistics companies, than catenary systems.

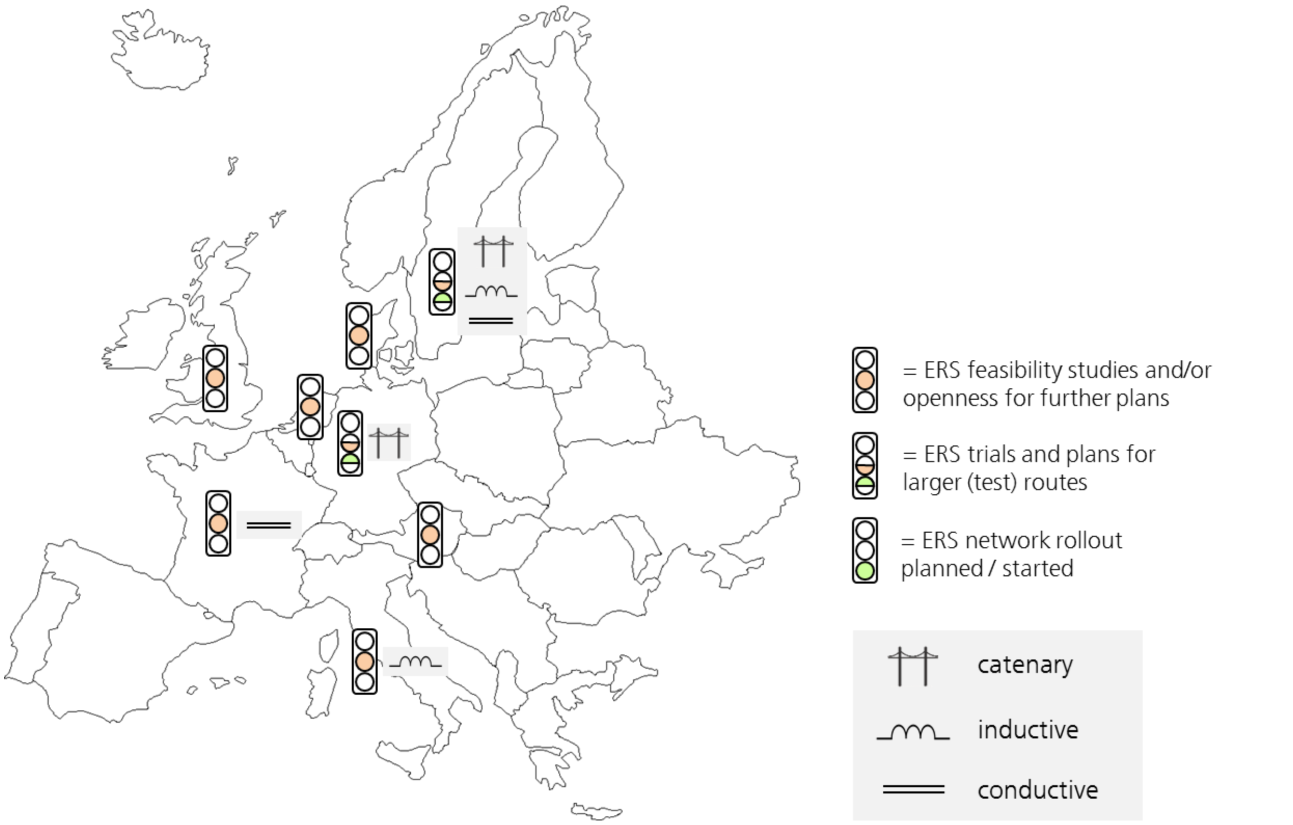
3.2.3 Results: European country perspectives (incl. Sweden and Germany)

This section presents the results of the interviews in different European countries under three subheadings. It first describes the past, present and future of ERS in Europe, followed by country-specific strengths and open questions or challenges for Austria, Denmark, France, Italy, the Netherlands, Great Britain, and Sweden. Second, it addresses recent developments and future pathway decisions in Germany. Third, it summarises the results of the interviews that were conducted about views towards ERS at the European level.

3.2.3.1 Past, present, and future of ERS in Europe

-Electric road systems have been discussed as a technology option to charge electric trucks throughout Europe. Figure 17 provides an overview of the extent of ERS activities and the technology focus in each country that was studied for this research project. Additionally, first (feasibility) studies on ERS have been performed by universities in Belgium and Hungary but since policymakers have not yet been publicly involved in advancing the technology in these countries, they were not included here.

Figure 17: ERS activities in Europe until 2022 and technology focus.



Sweden and Germany are considered as early movers in ERS for trucks. As the figure illustrates, both countries have conducted field trials in the past, with the German field trials still ongoing in 2023, and have published plans for larger (test) routes. In Sweden, this relates to a tender for electrifying the E20 between Hallsberg and Örebro (Trafikverket 2020); in Germany this relates to the so-called innovation clusters (BMVI 2021a). Sweden has tested all three ERS options, that is catenary, inductive, and conductive solutions, and has not specified the technology in their tender, while German activities focus on catenary technology. In both countries, the national plan for the decarbonisation of road transport includes ERS as a potential option.

Austria, Denmark, France, Italy, the Netherlands, and Great Britain are further interested parties who have carried out ERS feasibility studies and/or are open for further developments with the technology in their countries. The decarbonisation plans for heavy-duty road transport in these countries do not include ERS yet. Great Britain has issued a feasibility study for ERS (Department for Transport 2021) and was planning to include the technology in calls for substantial demonstration projects as well (GBR-1, interview, 2022) but has since published these calls with an exclusive focus on BEV and FCEV, specifically excluding ERS (Department for Transport 2022b, 2022a). Austria, Denmark, the Netherlands, and Great Britain have not specified which ERS technology they would prefer or consider most likely to be introduced in their country. French studies have come to the conclusion that conductive systems would have most advantages in comparison to other ERS solutions. A field trial with buses in Italy focuses on inductive ERS (IVECO 2021) but Italian decisionmakers also see a potential future for other ERS solutions (ITA-1, ITA-2, interviews, 2022).

For both their present and future activities, interviewees pointed to the interconnections between countries. Denmark, the Netherlands, and Austria mentioned their intention to match the technology option chosen by Germany (and to a smaller extent Sweden). Denmark additionally mentioned that they were watching the developments in the Netherlands as a similarly sized country. The interviewee from Great Britain considered it important for them to align with solutions chosen in the EU so that cross-border, i.e., cross-channel, freight traffic would be ensured in the future. Swedish interviewees also referred to the importance of developments in Germany and also France for their future decisions on ERS: *„And of course we are a small, small country in the north of Europe, so of course we will be affected by what happens in central Europe, in the big countries like Germany and France and so on*." (SWE-1, interview, 2022). For the future, all countries also mentioned the need for collaboration to ensure the success of ERS as illustrated by the following quotes:

"That means that building such an infrastructure on a nation state level just within Austria makes no sense. And it will not happen. It can only happen if there is a European coordination." (AUT-2, interview, 2022)

„Again, this is my opinion, but we need to go international on this. Because there needs to be standards. It won't improve the cooperation of the ERS systems if you have different systems in different countries. Induction in Sweden and catenary lines in Germany and whatever, we need to decide on what technologies we use and what standards should we use. I don't care who produces it or puts it up but we should be able to use it everywhere." (DEN-1, interview, 2022)

"*There can't be two solutions of ERS and a pan European and clear decision must be made. Worst case: Charging infrastructure, H2-infrastrature, biogas- and ERS in parallel. Waste of money*." (FRA-1, interview, 2022)

„I think getting an agreement within the EU will be quite key about which technology or mix of technologies will be rolled out." (GBR-1, interview, 2022)

„Not independently. I do not think that I can convince my stakeholders to set up 300 kilometers of eHighway without European coalitions." (NED-1, interview, 2022)

For the future, interviewees in all countries pointed out the need for standardisation and a clear standpoint on the role of ERS versus battery-electric and hydrogen options in European and country-level policies as necessary conditions for the success of ERS.

3.2.3.2 Country-specific strengths and open questions or challenges for ERS

While collaboration, standardisation, and clear policies were expressed as necessities across countries, our analysis also reveals strengths and challenges for individual countries. In the following, we first summarise these points for each country in the analysis and then provide an overview of similarities between them.

Austria

Interviewees from Austria pointed to the absence of specific OEM interests as a strength. This means that the country can decide for or against ERS and between the different ERS options without having to consider the implications for heavy-duty vehicle manufacturers. Additionally, they considered the potential for the Austrian infrastructure provider Powerlines to become involved in technology provision, if a catenary solution is considered in the future, a strength.

As challenges, Austrian interviewees pointed towards the many bridges and tunnels in the country. With key road transport corridors in the alpine region, this is a special characteristic of the country. Further, the scarcity of electro technicians and the workload of construction companies in the country were named as potential problems for the construction of ERS as well as the potential for public acceptance issues in the future, once the technology would be more widely known. On the institutional side, interviewees in the country named as challenges the uncertainty around the role that the highway authority Asfinag would play for ERS, the open discussion about how ERS would be included in the truck toll system in Austria, as well as the generally long duration of planning processes, which could make a fast rollout of ERS challenging. Overall, the general lack of a lobby for ERS in Austria was summarised by one interviewee as a key challenge to the development chances of this technology there: *"I know nobody who jumps up excitedly for this topic, expect for the industry who wants to build this. [...] It's not that the ministry says this does not work, never ever. Otherwise this study would not have been financed. But overall, I do not believe, from today's viewpoint, that we will have this in Austria."* (AUT-3, interview, 2022).

Denmark

Interviewees from Denmark pointed to two infrastructure-related strengths for building ERS in the country. First, the highway grid, with its main corridors laid out in an "H"-shape was considered suitable for the introduction of ERS. Second, the construction of the Fehmarn belt tunnel and the surrounding infrastructure was considered a potential driver for introducing ERS in the country. Interviewees furthermore saw potential in the Danish infrastructure provider Vestos for supplying catenary infrastructure in the future, if this would become the preferred solution.

Regarding challenges, interviewees named the high up-front costs of ERS infrastructure, especially as they considered the introduction of such a technology to be a government-led endeavour: *„We are not a huge supporter of this technology, mainly because of costs. It has a lot of costs mainly for the government [...]."* (DEN-2, interview, 2022). Furthermore, they considered public acceptance as a potential issue for the future as the country had made large efforts to put electric powerlines underground in the last years and installing additional overground infrastructure, such as catenary systems, could therefore be met with opposition: *„Catenary lines are not very beautiful to look at, I guess, and that could be a problem*." (DEN-1, interview, 2022).

France

French interviewees pointed to the know-how of the French railway technology company Alstom on ERS as a country-specific strength. Alstom focuses on the ERS technology of electric rail but points out that: *"Alstom doesn't want to manage all the ERS. They can bring [...] their system and their experience, but don't want to do everything and are therefore not pushing like other competitors."* (FRA-2, interview, 2022). Additionally, ERS could be incorporated in the toll system that is already in place in France. On the infrastructure side, interviewees considered it a strength that road concessions in France are mainly owned by private companies which could also deploy ERS: "*After the study in 2021, the road operators (concessioners) are motivated to work and demonstrate, make some trials on their network. [...] Highway companies and public work companies [already] combined forces for call for project [with] over 20 mn. € private investment in research*" (FRA-2, interview, 2022).

Reaching a political decision and choice for a single ERS solution was seen as a challenge by French interviewees both within the country and beyond. Furthermore, public acceptance of certain ERS solutions was considered a challenge with the visibility and perceived safety of catenary systems as a specific example.

Great Britain

The interviewee from Great Britain considered the country's great expertise in the supply chain of railway technology a key strength.

As country-specific challenges, two points were made. First, the different allowed vehicle heights between Great Britain and the European mainland were mentioned with its implications of interoperability between countries. In Great Britain, the maximum allowed height of heavy-duty vehicles is higher than in the rest of Europe so the interviewee reflected on potential future challenges for UK-built OC-trucks driving in other countries. Second, the interviewee considered remote areas in, for example, Scotland and Wales as challenges for an electrification with ERS as heavy-duty traffic volumes there might not be great enough to ensure a sufficient usage of such a system. Additionally, as a point made by the UK interviewee for all countries, the public acceptance of ERS was a factor that was thought possible to achieve but *"potentially more of a journey that we'll have to take the public on when compared to the other two technologies (stationary charging and hydrogen infrastructure)."* (GBR-1, interview, 2022).

Italy

Interviewees from Italy considered it a country-specific strength that ERS technology choice would not be significantly biased by local industry as there were no Italian companies involved in ERS technology development at the time. They also considered it a positive example with a promising future as the inductive test track in Italy was mainly financed by private industry.

As challenges, the interviewees mentioned the many viaducts, bridges, and tunnels in the country, which could complicate building up ERS infrastructure. On the infrastructure and regulatory side, they also considered the high mandatory distance between roads and polls a challenge. As a final challenge, interviewees pointed to the technologically conservative vehicle industry in Italy.

The Netherlands

In the Netherlands, the presence of the heavy-duty vehicle manufacturer DAF Trucks was considered a potential strength as they could move forward on this topic in the future[11].

As challenges, the Dutch interviewees named four factors related to governance and institutions, and one practical or market consideration. First, the typically heterogeneous government in the Netherlands was seen as a potential obstacle for introducing ERS. Second, despite a potential construction of the system by private companies, the procurement costs for the Ministry were seen as a challenge. Third, the still unclear links of such a new infrastructure system to the new toll system for heavy-duty vehicles was considered a challenge and finally the unclear role for the highway authority Rijkswaterstaat. As a practical obstacle, the scarcity of construction personnel in the country was mentioned.

Sweden

Swedish interviewees considered the support for ERS technology of the central government and of the traffic administration a key strength. Additionally, they pointed out that Scania as a Swedish OEM was committed to ERS and had already collected know-how from multiple field trials.

As country-specific challenges, the interviewees mentioned that the number of potential ERS users was still unclear or considered on the low end, with most transport in Sweden focused on regional rather than long-distance routes, illustrated by the interview quote: *"I think it's the demand, I mean the amount of traffic. If that is enough for justifying building another infrastructure kind of. I think that's the main issue."* (SWE-2, interview, 2022). Finally, with their roads being close to nature, they considered public opinion as an important factor.

[11] This has since indeed happened, see Section 3.2.1.1.

Comparison of strengths and challenges between countries

When comparing the country-specific strengths and challenges, six commonalities stand out. First, four countries mention heavy-duty vehicle manufacturers as playing a key role. Austria, the Netherlands, and Sweden mention OEMs in a positive capacity and point to either already occurring involvement, as in the Swedish case with Scania, a potential future involvement, such as with DAF Trucks in the Dutch case, or the absence of influential interests, such as in Austria. Italy, on the other hand, points to the country's vehicle industry as a potential barrier for ERS.

Second, five countries mention infrastructure providers as a positive factor for the development of ERS. Austria mentions a potential for Powerlines to become involved in the future, Denmark for Vestos, and Great Britain companies in the supply chain for railway technology in general. Italy considers an absence of strong infrastructure interests as a positive factor while France and Germany consider the know-how provided by Siemens and Alstom respectively as country-specific strengths for the development of ERS.

Third, two countries mention the critical future role for highway authorities. In both Austria and the Netherlands, the role of highway authorities (Asfinag and Rijkswaterstaat respectively) for potentially establishing ERS in the future was still unclear and mentioned as a potential barrier.

Fourth, public acceptance was mentioned as a potential challenge in the future in the five countries Austria, Denmark, France, Great Britain and Sweden. In all cases, the envisioned public concerns were linked to the overground infrastructure associated with catenary systems. However, only in Germany, the concerns could be linked to available research data collected on public acceptance in the field trials while in other countries concerns for public acceptance in the future were envisioned by the interviewees themselves.

Fifth, the integration with existing or future toll systems was mentioned in multiple countries. Austria and the Netherlands considered this a challenge for the future, while France considered the already existing tolling system in the country as an advantage for the integration of ERS.

3.2.4 Recent developments and future pathway decisions in Germany

Since all interviewees in European countries that have shown an interest in ERS point to the importance of decisions made by Germany for the further development of ERS technologies, we report on the results for Germany separately. A comparatively substantial amount of research has already been done for the German context in various research projects, both related to as well as independently from the catenary trial projects in the country. This means that a lot is already known about the country-specific strengths and challenges for building up ERS systems (see e.g. Wietschel et al. 2017; Fraunhofer ISI 2023; IKEM 2023). Additionally, activities in Germany have been going on for more than one decade already, if early R&D activities by Siemens, which were also funded by the federal government, are included. Here, we therefore focus on changes over time observed by the interviewees, as the system developed, as well as crucial pathway decisions they perceive as coming up in the German context.

Observed changes over time

German interviewees considered three actors or actor groups as central for originally initiating the work on ERS in Germany: the infrastructure manufacturer Siemens and researchers as key and proactive in the beginning, and the support of these activities by government funds. Here, they pointed out policymakers at the German Federal Environmental Ministry (and after the change in government in 2021 at the Federal Ministry for Economic Affairs and Climate Action) as early supporters of the technology of catenary trucks. An important change they pointed out in this constellation was the transfer of the main governmental responsiblity for the topic of ERS from the Ministry fo Economic Affairs and Climate Action to the Ministry for Digital and Transport. They saw this as a logical consequence of political developments but also observed changes in the support the technology was receiving and will receive in the future as potentially associated to this switch:

"[...] and it was clear relatively quickly, that from a departmental perspective, one wanted to get the lead management, that was still with the Environmental Ministry back then, to the Ministry of Transport. Because it just makes sense to integrate it there because the whole area of road construction, road traffic is in that department and it just fits with all those activities that would then have to be done much better." (GER-2, interview, 2022)

"What is really important from my perspective is also an official statement of the Ministry [of Transport] in October last year [...] that they wanted to or will do this. And that was, I think, a sort of in-house coup because the technology is not uncontroversial in the Transport Ministry and also among truck manufacturers [...]. So also a commitment of the Ministry, we are spending money here, we want to test this technology at a larger scale. This does not mean that we build 4,000 kilometres but that we see the readiness of the technology [...] the units that we deal with in this context are still intensely concerned with pushing this against some internal and external opposition." (GER-2, interview, 2022)

Additionally, interviewees observed a change in the main focus of the purpose for the technology and its relation to other decarbonisation options for heavy-duty road transport. In 2019 and 2020, before the Overall Approach to Climate-Friendly Commercial Vehicles was issued by the BMDV (cite), remaining challenges with BEV and FCEV for long-haul transport still painted catenary trucks as an advantageous solution, resulting in all three being included in the approach. With BEV becoming a more realistic option also for long-haul transport, for example in combination with fast charging, in recent years, interviewees observed a change in public discussions towards entirely battery-powered catenary trucks rather than hybrid vehicles and an increasing focus on the interaction between dynamic charging and stationary charging infrastructure. They considered it a crucial point for the success of ERS solutions to figure out exactly what the role of each infrastructure solution will be in the future.

Future pathway decisions and determinants of further developments

After the switch in responsibilities to the Ministry of Transport, in 2021 a taskforce was initiated to get an overview of the available knowledge and perspectives towards both stationary and dynamic charging, resulting in a target image (BMVI 2022). In parallel to this process, so-called innovation clusters for climate-friendly heavy goods vehicles were announced, as had been set out in the Approach to Climate-Friendly Commercial Vehicles. Three clusters were intended to be supported, for which two state-specific consortia including dynamic charging and one consortia focused on stationary MCS developed (BMVI 2021b). The latter project, called HoLa, has since picked up work and is focusing on developing megawatt charging for battery-electric trucks along the A2 in Germany, including substantial accompanying research (Fraunhofer Institut für System- und Innovationsforschung 2023). For the other two potential innovation clusters, in which ERS and specifically catenary technology could play a role beyond the extent of what was previously done in field trials, project proposals have been submitted but no decision has been made by the Ministry yet:

"[...] the innovation cluster or the potential extension of an existing transport network, that is currently unfortunately still a little bit up in the air." (GER-2, interview, 2022)

"And yes, I think actually, at the moment the catch is that there is no real decision what happens with this technology." (GER-2, interview, 2022)

"And I think the deciding point now for this further development, one of the deciding points will be, how our house so-to-speak decides, with relation to these larger projects, these innovation cluster projects. Where the catenaries would respectively play a larger role. And this decision is imminent, I reckon. Cannot be made by me but further up." (GER-1, interview, 2022)

Interviewees at the German government level considered the decisions on whether or not the two remaining planned innovation clusters would be supported a crucial pathway decision that could determine whether catenary technologies would further develop or not, both within and beyond Germany:

"I think that a lot is connected to what happens in the innovation clusters, will they materialise or not? And to which extent will infrastructure be built? If, of course, battery-electric vehicles keep being in the focus and infrastructure is built for those, then I would say, one misses the point in time, at which there is an investment in catenary technology. Then it would no longer make sense at some point." (GER-2, interview, 2022)

"[...] if these projects, or just one of these two projects, that are still on the table, would be done, that would be very important for the further development [...]. Plus it also maybe has a certain signalling effect for the European neighbouring countries [...] that [...] show a lot of interest but do not necessarily have large-scale activities but rather look at little bit at what Germany is doing." (GER-1, interview, 2022)

"I think it is currently a close decision so-to-speak, whether this development continues or not. So I believe, it is not so improbable that this decision even stops- so that it doesn't continue. That would be my assumption. I don't know how strongly the actors that push this would still try to continue [...] and maybe the BMWK would also continue somehow with projects still. But I think it would be quite a setback if there is no larger project now after all." (GER-1, interview, 2022)

„[...] a very concrete decision has to be made. Let's say especially in our Ministry but lastly by the federal government, that the system is given another push by a larger project. That is, I would say, quite realistic. But we can talk about that again in a few weeks, how it then really turns out." (GER-1, interview, 2022)

German decision-making and connection to other countries

As the previous section shows, German decisionmakers considered the effects that their decisions on ERS could have on other countries which have so far refrained from activities besides first studies on ERS potentials. Interviewees both pointed out that they recognised the potential signalling effects of German activities and also explicitly referred to bilateral inquiries that had been made by multiple countries to the ministry about ERS activities in Germany and future plans. In addition to effects on policymakers, they also expected German decisions to impact the involvement of vehicle manufacturers, which could increase if larger infrastructure commitments by the government were made.

In addition to recognising their central role in current European discussions around ERS, interviewees also pointed to the necessity for further collaboration between countries. Collaboration was both regarded necessary to agree on the type of ERS technology that was to be developed further as well as for ensuring cross-border operability in the future.

„I also consider it a very important point that one succeeds at bringing about a harmonisation in the community of ERS supporters. Because this, in Germany we do catenary, in France we do it with a conductor line in the ground, in other countries, Israel or elsewhere, it is completely different again [...]. This can all be done from a research perspective, but if one says we want to get to a scaling-up and we really want to reduce emissions by 2030, 2040, then the vehicles will have to be on the road and those need to correspond with the infrastructure. So actually we would have to already know now exactly what we want to build and when. That means, we cannot afford this particularism anymore." (GER-2, interview, 2022)

[...] that for example Siemens and Alstom work together and commit to one [ERS technology]. That would already help a lot, that would, I think, make a few things easier. And on a strategic level between the countries, for example, so on the political level, Germany and France could then, I believe, somehow pull together more strongly." (GER-2, interview, 2022)

„I also believe that it should be looked at holistically, that means that different EU countries have to come to an agreement. There are core networks, that have been agreed upon [...]. And exactly based on these foundations the infrastructure build-up would have to be coordinated. Because it is clear, of course, that somebody who drives the entire east-west-connection, will not buy a catenary truck just because a few sections are covered in Germany." (GER-2, interview, 2022)

Finally, interviewees discussed the inclusion of ERS technologies at the EU level. Here, the level of necessary and desirable inclusion differed between the interviewees at the ministry and the government agency. Interviewees at the government agency pointed out that more specific inclusion of ERS in EU policies could benefit the technologies' development:

"Internationally, something would have to happen. Maybe through a kind of bonus system [...]. But, in any case, incentives would have to be created to use the technology because currently incentives are created for battery-electric or hydrogen vehicles. Of course, in the AFIR catenary trucks are considered but not to the extent that, for example the build-up of infrastructure for battery-electric vehicles is considered. For that, there are strict

specifications for every 60 or 200 kilometres, depending on, then it says exactly, which charging amount has to be provided so to speak. Yes, the catenary truck, I now phrase it very drastically, has received a half-sentence in the whole AFIR and that already shows, that exactly there, the collaboration or the specifications would have to be adjusted to be able to reach this goal." (GER-2, interview, 2022)

The interviewees at the ministry, on the other hand, reported that specific requirements for catenary systems had not been a lobbying goal of the German ministries in the process of devising the AFIR and that decisions at the national level would be key for the future development of dynamic charging:

"Yes, we of course also always pondered, should that go in this AFIR now, where the determinations are made, where they are not talking about catenary currently. [...] Would it be important to feed that in there. That's a matter of feeling now; I rather do not think so. So we did not drive this very much, I think also in agreement with the [other Ministry], [...] because we do not believe, that [...] at the current stage, that would have resulted in a binding commitment. What we have for hydrogen fuel stations already until 2030, but especially now for truck charging infrastructure with binding targets for '25, that would have been unthinkable to do something like that for catenary. To do that, it is still much too far away for most people. I think [...] this scaling up is dependent on political decisions in a few countries, whether this has a chance at all. And Germany will be central for that, but maybe also two, three, four neighbouring countries. And if these all profess their support and start this at a larger scale, I believe, this will potentially lead to European momentum again. I think, in this case it is really for once the other way around." (GER-1, interview, 2022)

3.2.5 Results EU perspective

Perspectives on ERS at the European level were collected through interviews with a member of the European Parliament (MEP) as well as an expert on truck decarbonisation at a European environmental NGO with strong ties at the European level. Both had strong ties to Germany, with the first representing the German central left in the EP and the latter originating from and working on Germany and contextualised their observations at the European level with developments specific to Germany. Both had also frequently been in contact with the German vehicle and infrastructure industry relevant for the development of ERS.

Regarding ERS technologies in general, the MEP noted that politicians at the EU level were not usually concerned "*with such [technological] details*" (EU-1, interview, 2022) but only when approached directly by industry. The interviewee also noted that OC-trucks were the most present ERS option for MEPs at the time of the interview and that the technology had first come to their attention around five years prior through the lobbying efforts of infrastructure company Siemens. Since then, the interviewee had also observed Continental to become active in pantograph development. Nevertheless, the person observed that most politicians and policymakers at the European level were not familiar in detail with ERS technologies. Regarding specific EU policies, the interviewee pointed out that the activities by proponents of ERS systems had resulted in the inclusion of a requirement for an additional impact assessment of ERS in the alternative fuel infrastructure regulation (AFIR) that was to supersede the alternative fuel infrastructure directive (AFID) with requirements for the member states. Furthermore, the interviewee mentioned the TEN-T as an option to support ERS: "*The [TEN-T guidelines] will also be decisive for whether the [catenary] technology will take hold. I mean, if a clear specification is made in the TEN-Ts, that could potentially fuel it.*" (EU-1, interview, 2022). However, the interviewee also stressed that the EU would not be in the position to specify how much ERS infrastructure would be build but rather provide incentives for a rollout of such a system: "*I think the European Union cannot prescribe or say 'this many catenary lines have to be built' but rather has to provide guidelines or incentives*." (EU-1, interview, 2022).

The interviewee of the environmental NGO echoed the observation by German policymakers that ERS had come up in the 2010s as no other technology option was thinkable for the decarbonisation of long-haul trucks (EU-2, interview, 2022). However, the interviewee also considered this a debate that was predominantly shaped by and centred around Germany, initiated by research and politics in the country and pushed forward by research. The European level, in form of the European Commission, was perceived as technology neutral. Nevertheless, the interviewee was under the impression that OC-trucks had disappeared to some extent from more recent discussions because vehicle manufacturers have since claimed that BEV and FCEV would be able to decarbonise long-haul truck as well. Regarding specific EU policies, the respondent pointed out that the AFIR would have *"binding targets for stationary fast charging points and hydrogen fuel stations but not for ERS"* (EU-2, interview, 2022) and that it would be an important decision for or against OC truck systems if ERS were included in this policy. In comparing the technology with other options, the interviewee considered MSC to also have its challenges but highlighted that ERS or OC-trucks would require political commitments soon to become established rather than further tests and stressed this urgency because of a perceived unlikeliness that there would be multiple parallel options for charging electric trucks in long-haul transport. Despite considering the technology as a "fantastic" and efficient idea, the interviewee considered the window for OC-trucks to be closing and the necessity for large-scale coordination across Europe to be a key obstacle for reaching a decision while the window was still open.

3.3 Discussion and policy recommendations

Our analysis set out to outline the perspectives of key decisionmakers in Europe on ERS and capture both perspectives held by truck manufacturers as well as by policymakers in different European countries.

Manufacturers

For manufacturers, the results show that there are critical, neutral, as well as positive positions. Up to the time of the interviews, Scania was the only involved manufacturer in developing ERS, more specifically catenary solutions. However, this picture has changed recently, with DAF Trucks and IVECO becoming involved as well, in catenary and inductive technologies respectively. Other manufacturers have either rejected ERS as an option for their portfolio or have a more neutral standpoint. Of the latter, interviewees have pointed out that their involvement hinges on government decisions. They could hence envision future developments of matching vehicles if certainty was provided by the government for a large-scale rollout of ERS infrastructure. Overall, manufacturers pointed out that they did not see the key challenges for ERS in technological developments but with political commitment and the consequential market development and development of demand. They addressed that the role of ERS amongst other charging and vehicle technologies was not clear to them.

Advantages and disadvantages of technologies as well as interactions mentioned by manufacturers pointed to a number of contradictions and uncertainties currently present in industry when it comes to ERS. First, battery improvements were seen both as a potential threat to the business case of catenary trucks while respondents also considered the advantage of using smaller batteries in combination with ERS for resource independency, irrespective of further technological developments in this component. Second, interviewees considered stationary charging infrastructure as more flexible and scalable while also pointing to the challenge of building enough charging points in a short amount of time and having enough parking spots available at which such charging points could be built. Third, inductive systems were discussed as visually more appealing than catenary systems but also as challenging because of high costs and the requirements of opening up large stretches of road. Finally, manufacturers considered the potential combination of ERS systems with multiple truck configurations as an advantage, but one manufacturer voiced that to them "*technology combinations with battery-electric catenary trucks make no sense.*" (OEM-6, interview, 2022). Overall, manufacturers hence presented a very heterogeneous picture that displayed multiple uncertainties surrounding the technologies of ERS.

Decisionmakers: developments on ERS in individual countries and at the EU level

The analysis of individual countries in Europe shows different levels of activities and commitment and reveals a great focus on the developments in Germany. Smaller countries that had become involved in the topic later, self-identified as second movers on the topic of ERS and planned to be prepared for a potential rollout in the future but to follow the developments in Germany. This was directly connected to the key factors they considered crucial for a future rollout: the collaboration between multiple countries in Europe, a clear role for ERS in EU policies, and the standardisation within and between ERS technologies. Second movers, such as Austria or the Netherlands, considered their own role on the heavy-duty road transport system to be too small to determine the direction of ERS technology choice and system development but highlighted their willingness to collaborate and find a solution that would be utilisable across borders. Both from within and outside Germany and in both government and industry, the German innovation clusters were correspondingly considered a crucial pathway decision for the further development of ERS and interviewees considered it unclear how ERS would develop independently of this decision.

The countries showed individuals strengths and challenges. Nevertheless, commonalities could be observed around industry preconditions, the perceived necessity for new roles for authorities if ERS would be rolled out, and expected challenges associated with the characteristics of existing road infrastructure and institutions. However, the second mover countries also specified that they expected that these individual country characteristics could be dealt with if a rollout of ERS was initiated by a first mover and would not present an absolute barrier.

Finally, the EU level showed an overall neutral and minimally involved approach to ERS. Interviewees highlighted the influence on individual countries and industry on decisions at this supranational level and commented on the stronger conditions that were developed for stationary charging and hydrogen under ongoing policy changes in contrast to supporting measures for OC-trucks and ERS in general, which have been limited to plans for further assessments. In parallel to policy processes, standardisation work has also been underway but the outcomes of this work and effects on the potential success of ERS have not been clear to the interviewees at the EU level so far.

Policy recommendations

The analysis shows that the commitment towards ERS of both the German government and in policies at the EU level is considered crucial by policymakers for a success of the technology. The openness towards OC-trucks and other ERS solutions in multiple European countries is considered fragile or temporary and considered to require a strong stance by a powerful first mover in order to come to fruition. The consequential policy recommendation based on this dependency is hence a clear government commitment moving from technology trial that are limited in their scope towards larger implementations of OC truck technology in Germany, such as had been announced in the matching innovation clusters and organised coordination efforts between governments to achieve a harmonised European ERS system

The results also show that the timeline of such a commitment and the accompanying narratives fostered by government and industry can play a key role. Both will determine whether a synergy or competition is perceived with other charging and refuelling options such as stationary (fast) charging for BEVs and hydrogen infrastructure for FCEVs. A combined buildup in which each technology can play out its individual advantages would look different from a situation in which the latter two options are widely rolled out and the USP for ERS would potentially decrease from a sufficient coverage of long-haul transport through these options. In addition to directly measurable factors such as road grid coverage with enough charging opportunities, public perceptions and emotions have been perceived by the interviewed key actors to play a role as well. The aesthetics and history of ERS technology in comparison with other alternatives could play a role for its acceptance and success; factors that were looked at in more detail in WP 1 (see Chapter 2).

Finally, the results reveal a challenge that can only be resolved by differentiating between the perspectives of individual companies and the system perspective of the government at the national and at the supranational level. Large-scale line infrastructure requires the coordinated construction of an entire initial system of routes to provide an incentive for usage (see Chapter 5). However, private interests are more readily inclined to incrementally build up charging stations that can be used independently, as the OEMs have already been doing, and different national governments have been in contact with ERS infrastructure manufacturers that support different solutions. These infrastructure manufacturers need government commitment to start building due to the necessary high upfront investments but national governments' hesitancy and the EU level's greater adherence to OEM perspectives has not provided such commitment. The main take-away is hence that in the vacuum created by open decisions towards ERS, stationary charging, which more readily fits a private sector logic, will further develop and could lead to a situation where the demand and distinct advantage for ERS becomes less pronounced even if it were more beneficial for efficient decarbonisation and resource usage at the system level.

4 Environmental evaluation

4.1 Background of the environmental evaluation

The amendment to the German Climate Protection Act (Bundesregierung 2021), which came into force on 31 August 2021, tightens the previous climate targets and sets the goal for greenhouse gas neutrality by 2045. By 2030, total emissions are to be reduced by 65% compared to 1990, and in the transport sector by almost 50%. A significant reduction in emissions is therefore necessary in the relatively short term. In road freight transport, however, CO_2 emissions rose by 14% between 2000 and 2020 despite more efficient vehicles (ifeu 2021). This is mainly due to the increase in transport volumes. Mobility- and vehicle-related measures of avoidance, shift and improvement alone can therefore not achieve the short-term goal for 2030 and, above all, the long-term goal of climate neutrality.

The additional use of renewable energies with sufficient potential is thus in all likelihood absolutely necessary in road freight transport. Even though biofuels and biomethane will continue to play a role in the fuel sector in the future, they will not come close to covering the total demand in road transport, especially since a large part could be needed in shipping and air transport. The use of renewable electricity for road freight transport is therefore essential for a complete decarbonisation.

For the local and regional transport segment, battery-electric trucks with a gross vehicle weight (GVW) of less than 12 tonnes are already on the market. Accordingly, the "Overall Concept for Climate-Friendly Commercial Vehicles" of the Federal Ministry of Transport (BMVI) envisages primarily battery-electric trucks in the segment below 26 tonnes GVW (BMVI 2020a). However, heavy-duty vehicles over 26 tonnes GVW and long-distance transport pose a greater challenge for defossilisation due to their high weight and long daily driving distances. According to the "Overall Concept for Climate-Friendly Commercial Vehicles", various approaches are to be tested and promoted here before path decisions are made from 2023 onwards (BMVI 2020a).

One such alternative concept to the use of conventional diesel in trucks with combustion engines are overhead catenary trucks (OC-Trucks) which have been tested within the field tests studied by the BOLD project. To make a sound assessment of their potential contribution towards the mid-term reduction of greenhouse gas emissions, technical, environmental and field test data have been evaluated within the working groups of the BOLD project.

For a comprehensive picture, however, also other alternative technologies have been considered in a comparative assessment, namely Battery Electric Vehicles (BEVs), Fuel Cell Electric Vehicles (FCEV) and the use of Power-to-Liquid (PtL) fuels. Their technological differences call for a life-cycle approach and to look beyond climate impacts, thus also to consider other environmental impacts. Some main findings of the assessment on climate impacts have already been published as part of a policy brief and a background paper (Helms and Jöhrens 2021) within the BOLD project and two scientific papers presented at Vienna Motor Symposium 2021 (Helms et al. 2021) und 2022 (Helms et al. 2022). These findings are now summarised in this report and complemented by the own evaluation of field test data and the presentation of additional environmental impacts beyond greenhouse gas emissions.

4.2 Evaluation of field test data

A large range of operational parameters has been recorded as part of the field tests. Since the conclusions which can be drawn from operational patterns on the field test infrastructure are limited, a focus of the analysis is on energy consumption by operation mode. Schöpp et al. (2020) have analysed the energy consumption in different operation modes based on one OC-truck (El Leon) in the ELISA project. Here, different steps of data cleaning were performed to eliminate invalid values. The analysis differentiates two operation modes: 1) electricity supply from the catenary and 2) energy supply without catenary, thus from the diesel engine/generator or the battery. For the total mileage of 8,317 km[12], an electricity consumption of approx. 16.4 kWh/100 km and a diesel consumption of 28.1 l/100 km were determined. Under the overhead line, where a distance of 172 km was covered, the consumption was 2.6 l/100 km diesel and 93.4 kWh/100 km electricity. Additionally, Schöpp et al. (2021) analysed the energy flow of ELISA OC-trucks in different driving modes. Accordingly, in electric driving mode on average 138 kWh/100 km are transferred from the catenary to the vehicle, but 25.6 kWh/100 km are charged to the battery. In hybrid mode under the catenary 3.9 l/100 km are consumed by the combustion engine and additionally 117 kWh/100 km by battery and electric motor.

The respective consumptions were determined, however, by the sum products of the instantaneous consumption values with the associated time intervals, divided by the mileage in the associated driving mode. Electricity consumption was defined by electricity consumption of the electric motor and not energy supply from the grid via the catenary. Therefore, recuperated energy from braking processes and electricity generated by the internal combustion engine are also counted as electricity consumption. This scope thus does not adequately reflect the electricity consumption from the grid, which is important in the environmental assessment which aims to account for final energy consumption of diesel and electricity. Therefore, further trips of the field test vehicles were analysed by ifeu to derive the final energy consumption also considering the overhead power supply and the energy flows to the battery.

4.2.1 Available data and processing

As of 08 January 2023, eleven vehicles have been in operation in the ELISA project, five in *FESH*, and another five in the *eWayBW* project. All vehicles have a total mass of 9,200 kg and a gross battery capacity of 18.5 kWh, but usage periods and technical parameters of these vehicles differ considerably. The telematics data have been stored on a cloud storage (CarMediaLab) and made available for further analyses. In some cases, there are data gaps due to storage or transmission errors, but also erroneous, implausible values. These occur primarily during the configuration period and the first test drives and have to be considered in the evaluation of the field test data. Therefore, measured values are filtered and corrected; some runs have been partially or completely discarded for the further evaluation. About 27% (8,092) of the runs available for analysis actually had plausible values in terms of a diesel fuel flow and positive voltage at the pantograph and could be used for further analysis.

Depending on the configuration status of the vehicles, the telematics data contain up to 115 variables on the status of the vehicles and their components in addition to environmental variables such as air pressure and ambient air temperature. The data points and status indicators are recorded at 10Hz intervals. The values can be roughly assigned to the subject areas powertrain, power electronics, battery, pantograph, catenary and vehicle including its ambient conditions and data logger.

The data analysis here has a focus only on the consumption of final energy for which the following data cleaning steps have been performed:

1. Only runs with a minimum driving distance of 50 km, a diesel fuel flow and a positive voltage at the pantograph have been considered. This ensures that only operational runs are considered and also significant driving without catenary is included, to level out effects of a catenary charged battery on conventional driving.
2. Remaining valid runs are purged of implausible values of the variables necessary for further analysis. Elimination thresholds for data cleaning are documented in Table 6.

[12] It has to be noted that the following consumption values are for first generation field test vehicles with a limited battery capacity of 18.5 kWh.

Table 6: Elimination Thresholds of the variables used for energy consumption assessment.

	Elimination threshold
Voltage of the battery	0 V ≤ BatteryVoltage ≤ 800 V
Current of the battery	-500 A ≤ BatteryCurrent ≤ 500 A
Voltage at pantograph	0 V ≤ MeasuredVehicleVoltageGbox ≤ 800 V
Current at pantograph	-500 A ≤ MeasuredVehicleCurrentGbox ≤ 500 A
Time difference	≤ 0.15s
Odometer difference	≤ 0.04km
Vehicle speed	≤120km/h
Current of Electric Machine	-300 A ≤ EM_Current ≤ 300 A
Voltage of electric machine	-300 V ≤ EM_Voltage ≤ 300 V
Battery state of charge	0% ≤ BatterySOC ≤ 100%

Based on these selection steps, a total of 8,961 km of driving under and 160,909 km off the catenary remain to determine the final energy consumption of six vehicles in the ELISA and *FESH* project (see Table 7). Based on this sample, the electrical power and fuel consumption per kilometre are determined. A distinction is made between two main operating phases: **catenary operation** with energy supply from the catenary and **conventional operation** without catenary. These two phases are distinguished by the status message of the pantograph. Connection to the catenary is considered to be catenary operation, all other distances as conventional operation.

The determination of the route-specific energy consumption is carried out according to the following calculation rules:

- Fuel Consumption:

$$fc_{phase}\left[\frac{l}{100km}\right] = 100 \times \frac{\sum(t_{n+1,phase} - t_{n,phase})[h] \times fuelrate_{n,phase}\left[\frac{l}{h}\right]}{\sum mileage_{n,phase}[km]}$$

- Electric Energy Pantograph:

$$ec_{panto}\left[\frac{lkWh}{100km}\right] = 100 \times \frac{\sum(t_{n+1,panto} - t_{n,panto})[h] \times voltage_{panto\,,n}[V] \times current_{panto,n}[A]}{\sum mileage_{n,panto}[km] \times 1000}$$

- Electric Energy Battery:

$$ec_{batt,phase,}\left[\frac{lkWh}{100km}\right] = \frac{\sum(t_{n+1,phase} - t_{n,phase})[h] \times voltage_{batt,phase,n}[V] \times current_{batt,phase,n}[A]}{\sum mileage_{phase,n}[km] \times 10}$$

Table 7: Parameters of the investigated trucks and the driving performance in the investigated operating phases.

Vehicle	Test-Site	Vehicle parameters	Mileage			
		Drivetrain	Conventional operation	Catenary operation	total	Share catenary operation
Femina	ELISA	HEV	11,752 km	639 km	12,392 km	5%
Fidel	ELISA	HEV (Shaefer DC/DC)	6,546 km	574 km	7,120 km	8%
Fondo	ELISA	HEV (Shaefer DC/DC)	12,601 km	655 km	13,256 km	5%
Lennon	*FESH*	HEV (Shaefer DC/DC)	39,646 km	3,450 km	43,097 km	8%
Leon	ELISA	HEV (Shaefer DC/DC)	81,096 km	3,062 km	84,158 km	4%
Salto	ELISA	HEV	9,268 km	581 km	9,848 km	6%

4.2.2 Results for the environmental assessment

In total, almost 9,000 km of catenary operation have been analysed. Here, the six OC-trucks consumed 125.7 kWh/100 km and additionally 4.2 l/100 km of conventional diesel. In conventional operation (162,000 kilometres have been analysed), fuel consumption was 27.3 l/100 km (see Table 8).

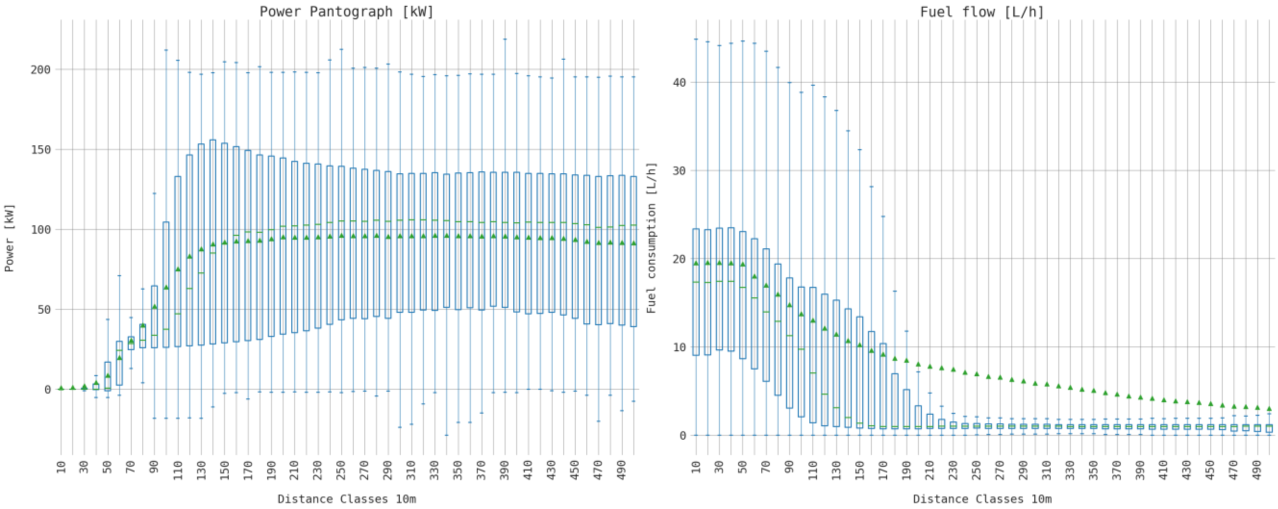
Table 8: Results of the average mileage specific energy and fuel consumption for the two investigated operating phases (catenary and conventional).

	Diesel consumption	Electricity from grid	Mileage
Catenary operation	4.2 l/100km	125.7 kWh/100km	8,961 km
Conventional operation	28.6 l/100km	NA	160,909 km
Total	27.3 l/100km	6.6 kWh/100km	169,870 km

It was observed, however, that the first 150 m after the connection to the overhead catenary are characterised by a continuous increase in electricity consumption from the catenary and a decrease in diesel consumption (see Figure 18). This phase (here coupling) thus leads to an overestimation of the diesel and underestimation of the electricity consumption under the catenary in Table 8, because the sections of catenary operation in the field tests are relatively short and the trucks are not yet continuously coupled to the catenary. In a scenario with a developed infrastructure, two effects should therefore be taken into account, which essentially concern consumption in catenary operation:

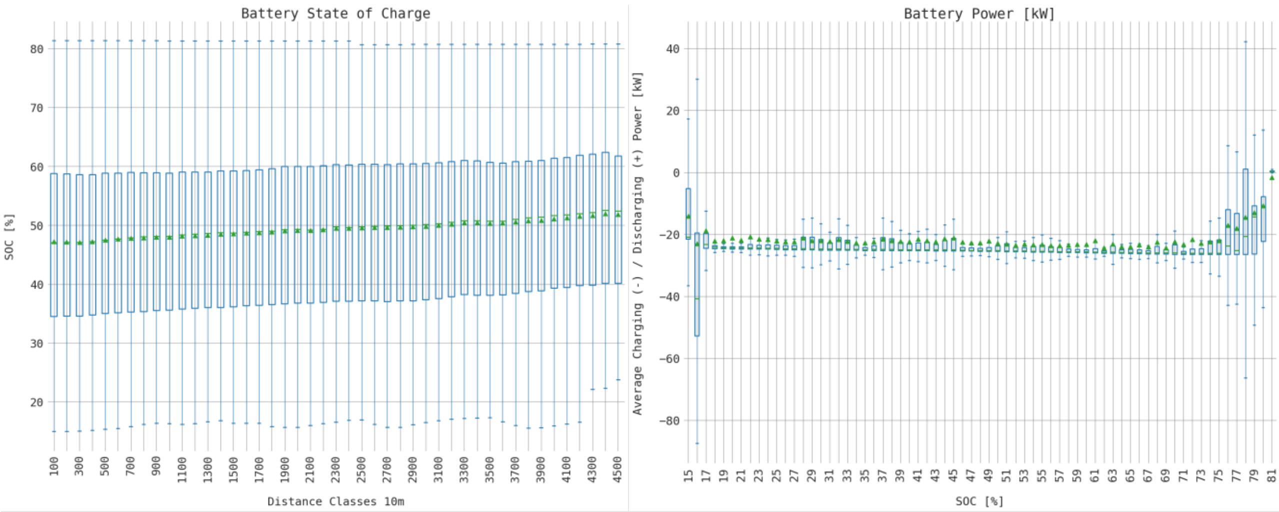
1. Storage of electrical energy into the battery during catenary operation (Figure 18, left)
2. Continued diesel consumption as well only slowly increasing electric power consumption via the pantograph directly after coupling to the catenary in relation to the respective overall averages during catenary operation (Figure 18).

Figure 18: Fuel flow distribution of the engine (right) and electrical power consumption distribution (left) at the pantograph over the driven distance during overhead line operation after coupling to the overhead line.



In order to be able to represent a long-distance overhead line extension, the diesel and electricity consumption in the overhead line phase was determined in a further step without the first coupling phase. This results in an electrical consumption of 127.47 kWh/100 km instead of 125.7 kWh/100 km and a diesel consumption of 2.9 instead of 4.2 l/100 km in catenary operation (see Table 9). In addition, immediately after coupling, if the battery charge status (SOC) is below approx. 80%, the traction battery is charged with an average of 27.1 kWh/100 km (see Figure 19)

Figure 19: Distribution of the battery state of charge over the driven distance (left) and charging or discharging power distribution in dependence of the state of charge (right) during overhead line operation.



SOC at the time of coupling with the catenary is on average about 49% (see Figure 19, left) and charging ends at about 80%. To calculate the potential energy consumption of a hybrid catenary truck (configurations as in Table 10) in the two operation phases under a developed infrastructure, the following equations are used:

- Conventional operation:

$$fc_{conv.}[l] = 28.6\ \frac{l}{100km} \times \frac{distance_{conv.}[km]}{100}$$

- Catenary operation:

$$fc_{cat.}[l] = 2.9\,\frac{l}{100km} \times \frac{distance_{cat.}[km]}{100}$$

$$ec_{cat.,SOC\leq 0.8}[kWh] = 127.4\,\frac{kWh}{100km} \times \frac{distance_{cat.,SOC\leq 0.8}[km]}{100}$$

$$ec_{cat.,SOC>0.8}[kWh] = 100.3\,\frac{kWh}{100km} \times \frac{distance_{cat,SOC>0.8}[km]}{100}$$

with

$$distance_{cat,SOC\leq 0.8}[km] = \frac{(0.8 - 0.49) \times battery\_capacity[kWh]}{27.1\,\frac{kWh}{100km}} \approx 21km$$

$$distance_{cat,SOC>0.8}[km] = distance_{cat}[km]\text{-}distance_{cat,SOC\leq 0.8}[km]$$

- Total:

$$fc_{total}[l] = fc_{conv.}[l] + fc_{cat.}[l]$$

$$ec_{total}[kWh] = ec_{cat.,SOC\leq 0.8}[kWh] + ec_{cat.,SOC>0.8}[kWh]$$

Table 9: Mileage specific fuel and energy consumption calculation parameters of different operation phases13

	Diesel consumption	Power consumption catenary
Catenary operation (short catenary distances, measured)	4.2 l/100 km	125.7 kWh/100 km
Conventional operation (measured)	28.6 l/100 km	NA
Catenary operation (long catenary distances, SOC ≤ 0.8, calculated)	2.9 l/100 km	127.4 kWh/100 km
Catenary operation (long catenary distances, SOC > 0.8, calculated)	2.9 l/100 km	100.3 kWh/100 km

4.3 Environmental comparison of catenary trucks with different technologies

4.3.1 Goal and scope of the environmental comparison

Currently there is no series production of dedicated overhead catenary trucks and no ERS infrastructure with open access. The operation of the field test trucks therefore has been limited to just few kilometres of catenary infrastructure. This also means that the usage patterns as well as the test vehicles do not yet reflect a potential operation in a mass market with developed infrastructure. In addition, hydrogen and charging infrastructure for fuel cell and battery electric trucks is still limited. Therefore, the assessment of the potential contribution of overhead catenary trucks and other alternative truck technologies needs to consider a projected future infrastructure and energy system. 2030 has been chosen as a reference year because a developed infrastructure

[13] Losses of the energy supply of the overhead line are not considered in Table 4 and thus need be added in the further environmental assessment.

and a mass vehicle market could be developed by 2030 if according path decisions are made (see (Jöhrens et al. 2020; Jöhrens et al. 2022)).

The goal of the analysis is thus to compare the lifecycle climate impacts of various alternative truck technologies and fuels entering the market in 2030. The main temporal adjustment made compared to the current situation are a developed infrastructure for energy transfer (i.e. a basic ERS infrastructure, hydrogen refuelling stations and public charging infrastructure), changes in the German electricity mix according to the current political framework, improvements in vehicle energy efficiency, changes in the fossil and renewable fuel supply and improvements in fuel cell and battery manufacturing (e.g. material composition, energy density, energy demand for production and production electricity). Vehicles entering the market in 2030 will also benefit from further defossilisation of energy production over their use phase, which is assumed to be 7 years. That means a vehicle usage between 2030 and 2036.

Trucks and articulated lorries are responsible for the majority (75%) of greenhouse gas emissions in road freight transport (ifeu 2021), so that alternative drive concepts can make a significant contribution to achieving the climate targets. Therefore, the **product system** of a generic articulated truck with a gross vehicle weight of 40 t is selected to compare different technical options for defossilisation in road goods transport. For this exemplary truck, the following alternative drivetrains and fuel options are assessed:

- Internal Combustion Engine Vehicle (ICEV) using
    - a) Conventional diesel fuel and
    - b) Power-to-Liquid (PtL) diesel
- Battery Electric Vehicle (BEV)
- Overhead Catenary Hybrid-Electric Vehicle (OC-HEV) with an electric motor and an additional diesel engine
- Overhead Catenary Battery-Electric Vehicle (OC-BEV) with a larger battery instead of the additional diesel engine
- Fuel Cell Electric Vehicle (FCEV) using
    - a) hydrogen produced from steam reforming (SMR) of natural gas (common today) and
    - b) hydrogen produced through electrolysis (Mix DE)

The assessment is mostly a technical comparison of vehicles similar in size and utility, which are in this case largely defined by the vehicle type (articulated truck) and size class (GVW of 40 t) as the **functional unit**. The average annual mileage of this truck category in Germany according to the TREMOD Trend Scenario (ifeu 2020) in 2030 is almost 117,000 km. This value is used to make plausible assumptions on the minimum driving range and life-time mileage. A minimum driving range of 500 km is defined, because the average annual mileage would require a daily driving distance of 467 km if 250 working days are assumed. If use patterns significantly deviate from this average, the daily range can be expanded by using fast chargers. This minimum driving range is mostly relevant to specify the BEV battery capacity and the hydrogen tank of FCEV, while the driving range of ICEV and ERS can easily be higher without significant adjustments.

For the technical comparison, the same use profile is assumed for all considered options even though in practice the driving range differences may lead to different use profiles and life-time mileages. Such potential differences are neglected since there is no broad evidence yet for new powertrain concepts which are just entering the market. The average life-time mileage is assumed to be 800,000 km, which will be reached after almost 7 years of operation with the average annual mileage. This value was also used as average in a comprehensive study for the EU commission by (Hill et al. 2020).

For goods transport, the tonne-km is often selected as the main **reference flow** because different payloads may apply due to technical restrictions (e.g. a high battery weight). In practice, however, such constraints are not always applicable since vehicles are not always operated at full load. The overall average load factor in

Germany for 40 t trucks according to TREMOD (ifeu 2020) is 46%, already indicating that a considerable share of transport is not weight limited. With an assumed empty weight of today's diesel truck in the range of 15 t, articulated trucks in Germany thus have an average payload of 11 tonnes which is well within the maximum load capacity of all considered drivetrain options. Therefore, the same average absolute payload of 11 t is assumed for all drive trains in a vehicle-km based technical comparison. This leads to different vehicle curb weights due to additional drive train specific components such as the battery. The impact of these different vehicle curb weights on energy consumption will be considered accordingly.

The **system boundary** covers the whole life cycle of the vehicles themselves, from manufacturing and fuel/ electricity production to the use phase (including maintenance) and the end-of-life (including battery recycling). Infrastructure for energy production is included due to the significance for renewable energies (e.g. solar power) for which impacts only originate from infrastructure. Since all vehicles analysed have the same need for road infrastructure (e.g. streets or parking spaces), these elements have been omitted. Nevertheless, differences in road wear might occur due to different vehicle weights, but are expected to have a neglectable overall effect.

Since charging and refuelling infrastructure can also be relevant in a comparative assessment of alternative powertrains (e.g. fast charging, hydrogen pumps, road electrification), a rough first assessment of potential climate impacts from this additional infrastructure has been undertaken (see (Helms et al. 2022)), assuming that

- BEV trucks will be charged overnight in the depot and use additional publicly accessible high-power charging (HPC) infrastructure for intermediate charging along the way,
- OC-HEV will require a network of catenary lines and OC-BEV will most likely additionally be charged overnight in the depot,
- FCEV will require dedicated hydrogen refuelling stations (HRS).

Hereby only roadside power infrastructure is considered. Thus, no potentially necessary upgrading of medium voltage electricity grids is considered. The scope thus only considers the components between the medium voltage connection and the vehicles (energy transfer). Operational energy (e.g. compression of hydrogen) and conversion losses associated with this infrastructure are included in the pre-chain emissions of the use phase.

4.3.2 Background data of the comparison

4.3.2.1 Vehicle production, maintenance and energy consumption

Due to the high life-time mileage of heavy-duty vehicles, **vehicle production** is expected to only play a minor role in the lifecycle climate impacts. A focus has therefore been on the components which differ between the different drive train concepts. Several updates have been considered for the final results presented here compared to the previous results published in (Helms et al. 2021; Helms et al. 2022).

For the background system (i.e. material provision and partly also components), the transparent and quality-checked LCA data from the Swiss ecoinvent database (cut-off system model) have been used in the version 3.8 (see (Wernet et al. 2015)) for all materials and energy. Values for material composition are based on a combination of different data sources, namely (Wollf et al. 2020) for the tractor production and (Argonne National Laboratory 2021) for the trailer. **Maintenance** was recalculated based on the replacement intervals of different vehicle components with a differentiation between electric and conventional trucks.

Differing vehicle components such as the electric drivetrain, the Proton exchange membrane fuel cell (PEMFC) and a hydrogen tank or a battery have afterwards been added or subtracted using the same vehicle glider for all concepts. This approach leads to results for largely comparable articulated trucks with different drivetrains. For all concepts therefore the same 352 kW motor/engine power and a minimum driving range of 500 km (defined above as the functional unit) have been assumed. The battery size of the BEV and the hydrogen fuel tank have then been scaled to allow for this minimum driving range (assuming net battery capacity accounting for 80% of the gross battery capacity or 50% of gross battery capacity for the HEV) (see Table 1). This leads to a 34 kg H2 tank for the FCEV and an 823 kWh battery for the BEV. For OC-HEV and FCEV a battery capacity of 72 kWh is assumed. The differing components lead to differing total vehicle weights which also affects energy consumption and available payload.

Table 10: Vehicle specifications

	Diesel	BEV	OC-HEV	OC-BEV	FCEV
Total Vehicle weight [t]	15.1	19.2	15.6	16.0	16.0
Motor/Engine power [kW]	352	352	352 / 352	352	352 (200 kW PEMFC)
Battery size [kWh]		823	72	160	72

The life cycle inventory for the electric powertrain and the vehicle battery were derived based on previous own modelling for passenger cars (see (Agora Verkehrswende 2019; Kämper et al. 2020)). Technological developments for the traction battery are particularly relevant for the differences between the drivetrain concepts. For 2030 an 8-1-1 NMC (nickel-manganese-cobalt) battery cell with an energy density of 200 Wh/kg at battery system level was modelled based on (Dai et al. 2017; Ellingsen et al. 2014; Dai et al. 2018). Battery recycling impacts were derived with data from GREET and EverBat (Dai and Winjobi 2019) . Accordingly, the carbon footprint of battery production and end-of-life in 2030 is about 60 kg CO_2eq/kWh.

The fuel cell electric truck uses two 100 kW PEMFC with the same basic design as the fuel cell for electric cars modelled by ifeu in (Agora Verkehrswende 2019). Modelling of the fuel cell is based on (Simons and Bauer 2015). For 2030, improvements in fuel cell design and lower platinum loadings were assumed leading to an impact of 25 kg CO_2eq per kW of fuel cell. Further impacts of the FCEV production are due to the hydrogen tanks. Here, a type IV hydrogen tank with 700 bar using carbon-fibre-reinforced plastic (CFK) is assumed and modelling of the tank is based on (Dai et al. 2016). To manufacture CFK, high amounts of electricity are needed. This is the main contributor to the greenhouse gas emissions of 372 kg CO_2eq per kg tank capacity in 2030.

To date, it is not clear how many batteries might be needed over the life-time of a BEV truck in 2030 and also the fuel cell might have to be replaced. The defined battery capacity of the BEV will have to go through almost 2,200 full cycles over the assumed life-time of 800,000 km. Therefore, a second battery might be needed during the vehicle life. For transparency reasons, a potential second battery and also a potential second fuel cell will be displayed separately. Vehicle **energy consumption** has already been derived for all considered drive train concepts with an average payload of 11 t in (Helms et al. 2021). The effect of different total vehicle weights (see Table 7) on energy consumption was considered. These energy consumption values are also used in the results presented here and only adapted for OC-HEV. For OC-HEV field test data shows that also relevant diesel consumption can be expected under the catenary, e.g., for acceleration and overtaking, which has not been considered so far. In order to still allow for a comparison with the other energy consumption values derived for 2030 vehicles, the total electric energy consumption documented in (Helms et al. 2021) is thus only differentiated into diesel and electricity consumption based on the field test values in Table 9[14]. Efficiency differences between electric motor and diesel engine are taken into account. Under the catenary, an energy consumption of OC-HEV is thus 3.4 l/100 km of diesel fuel and 107.3 kWh/100 km. These values are assumed for all highway driving leading to total cumulative values for the assessment as shown in Table 11.

[14] Equal shares of short catenary distances and long catenary distance > 0,8 SOC have been assumed.

Table 11: Energy consumption with average load of 11 t (* cumulative values)

	Diesel	BEV	OC-HEV*		OC-BEV	FCEV
l/kWh	26.5 l	137 kWh	11 l	70 kWh	124 kWh	6.8 kg
MJ	857 MJ	494 MJ	663 MJ		445 MJ	820 MJ

4.3.2.2 Energy provision

For all options, domestically produced electricity with the average German grid mix is considered. Nevertheless, for hydrogen and especially synthetic fuels the import from countries with more favourable conditions for renewable electricity generation is being discussed, e.g. from the so-called MENA region (Middle East and North Africa). However, hydrogen imports require new transport solutions. Thus imports from more distant regions will probably only play a role in the medium to longer term - if transport costs are reduced (Matthes 2021). For PtL existing transport solutions could be used, but these import options presuppose that the necessary production capacities for PtL can be built up by 2030. Although the export potential is theoretically large, this approach is associated with considerable geopolitical challenges and new dependencies. In addition, it must be ensured that sustainability criteria with regard to political, social and ecological requirements are met alongside the economically and technically demanding technology ramp-up. Therefore, production with the German electricity mix is considered here as the potential fall-back option.

It has to be noted, however, that the operation of electric trucks or the domestic production of hydrogen or synthetic fuels then leads to an increase in electricity demand in Germany. The so-called "marginal electricity mix" used to cover this additional electricity demand can then deviate from the average electricity mix (calculated across all consumers). In a short-term perspective with an unchanged power plant park and given feed-in of renewable electricity, the electricity demand of additional consumers is usually covered by higher utilisation of natural gas or coal-fired power plants. Under certain conditions, it is also possible to use otherwise deactivated renewable energy during periods of strong winds or high solar radiation. However, consumers are constantly being switched on and off in the electricity grid and it is therefore hardly possible to assign a clear marginal electricity mix to certain consumers. Furthermore, electricity consumption is also increasing in other sectors (e.g. through heat pumps in the building sector), effects can thus hardly be separated, while other sectors lower their electricity demand due to efficiency improvements.

For a 2030 perspective, the assessment must also take the changes in the German power plant composition into account that will result in the medium term in order to correctly depict cause and effect. For example, the current support instruments for renewable energies are aligned with the relative expansion targets in the electricity sector (80% in 2030 according to the latest coalition agreement). Therefore, in order to meet the additional electricity demand for the operation of trucks, renewable generation capacity must also be expanded more strongly in order to achieve these targets. These additional generation capacities are therefore additionally supported within the German renewable energy law (EEG) due to the additional demand from electric trucks. Furthermore, there is emissions trading, which ensures that higher electricity demand from electric trucks leads to rising certificate prices, which in the short term favours the use of gas instead of coal and in the medium term also provides an additional incentive to expand renewable energies. In order to take these effects into account, to enable equal treatment of consumers and to avoid double counting, the consideration of the average electricity mix has become widely accepted today for policy direction analysis. In the long term, the approaches will converge due to the expansion of renewable energies and the coal phase-out.

The future development of the German grid mix is a key factor influencing the emissions for electric vehicles. In recent years, greenhouse gas emissions of the German grid mix have decreased significantly and policy developments such as the planned phase out of coal power are expected to lead to further significant improvements in the coming years, despite a temporary increase in the use of coal power. In 2020, the share of renewable energies in electricity generation in Germany was already at 46%, and a current scenario for achieving greenhouse gas neutrality in Germany in 2045 (Prognos AG et al. 2021) envisages an increase to almost 73% by 2030. To quantify this scenario in terms of greenhouse gas emissions, data from (Hill et al. 2020) have been used covering the emissions for different electricity generation types. The climate intensity of electricity supply would accordingly be halved from 440 g CO_2-equivalents per kilowatt hour in 2020 to 215 g CO_2-equivalents per kilowatt hour in 2030 if the targets in the electricity sector are met.

Hydrogen production has been calculated a) via steam reforming using natural gas and b) from electrolysis with the German grid between 2030 and 2036. For hydrogen production via steam reforming, ifeu has used various process data from plant operators that have been aggregated into a generic value of 88 g CO_2eq/MJ of H_2. For the modelling of hydrogen production via electrolysis a comprehensive LCA model for PtX is used. This model has already been used in previous ifeu studies and is continuously updated. The data used here consider a decentralised hydrogen production using the expected German electricity mix over the vehicle life from 2030 (see above). The German 2030 to 2036 grid mix used in this study leads to 83 g CO2eq/MJ of H2. Hydrogen is then compressed to 900 bars for dispensing.

The GHG emissions for PtL diesel production with the German grid mix between 2030 and 2036 have been calculated with a similar approach based on the same ifeu data which leads to impacts of 110 g CO_2eq/MJ. The (largely fossil) fuel chain for diesel used is from the latest TREMOD version 6 (ifeu 2020). For biofuel shares, TREMOD assumes that the biodiesel share will increase to 6.5% by 2020 and then remain constant until 2030.

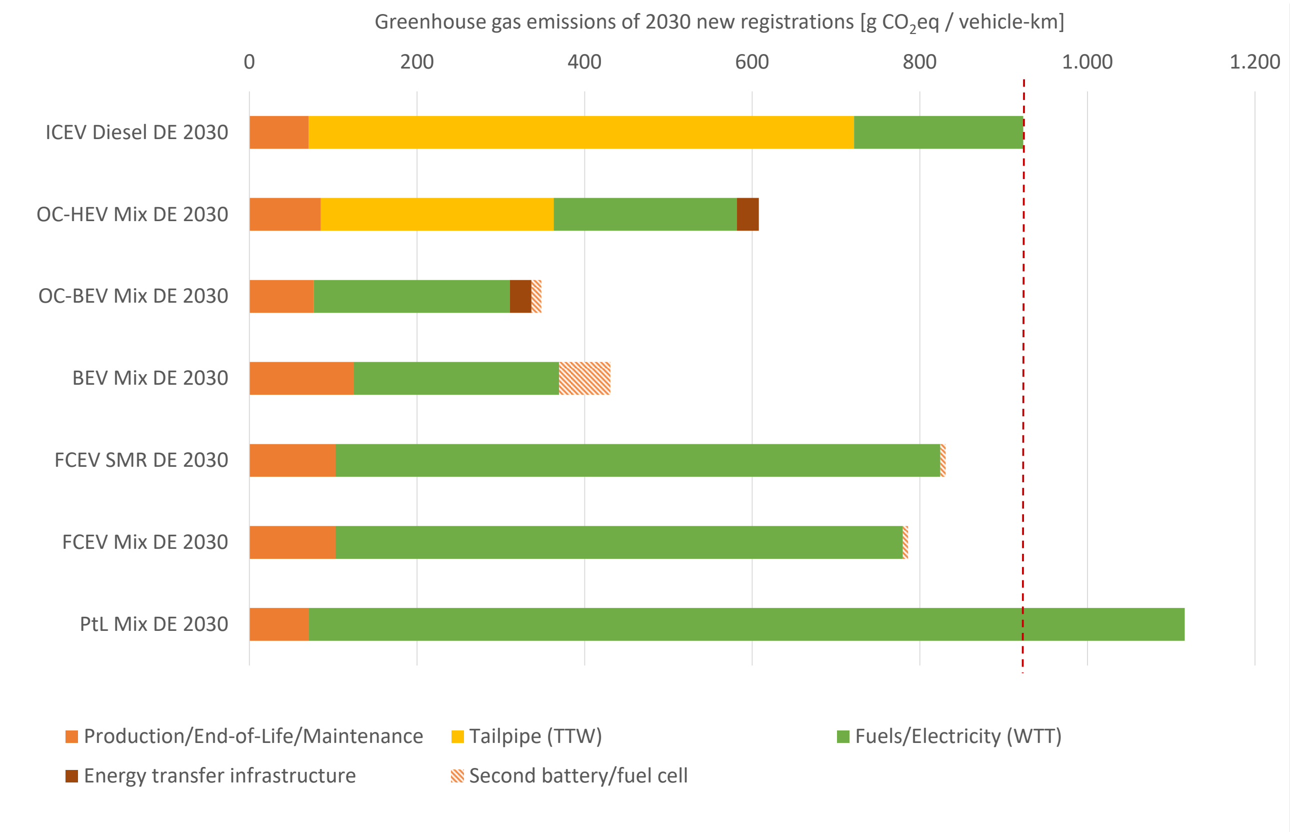
4.3.3 Climate impacts compared

Figure 20 shows the resulting greenhouse gas emissions over the entire life cycle of an articulated truck registered in Germany in 2030 with different drive concepts and fuels per kilometre driven. Climate impacts are assessed as CO_2-equivalent emissions (CO_2e) using the latest global warming potential factors from (IPCC 2013) for a time horizon of 100 years and without climate carbon feedback. Hereby, the potential further defossilisation of use phase energy over the assumed 7 years operational life-time of the vehicles after 2030 has been taken into account. All concepts presented in Figure 20 (except for the fossil-fuelled ICEV and FCEV using H2 from steam reforming) use the expected German electricity mix (Mix DE) between 2030 and 2036. Roadside infrastructure for energy transfer for BEV, FCEV and OC-Trucks has also been considered according to (Helms et al. 2022).

The scenario leads to a significant climate benefit compared to ICEV using conventional diesel fuel in the range of 53-62% for the concepts with direct electricity use, i.e. BEVs and overhead catenary BEVs (OC-BEV). The OC-BEV benefits from the smaller battery compared to long-distance BEVs while still using only electricity. The OC hybrid electric vehicle (OC-HEV), despite the tailpipe emissions still assumed off the motorway (about 35% of the driving distance) and partly also under the catenary for acceleration and overtaking, still shows a significant reduction potential of about 34% compared to a diesel ICEV.

In contrast, the greenhouse gas reduction potential of the fuel cell electric vehicle (FCEV) using hydrogen produced via electrolysis in Germany is around 15% and thus much lower. The use of synthetic diesel (PtL) based on this hydrogen even leads to higher climate impacts as expected for the diesel truck in 2030. The reason for this comparably unfavourable climate balance of hydrogen and synthetic diesel produced with the German grid mix are the high conversion losses. In order for hydrogen to contribute to climate protection, additional renewable energies would have to be tapped for their production in the next decade. But whether a use of genuine additional renewable electricity for the production of green hydrogen can be established in Germany, is still questionable (Helms and Jöhrens 2021). The use of hydrogen from steam reforming – the prevailing method of hydrogen production today - leads to even smaller climate benefits of 10% due to the use of a fossil energy carrier only.

Figure 20: Greenhouse gas emissions of articulated trucks (40 t GVV) registered in 2030 with different drive trains or fuel types including infrastructure for road side energy transfer. Typical usage parameters in Germany (800,000 km mileage over 7 years of operation, 11 t average payload, German electricity mix).



Sources: Own presentation based on (Helms et al. 2021; Helms et al. 2022). TTW = Tank-to-Wheel, WTT = Well-to-Tank.

Due to the challenges of a massive expansion of renewable energies in Germany as well as the partly limited suitability of German locations in international comparison, the import from favoured producer countries is being discussed, especially for hydrogen and synthetic fuels, e.g. from the so-called MENA region (Middle East and North Africa). The National Hydrogen Strategy 2030 sees only a fraction of the projected demand covered by domestic production. However, hydrogen imports from more distant regions will probably only play a role in the medium to longer term, if transport costs are reduced (Matthes 2021). In contrast, PtL in road transport foreseeable only makes sense as a renewable import. However, the advantages of renewable PtL production may be limited due to the emissions associated with the construction of the production infrastructure. ifeu calculations on supply paths for PtL from Morocco (Liebich et al. 2020) show that the capacity utilisation of the production plants is an important variable here. This is reflected not only in terms of costs, but also in the carbon footprint. The import of electricity-based fuels also leads to new dependencies and sustainability issues.

In the MENA context, however, at least financially induced additionality is conceivable compared to the situation in Germany and is being discussed in the context of development cooperation. However, these import options presuppose not only a high potential for renewable electricity generation in the potential countries of origin, but also that the corresponding production capacities for PtL can be built up by 2030. Although the export potential is theoretically large, this approach is associated with considerable geopolitical challenges and new dependencies. In addition, it must be ensured that sustainability criteria with regard to political, social and ecological requirements are met alongside the economically and technically demanding technology ramp-up. To this end, in particular the potential for domestic use of renewable electricity should already be utilised before the electricity is converted to PtL or hydrogen with energy losses and then exported.

4.3.4 Further environmental impacts compared

To complement the picture on climate impacts, further environmental impacts have been calculated, namely the following:

- **Cumulative energy demand (CED)** is an indicator for the primary energy demand per functional unit. It thus complements the indicator climate change. CED is not an environmental impact but a resource indicator. In view of the fact that a significant share of energy 2030 may still be obtained from fossil fuels and the availability of renewables remains will remain limited, the efficient use of energy is an important objective.
- **Acidification** means a lowering of the pH value and can be both a natural process and caused or accelerated by human activities. Acidification, among other things, restricts plant growth and reduces agricultural yield. In order to summarise the acidification effect of the different substances for a process, they are converted into the effect equivalent to sulphur dioxide via characterisation factors and expressed as SO_2 equivalents.
- **Eutrophication** stands for nutrient supply in excess and results in increased productivity, but also in a spread of nitrogen-loving plants, which consequently leads to a loss of biological diversity. Phosphate equivalents are used to summarise the eutrophication effect of the different substances for a process.
- **Particulate matter (PM) formation** is used as an indicator for negative effects on human health. A number of international studies show that an increase in particulate matter concentration is associated with a strong increase in mortality due to respiratory and cardiovascular diseases. The indicator PM formation also considers substances responsible for secondary particle formation such as nitrogen oxides and sulphur dioxide. These are summarised equivalents of particles with an aerodynamic diameter of less than 2.5 micrometres (µm) (PM2.5 formation). Only direct emissions from combustion processes are considered, not those from abrasion and resuspension.

In Figure 21, these indicators are shown relative to the conventional diesel truck. It has to be noted, however, that the infrastructure of energy provision is not included in this comparison due to the uncertainty associated with the rough assessment of energy provision infrastructure. In terms of CED, like for GHG emissions, considerable and comparable advantages exist for the concepts with direct use of electricity. The use of hydrogen (FCEV) or PtL produced in Germany leads to a considerably higher primary energy consumption than current diesel technology and also direct use of electricity.

The background to the poor energy efficiency of hydrogen and PtL are the conversion losses. While direct electric drives (OC and BEV trucks) only have low losses due to transmission and, if necessary, intermediate storage in the battery, the additional electricity demand for the use of electrolytically produced compressed hydrogen is about 2.5 times higher (Göckeler et al. 2020a), since the production of hydrogen in the electrolyser and subsequent conversion back into electricity in the fuel cell is associated with energy losses of about 30% and 45% respectively (Matthes et al. 2020). When using synthetic fuels, even 3.5 times the amount of additional electricity is required over the entire conversion chain (Göckeler et al. 2020a). This disadvantage of hydrogen and PtL in CED is still significant in 2030, while greenhouse gas emissions already benefit from a very high share of renewables in 2030.

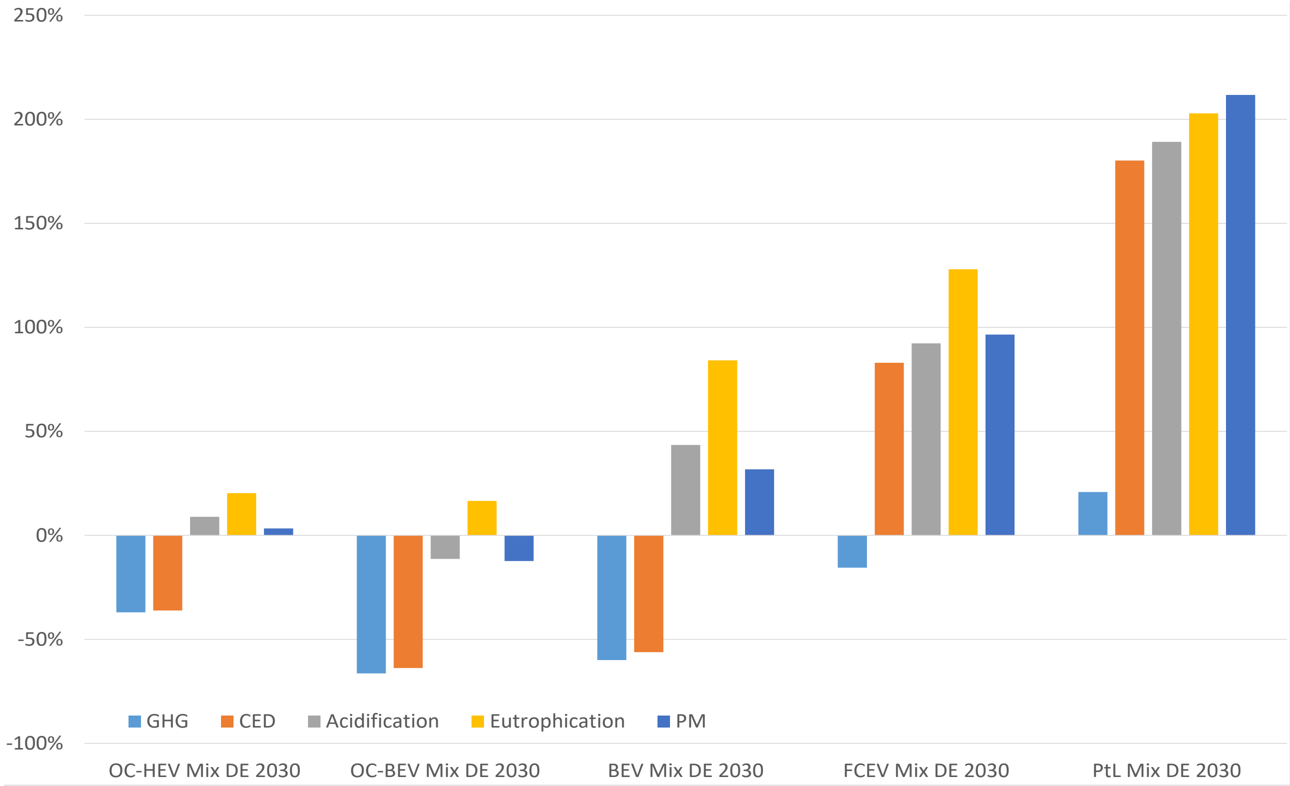
A different picture is evident for the other environmental impact categories, i.e., acidification, eutrophication and PM2.5 formation. Here, the alternative drive trains partly lead to higher impacts than the diesel trucks because vehicle manufacturing contributes significantly to overall impacts. For the use of hydrogen and PtL, also energy provision plays an important role due to the significantly higher energy demand.

- Acidification is caused by vehicle production and energy provision alike and thus increases with battery size and also energy demand. Higher emissions than for diesel trucks are thus associated for BEV due to their large battery and for FCEV and PtL due to the high energy demand. Impacts for OC-trucks, however, are almost comparable to diesel trucks since the energy efficiency is high and battery capacity remains limited. Since direct exhaust emissions of the diesel engine are also relevant, acidification may even be lower for OC-BEV compared to the diesel truck.

- Similarly, eutrophication is caused by vehicle production and energy provision alike. While the disadvantage of OC-trucks compared to the diesel truck remains limited, impacts are almost 80% higher for the BEV truck. For FCEV and use of PtL, the higher energy demand leads to impacts more than two times and three times higher, respectively.
- For PM2.5 formation results for OC-trucks are almost comparable to the diesel truck; possibly even more favourable in case of OC BEV since exhaust emissions are avoided entirely. This advantage is compensated for the BEV by battery production impacts. The additional impacts, however, remain limited at a 28% increase. The high energy demand of FCEV and PtL use again leads to impacts two times and three times higher, respectively.

OC-trucks thus combine a very efficient use of (renewable) energy and thus a high greenhouse gas advantage with no significant disadvantages in other categories. Minor advantages or disadvantages can be neglected in light of the expected uncertainties. Here, a more detailed and robust assessment of the impacts of energy transfer infrastructure should be conducted in future research to complete the picture. A similar energy efficiency and climate benefit can be achieved with BEV trucks but comes with negative impacts in other areas, especially eutrophication. For the use FCEV and PtL, the high overall cumulative energy demand not only limits potential benefits in terms of greenhouse emissions but also leads to high negative impacts in other categories.

Figure 21: Environmental of articulated trucks (40 t zGG) registered in 2030 with different drive trains or fuel types relative to a conventional diesel combustion engine (without roadside infrastructure for energy transfer). Typical usage parameters in Germany (800,000 km mileage over 7 years of operation, 11 t average payload, German electricity mix).



Sources: Own presentation based on (Helms et al. 2021; Helms et al. 2022). TTW = Tank-to-Wheel, WTT = Well-to-Tank.

4.4 Conclusions of the environmental evaluation

Reduction of climate impacts remains a main goal of current environmental policy. Due to the low energy efficiency as well as technical, economic, social and environmental challenges of renewable hydrogen and PtL production, these fuels should mainly be used in areas where no alternatives are available. In industry and air transport in particular, the demand is high and building the necessary capacities to meet this demand remains a challenge.

In road freight transport, on the other hand, direct electric concepts, whether with stationary charging of batteries or dynamic supply via overhead lines, will provide alternatives for large areas of road freight transport that are technically feasible and whose climate balance is advantageous even in the short term within a national framework. Here, OC-BEV have the advantage of direct electricity use combined with a significantly smaller battery compared to BEV-trucks. This not only results in slightly higher greenhouse gas savings, but also significantly reduces other environmental impacts compared to BEV-trucks, e.g. acidification and eutrophication. So, while BEV trucks reduce greenhouse gas emissions, but increase other environmental impacts, no significant adverse effects can be attributed to OC-trucks. At least in terms of greenhouse gas savings, the infrastructure for energy transfer (i.e., catenary lines, charging stations) only has a small impact on the total results.

Concepts with direct use of electricity should therefore be pursued as a matter of priority and only supplemented where their use is limited for technical or economic reasons. Among the concepts with direct use of electricity, reduction of battery capacity should be a secondary goal in order to reduce adverse effect in other impact categories.

5 Expansion of the overhead catenary system

The following discussion on the expansion of the overhead catenary system is based on four comprehensive discussion papers that were developed in the BOLD project. They summarise the existing knowledge on economic efficiency and network expansion strategies for the overhead catenary system (Hacker et al. 2020b), discuss possible interactions of the overhead contact line system with stationary high-capacity fast chargers (Plötz et al. 2021), derive a possible network expansion in Germany (Hacker et al. 2022) and identify challenges and action requirements for the network expansion (Mottschall et al. 2023).

5.1 Overhead catenary (OC) trucks and their necessary energy infrastructure

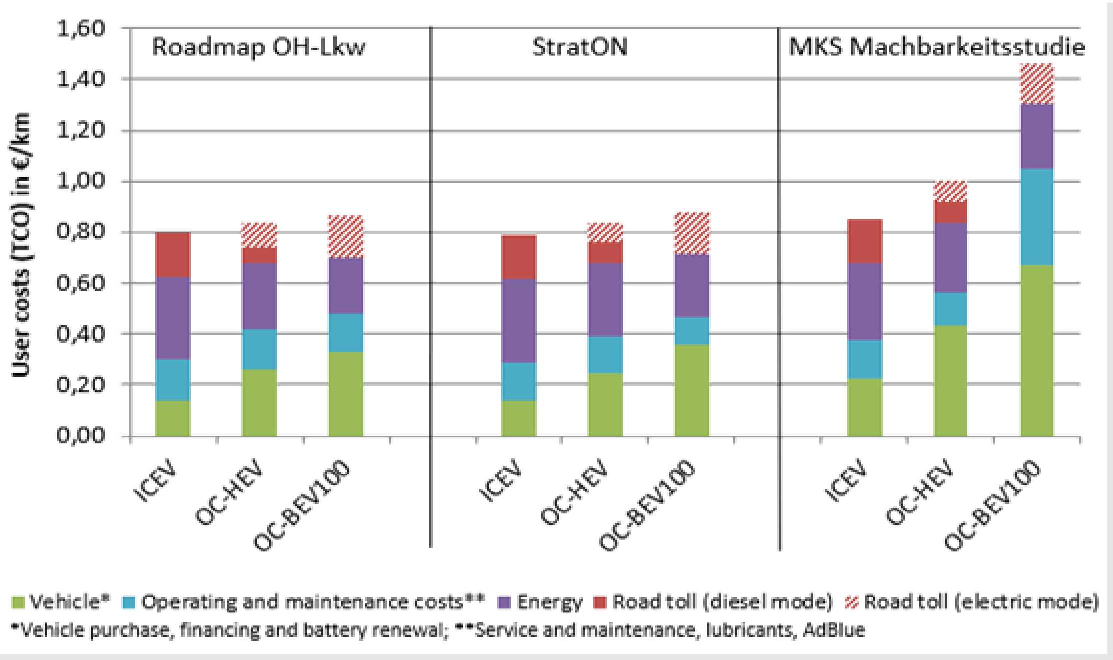
5.1.1 Cost comparison of OC-trucks from different perspectives

The economic viability of OC-trucks concerns the cost-benefit ratio from different perspectives or for different stakeholders. The analyses performed shed light on the costs from the truck operators' perspective, the infrastructure costs as well as the cost balance considering both aforementioned aspects.

Under current conditions, the full cost of using OC-trucks - as with other alternative drive systems - is slightly higher than those of diesel trucks, excluding infrastructure costs. If they succeed in entering the mass market, significant cost savings can be expected compared to diesel trucks.

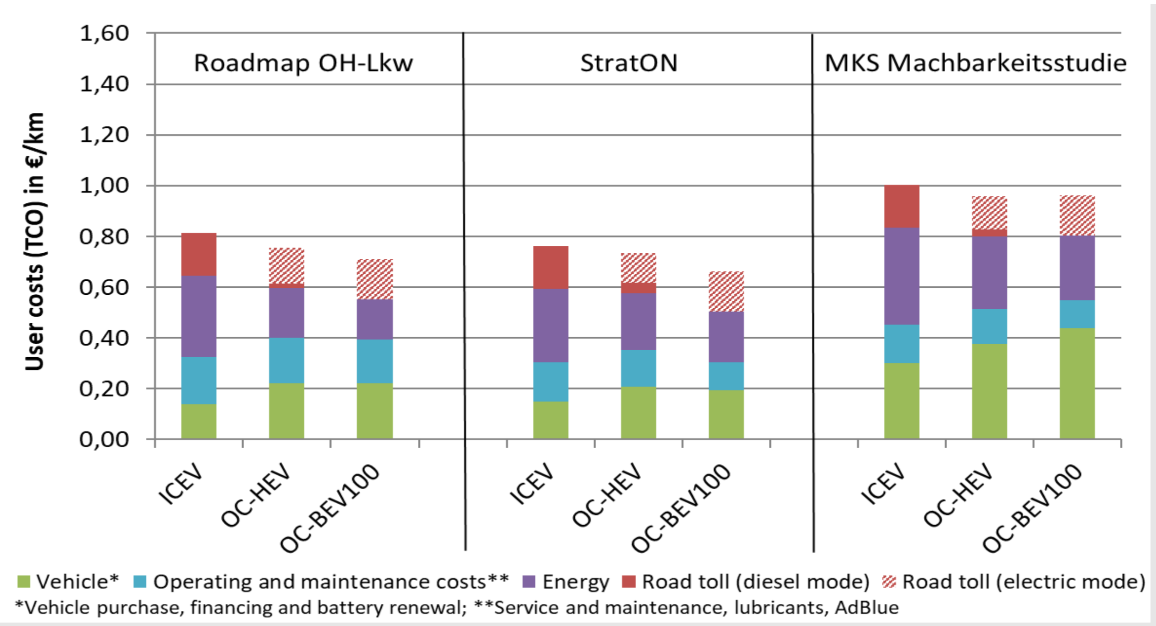
In the following, only the differential costs between overhead line trucks of different configurations and conventional diesel trucks are discussed. Full cost from the truck operator's perspective (total cost of ownership, TCO) is considered for diesel trucks (ICEV), overhead hybrid trucks (OC-HEV) and purely electric overhead trucks, whose traction battery enables a range of about 100 km away from the overhead line (OC-BEV100). Major differentiating cost components are vehicle depreciation, energy costs, and (depending on the regulatory framework) toll expenses. In various studies, the values shown in Figure 22 for the start of an overhead line truck system introduction and the scenario year 2030 were determined for this purpose ((Jöhrens et al. 2020), (Wietschel et al. 2017), (Kühnel et al. 2018)). The studies assume the existence of an overhead line infrastructure on the main axes and a mass market for overhead line trucks. The values shown do not include the cost of building the infrastructure, only the cost for purchasing and operating the vehicles.

Figure 22: User costs of diesel trucks and OC-trucks at the beginning of OC truck deployment[15]



Source: Own representation (Hacker et al. 2020b)

Figure 23: User costs for diesel trucks and OC-trucks (reference year 2030).



Source: Own representation (Hacker et al. 2020b)

[15] The reference year for StratON and the MKS study is 2015, while the reference year for Roadmap OH-trucks is 2020. However, the additional vehicle costs of OC-trucks as the main differing cost component depend to a large extent on the number of units produced and only secondarily on the external framework conditions, which is why the assumed start of system introduction in the studies is chosen as the point of comparison here. Only cost items that are related to the drive system are listed in the diagram. The assumed share of electric driving in the OC-HEV is 55% in Roadmap OH-trucks and the MKS study, as well as 50% in StratON. It should be noted that costs from the necessary replacement of the traction battery during the life of the vehicle are included in the O&M costs in the MKS feasibility study, while they are included in the vehicle costs in the other studies.

The studies considered arrive at significantly different absolute costs, which is primarily due to different definitions of the cost items. However, there are clear parallels with regard to the trends when comparing the drives for the respective year under consideration:

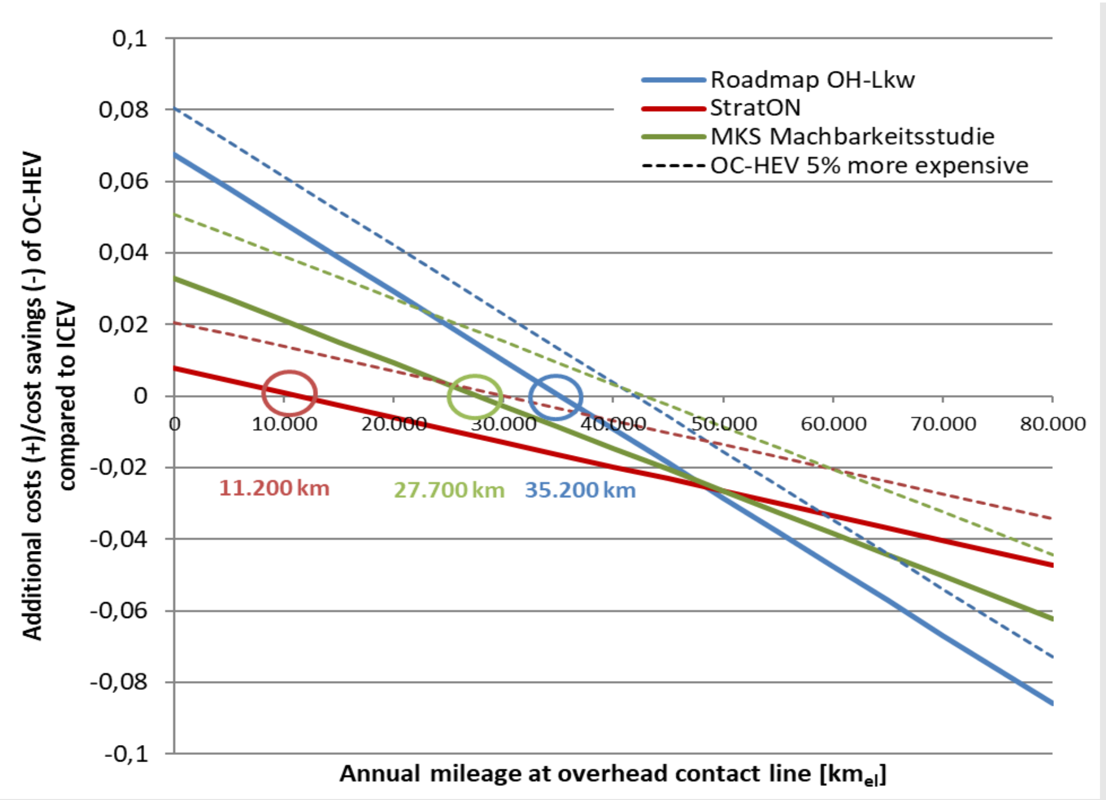
At present, the full costs for overhead line trucks are in most cases slightly higher than the costs for diesel trucks. Only in particularly suitable application profiles (very high proportion of driving under overhead contact line) can an overall cost advantage already be achieved today. The differences in the costs of the OC-BEV primarily stem from differing assumptions on battery costs.

For the year 2030, cost advantages for OC-trucks, in particular for OC-BEVs, are shown throughout. This is mainly due to a more favourable ratio of diesel and electricity costs for OC-trucks and lower costs for the electric drive.

Cost assumptions for technologies that are still at the prototype stage are generally associated with greater uncertainties. Production and development costs are a secret of vehicle manufacturers and can only be roughly estimated. In addition, manufacturers' pricing for technologies newly introduced to the market is determined by various strategic factors, such as legal requirements (CO_2 fleet limits for commercial vehicles from 2025) and incentive measures (e.g. purchase premiums).

From the fixed and variable cost components assumed in the various studies, the economic break-even distance can be calculated in each case, i.e., the distance that a OC hybrid truck must travel at least under overhead contact line in order to achieve an economic advantage over the diesel truck (Figure 24). In the "Roadmap OH-Lkw" project, a break-even of about 35,000 km per year under overhead contact line was determined for the year 2030, which corresponds to about one third of the annual mileage of an average tractor-trailer in Germany. In the other studies, an economic parity is achieved earlier.

Figure 24: Cost difference of OC-HEV to diesel trucks [€/km] depending on mileage under overhead line (reference year 2030).



Source: Own representation

The range in break-even distances between the studies can be explained by the fact that the absolute cost differences between the drives are comparatively small (see Figure 3). Thus, even small differences in energy cost assumptions can significantly shift the break-even distance. However, the order of magnitude proves to be robust. Even an increase in vehicle costs assumed in the studies for OC-HEVs by 5% in each case (dashed lines in Figure 24) does not fundamentally change the findings.

The construction of an overhead contact line base network of about 4,000 km on Germany's most frequented highways would require investments of about 10 billion euros over a period of about 10 years.

To assess the economic viability of OC-trucks from a system perspective, the costs of the vehicle operators and the public sector must be considered together. Differential costs for energy and vehicles are included in the truck operators' costs. Infrastructure costs can, in principle, be pre-funded by the government or the private sector, or financed directly by the users of the system. The costs to the state must also take into account possible changes in energy tax revenues resulting from the change in drive system. Depending on the design of the funding framework, the government may also incur costs to support the market introduction of OC-trucks. In addition, the introduction of an overhead line truck system will in principle also have economic effects (employment effects, effects on other industries, etc.); however, these have not yet been investigated.

Several studies conclude that an OC truck system can only be economically viable from a system perspective once a broad user base has been reached. Overhead catenary truck users in the first phase of system introduction usually have a relatively small cost advantage per km, the absorption of which cannot cover the expenses for construction and operation of the infrastructure. Pre-financing of network construction is therefore required, which in principle can be provided either by the state or by a private operator. As the market for overhead catenary trucks ramps up, there will be better utilisation of the infrastructure, which will then result in lower infrastructure costs per vehicle and enable the infrastructure to be financed by users in the medium term. In the longer term, an overhead contact line system can thus pay for itself financially (Hacker et al. 2020b)).

Since a large proportion of long-distance road freight traffic in Germany is concentrated on a limited part of the trunk road network, the additional benefits and thus the economic efficiency of the system decline again once the overhead contact line infrastructure reaches a certain level of expansion.

5.1.2 Target network for the overhead catenary infrastructure and its impact

A core highway network of around 4,000 km is particularly suitable for the development of an overhead line infrastructure. In Germany, over 65% of long-distance truck traffic on highways takes place on this network, which accounts for only one third of the total network. Individual routes with significant logistical transshipment points at the start and end points show particularly high potential for early electrification. The highway sections between Hamburg and the Ruhr region (A1) and Hamburg and Kassel (A7) are particularly promising.

Figure 25: Target networks in MKS Machbarkeitsstudie, StratON, Roadmap OH-Lkw (from left to right).

Source: Own representation

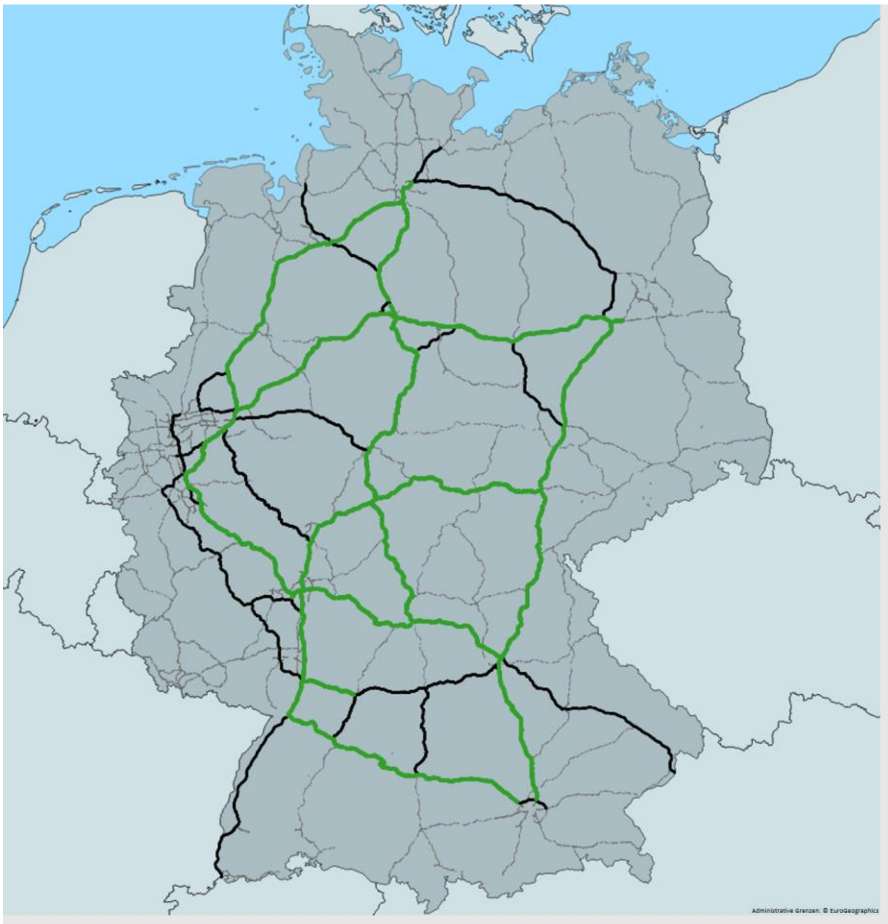
According to the above-mentioned three studies, a share of 8% to 17% of the mileage of heavy commercial vehicles can be covered electrically by OC-trucks by 2030. With full network expansion, an electric share of over one-third is possible in perspective. If the electrification potential is tapped, transport-related emissions from overhead line trucks can be reduced by 2 to 4 million tons of CO_2 by 2030, and by up to 6 million tons of CO_2 if the network is expanded rapidly. In the long term, a reduction of up to 12 million tons of CO_2 can be achieved and road freight emissions can be reduced by about 20%. With a share of 4% of total electricity demand, electricity demand from OC-trucks is of secondary importance compared to electric passenger cars with a share of 14%.

5.2 Possible expansion steps for an overhead catenary infrastructure for road freight transport in Germany

5.2.1 Background / Motivation

While battery-electric drive is also expected to become the dominant standard solution in regional transport for heavy commercial vehicles in the future, gradually displacing the diesel drive that has been predominant to date (BMVI 2020a; Göckeler et al. 2020a) the future technology mix in long-distance transport with significantly more demanding performance requirements is still unclear (Göckeler et al. 2020a). The German government's concept for climate-friendly road freight transport pursues overhead contact line technology - alongside battery electric and fuel cell propulsion - as a technical solution for decarbonising long-distance road freight transport. By 2024/25, the technologies are expected to reach a level of market maturity that will make path decisions feasible. Possible target networks for overhead line infrastructure are identified in various studies for a core network of highways with a total length of about 4,000 km (see also Section 5.1.2) are discussed. However, it has not yet been clarified how the gradual expansion - starting from the current pilot projects with only a few kilometres of overhead contact line - is to take place.

Figure 26: Target networks considered in existing OC-truck studies (corridors considered in all studies = green / corridor considered in at least one study = black).



Source: Own representation (Hacker et al. 2022)

In the following, suitable routes for electrification are identified for different development stages on the basis of central evaluation criteria and possible expansion paths are shown. For this purpose, central individual criteria are described and classified with regard to their significance at different implementation times and - where possible - discussed with a view to their significance for specific routes of the core highway network. The criteria are both suitability criteria and exclusion criteria, which can be both spatially limited and have a superordinate effect. Their effect can also have a different effectiveness or even direction of effect in different implementation phases. The evaluation criteria identified are discussed in their interplay and with regard to their significance for different phases of network development. Based on this, particularly suitable initial routes and possible network extensions are identified. Finally, possible interactions with the expansion of stationary truck charging stations are discussed.

5.2.2 Importance of evaluation criteria over time

Current pilot tests primarily serve to test the technology under real conditions on public roads. High capacity utilisation and economical operation are not yet the goal. In view of the short distances, further use and integration capability in a future long-distance transport network is also not a central criterion. However, with the increasing expansion of the network and in view of the overriding objective of a far-reaching electrification of road freight transport in a relatively short period of time, the development of relevant traffic volumes and the networking of the infrastructure to be built are becoming increasingly important.

In the analyses, a number of possible criteria for the suitability assessment of overhead contact line routes were identified and evaluated in terms of their relevance at different points in time (Hacker et al. 2022). The results can be summarised as follows (cf. Figure 27):

Characteristics of the vehicle application profiles on the routes in question are highly relevant, especially for the selection of initial routes. For these routes, the primary objective is to ensure a high level of benefit from the infrastructure for selected anchor users. In the case of pilot routes, this enables the rapid collection of practical experience, and in the case of initial expansion routes, it enables reliable basic utilisation of the infrastructure. Suitable application profiles are ideally high-frequency commuter services and generally have low pre- and post-trip distances away from the electrified road section. It is particularly advantageous if a larger number of such suitable transports are clustered at individual anchor users. With increasing network expansion, connection of initial sub-networks and the resulting increase in the number of users, higher-level considerations (e.g. absolute traffic volume, international connections) come to the fore in planning, and the specific needs of individual users become less important.

Road construction projects (rehabilitation/expansion) that are already specifically planned can influence the suitability of individual routes for overhead line construction, especially in the short to medium term: If work on the roadway and the overhead contact line can be combined, the overall impact on traffic can be reduced.

The coordination of overhead contact line construction with other infrastructure measures in both road and rail transport is primarily relevant for medium- to long-term planning. Here, it is primarily a matter of developing long-term infrastructural roadmaps in the sense of a systemically efficient use of all modes of transport.

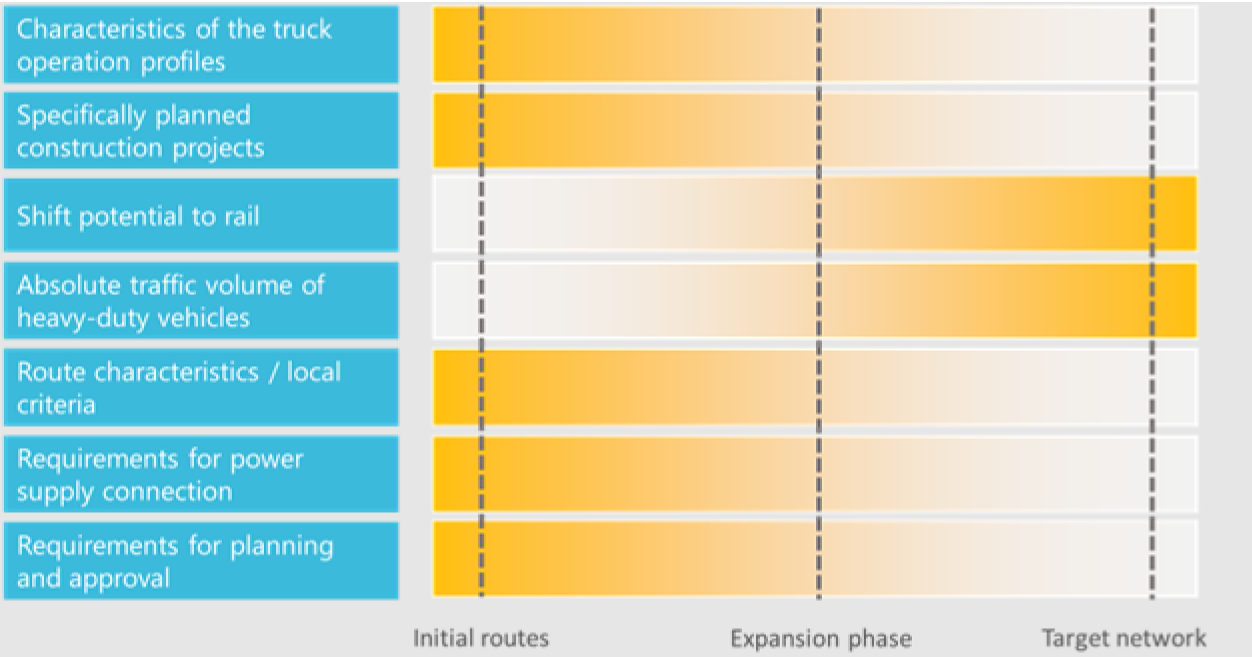
The traffic volume on the routes in question is a good indicator of the user potential of a route in a steady-state system or with an expanded network. It should therefore be used primarily to prioritise network expansion beyond initial routes. Cross-border traffic in particular becomes more relevant as soon as there is concrete interest in international system expansion in neighbouring countries.

Route characteristics as a criterion summarise influences on the feasibility of overhead lines at the local level. Initial estimates show that there are only significant obstacles to the construction of overhead lines on around 6% of the total route on the core network under consideration. Beyond this, however, there are a number of other factors that can complicate planning and approval processes or operation on individual lines. These are primarily relevant as obstacles to the realisation of initial lines. When the network is expanded at a later date, particularly difficult sections can be left out of the electrification process, so the local factors are likely to be of little relevance to the macroscopic planning of an expansion network.

The connection of the overhead contact line system to the power grid is to be evaluated as a criterion in a similar way to the route characteristics: In the case of initial routes, difficulties with the grid connection can significantly delay planning and implementation and should therefore be avoided if possible. In the longer term, the necessary expansion of the fast charging infrastructure for cars and trucks alone will require considerable additional electrical connection capacity to be brought to the federal trunk roads; an overhead line infrastructure simply has to be given appropriate consideration in the planning.

Administrative criteria primarily concern the lead time for planning and approval procedures. This is naturally most relevant for initial routes, and adjustments to the legal framework can also simplify future planning processes.

Figure 27: Relevance of different evaluation criteria for the selection of overhead contact line routes over time.



Source: Own representation (Hacker et al. 2022)

5.2.3 Possible expansion paths

With a view to the criteria discussed above and their importance over time, the analysed routes can be prioritised. Routes that both meet the short-term requirements for electrification and could assume a high significance in a potential future overall network turn out to be particularly advantageous.

Against this background, the Hamburg-Dortmund (A1) route and the connection between the industrial centres of Rhine/Ruhr and Rhine/Main (A3) and Rhine/Neckar (A61) are particularly suitable for initial overhead line corridors. In the case of the latter, no clear preference can be expressed due to the largely parallel course of the routes, since the electrification of a route could also result in traffic shift effects. The Hamburg - Kassel line follows with certain reservations, possibly going as far as Fulda (A7). These high-priority routes are characterised by significant freight handling points (including the port) at the origins and destinations and a resulting high proportion of journeys with low pre- and post-trip distances beyond the routes under consideration, as well as strong commuting relationships. Given the significant industrial and logistics centres at origins, destinations, and along the route, attracting early anchor users with significant transportation service on the route appears likely. In addition, given the capacity constraints of the parallel rail corridors, direct competition to shift to rail is unlikely.

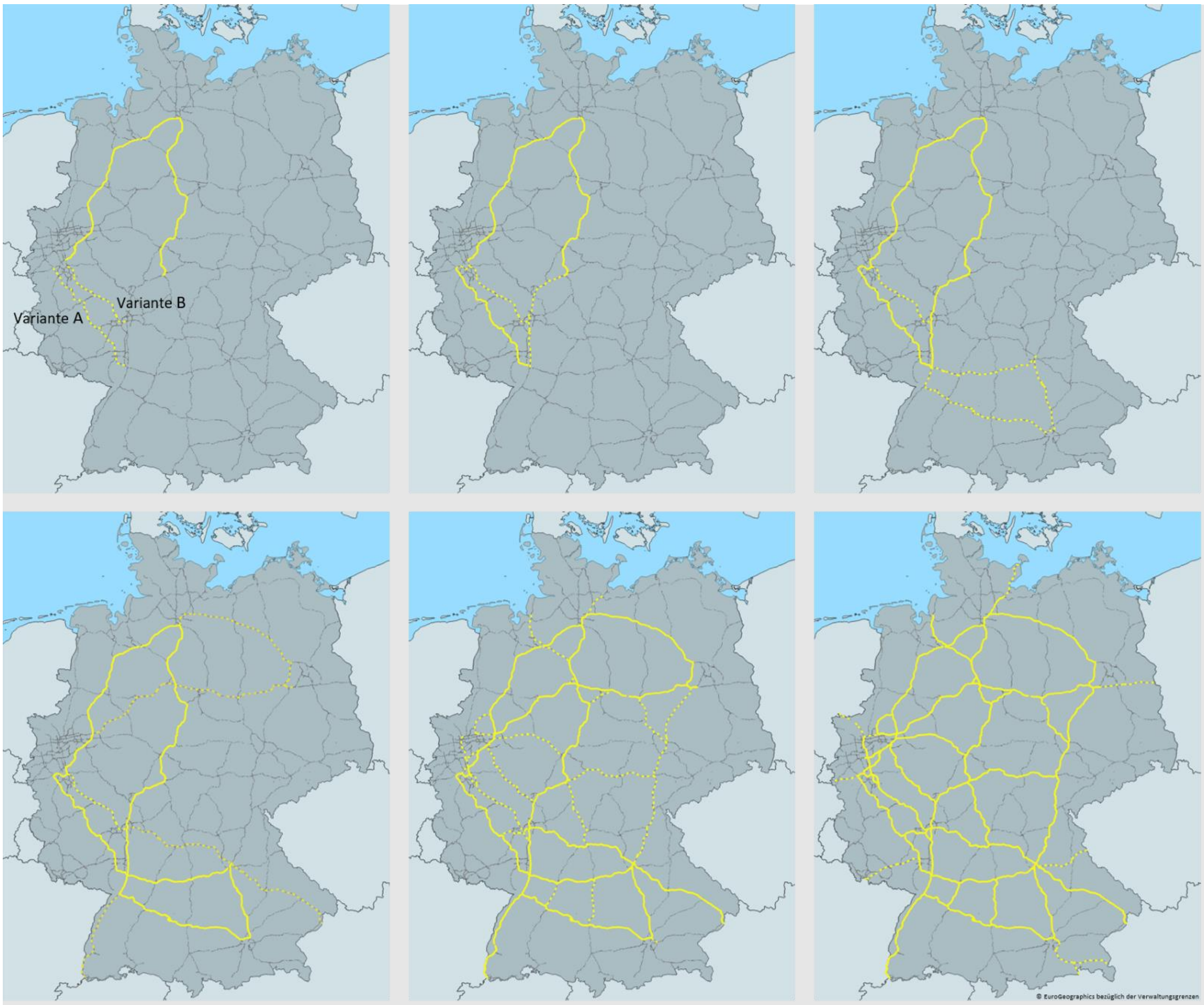
A possible subnetwork would be a gap closure of the above-mentioned routes, creating a connection between Hamburg, the Ruhr area and the Rhine/Main or Rhine/Neckar region. This subnetwork along the busiest highways in Germany could already reach a high proportion of domestic German traffic and open up relevant long-distance corridors for the use of OC-trucks.

This could be followed by the connection of the Rhine/Neckar region to Munich (A8) or Nuremberg (A6 and A9), which are also characterised by a high commuting share between industrial centers. The increasing network formation could also open up traffic with longer pre-carriage and onward carriage beyond the respective section.

Against the background of a European integration of overhead contact line technology, international transports become significant and the network extension to the routes Ruhrgebiet-Hannover-Berlin (A2), Karlsruhe - Basel (A5), Rhine/Main - Nuremberg - Passau (A3) and possibly Hamburg - Berlin (A24) would be appropriate.

The other routes of the target network are not a priority in view of the traffic potential - both within Germany and in international traffic. Nevertheless, they may be important in the future as gap closures for a continuous target network.

Figure 28: Suitable initial routes with two variants A and B (dashed), routes with high suitability for further expansion, towards a target network incl. possible international connection (from top left to bottom right).



Source: Own representation (Hacker et al. 2022)

The suitability of specific lines for the overhead contact line infrastructure at different points in time must be subject to some limitations. For example, line-specific evaluations are not available for all the criteria discussed, or information from the same source is not available for some criteria for all sections of the target network. The analyses are therefore incomplete in some cases - particularly suitable routes can be identified; however, it cannot be ruled out that other routes in the target network also fulfil these criteria but were not explicitly considered in the underlying studies. In addition, only the so-called target network was considered in more detail. Particularly with a view to anchor users and commuter traffic, less significant routes may be attractive in the early phase - in terms of total traffic volume (e.g. Rostock-Lübeck (A20), Dortmund - Kassel (A44), Chemnitz - Erfurt (A4), Regensburg - Hof (A93), Munich - Memmingen (A96)). However, these were not examined in more detail here. The focus was on the routes of the possible target network, the busiest highways in Germany. In addition, possible interactions with other alternative energy supply infrastructures (e.g., fast charging network) were not taken into account (see following section and Plötz et al. 2021).

5.2.4 High -capacity fast charger and overhead contact line in comparison and possible synergies

Currently, the series production of battery trucks is being planned and introduced by many manufacturers. Electric trucks will experience considerable market penetration and, in addition to regular charging at the depot, will need infrastructure for recharging for their use in long-distance transport. High-voltage charging and overhead lines are currently being discussed and tested as infrastructures for electric trucks in long-distance transport. The existing CCS standard allows charging powers of up to 350 kW and a range of approximately 300 km could be recharged in 60 min. A charging standard with a higher charging power of up to 1 MW (so-called megawatt charging (MCS) is currently being planned) could allow up to 750 km during the statutory break time of 45 min recharging from 2025. In parallel, catenary trucks are currently being tested on several public roads in Germany and Europe.

However, especially in the initial phase (with a low number of users), the decentralised installation of fast-charging stations is more flexible and involves fewer hurdles. A certain basic equipment with fast-charging stations along the trunk road network is probably sensible in any case, and thus also a rapid development of such an infrastructure in the introduction phase of electric trucks. In the medium term, the partial electrification of motorways with overhead lines already offers the possibility to charge battery-electric trucks while driving and to reduce the expansion of fast-charging locations, especially due to the sometimes limited space available for trucks along motorways. Overhead line infrastructure can also help to improve the scalability of battery drives in long-distance transport on busy routes. In the longer term, however, infrastructure planning should primarily be oriented towards the sustainability goals pursued with the introduction of alternative drives. In addition to the system costs, interactions with the energy system and resource requirements must be taken into account.

Table 12: Strengths and weaknesses of high power fast charging and overhead line systems.

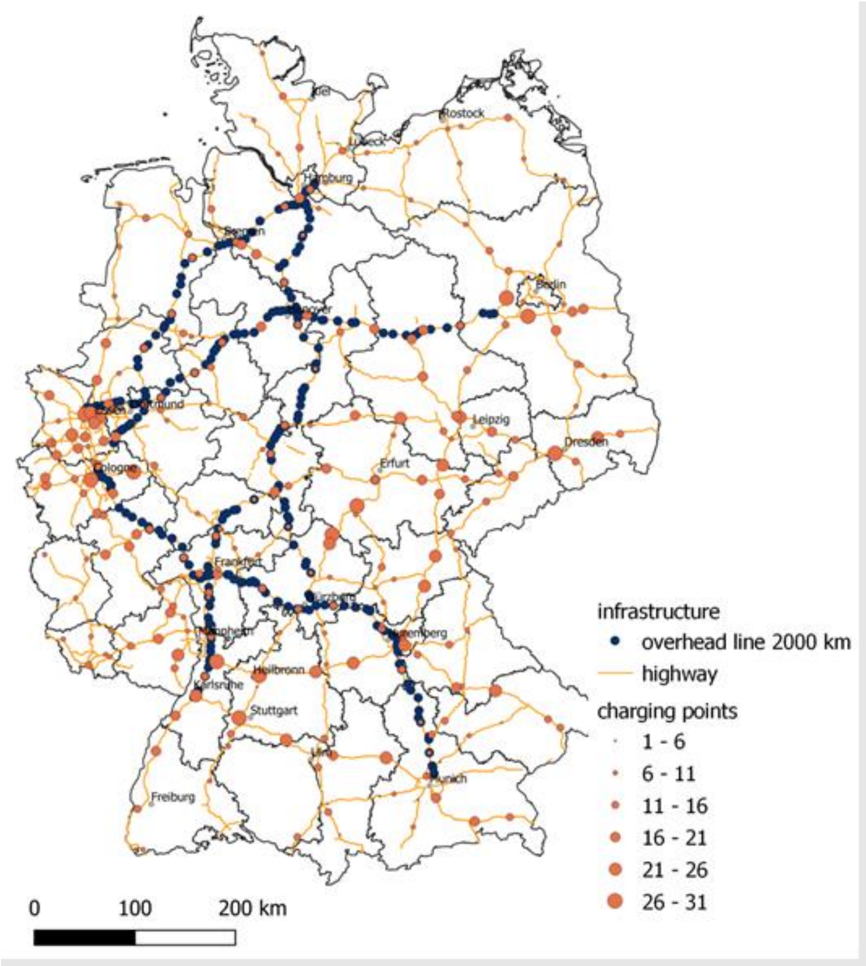
Technology	Strengths	Weaknesses
High power fast charging	• Simple stand-alone solutions and gradual build-up with large spacing and few points per location possible. • Gradual expansion possible (basic network can be expanded at locations of high demand). - Batteries for significant range increase empty weight and thus energy demand or reduce payload.	• Charging at high power increases battery wear and is associated with energy losses. • Charging in long-distance traffic only possible during legal breaks or expensive additional breaks necessary. • Very high local grid load with corresponding grid connection costs. • Hardly any flexibilisation of the load profile possible.
Overhead line	• High capacity, i.e. many vehicles can be charged at the same time.	• Considerable network effects to be expected, cost balance of the system

	• Hardly any additional space required for infrastructure on the transport areas. • Established technology from the railway sector, manageable adaptations necessary for the road. • Certain temporal flexibility in the load profile, depending on the design of the vehicles.	therefore only positive with a certain minimum expansion. • Higher barriers to entry, as a significant distance must be electrified for economical truck operation (e.g. longer commuting routes with large traffic flows). • Pre- and on-carriage of trucks with additional storage (e.g. battery) or drive. Thus technically more complex. • Technical maturity of the vehicles is lower than for battery trucks. • Space requirement due to pantographs.

Source: Own illustration (Plötz et al. 2021).

From today's point of view, a certain basic equipment with fast-charging stations along the trunk road network seems to make sense in any case due to the upcoming market launch of battery-electric trucks, and thus also a rapid development of such an infrastructure in the introduction phase of electric trucks. In the medium term, the partial electrification of motorways with overhead lines already offers the possibility of charging battery-electric trucks while driving and reducing the expansion of fast-charging locations, especially due to the sometimes limited space available for trucks at service stations and in order to charge outside the statutory break times. Overhead line infrastructure can also help to improve the scalability of battery drives in long-distance transport on busy routes by reducing the required number and size of fast charging stations as well as operational restrictions (charging times).

Figure 29: Joint MCS and overhead line network for Germany



Source: Own illustration (Plötz et al. 2021), map background: © GeoBasis-DE / BKG 2020

In the next years, both infrastructures for long-distance transport will probably be expanded in small quantities. In the market introduction phase of electric trucks, it will be easier and cheaper to build MCS on a broad scale. On routes with a high proportion of commuter traffic, however, individual overhead lines can also be attractive in this phase compared to stationary charging systems. To ensure sufficient operational flexibility, overhead hybrid vehicles can initially be used, as is currently being tested in field trials. The trial phase of both technologies until 2025 seems reasonable. Already in this phase, synergies on the part of the vehicles or the infrastructure development (such as a common connection to the power grid) could be used.

From 2025 to 2030, MCS and overhead lines could be installed in parallel on a larger scale. Overhead lines could then also be used as charging infrastructure for purely electric trucks if they are equipped with a pantograph. In this context, the possibility of retrofitting battery trucks with pantographs should also be examined. For the construction of the overhead line, this means that from 2030 onwards, a significant utilisation of the overhead line infrastructure could occur quite quickly and the phase of underutilised infrastructure would be short or skipped. If electric trucks were to play a central role in the long-distance truck fleet in the second half of the 2030s and a basic network of MCSs were in place in Europe, the expansion of overhead catenary lines could go wide and gradually cover the most important third of the European motorway network or about 25,000 km along the TEN-T corridors. With this mixed infrastructure, even low utilised routes would be covered by MCS for electric trucks and on the central axes, charging could be done dynamically during the journey, independent of break times, limiting the need for parking spaces for MCS and at the same time spreading the load on the medium voltage network over longer distances.

The joint development of the infrastructures can also have a positive effect on social acceptance, especially on the market side, because more providers would pursue both technologies, but also socio-politically and in terms of local acceptance, because depending on the location, the technology could be built with better local feasibility. Above all, the overhead line technology benefits from this. However, proactive communication and participation is important for the broad acceptance of both technologies. Both the expansion of a network of high-capacity charging points and overhead lines also require European coordination and technical standardisation.

Stationary charging of trucks via pantographs has the potential to simplify truck operations (no need to plug in cables), to increase safety (no tripping hazards, low risk of tampering) and to reduce the space required for the charging infrastructure (no charging station in confined spaces). It could thus provide incentives for users to use trucks with pantographs and thus broaden the potential user base for an overhead line infrastructure. For overhead line catenary trucks, pantographs have already been developed and tested for the special requirements of trucks.

5.3 Challenges and action steps for a successful market ramp-up of overhead catenary trucks

The national climate protection targets and the accompanying regulation at national and EU level require a rapid move away from conventionally powered diesel trucks as the standard solution in road freight transport.

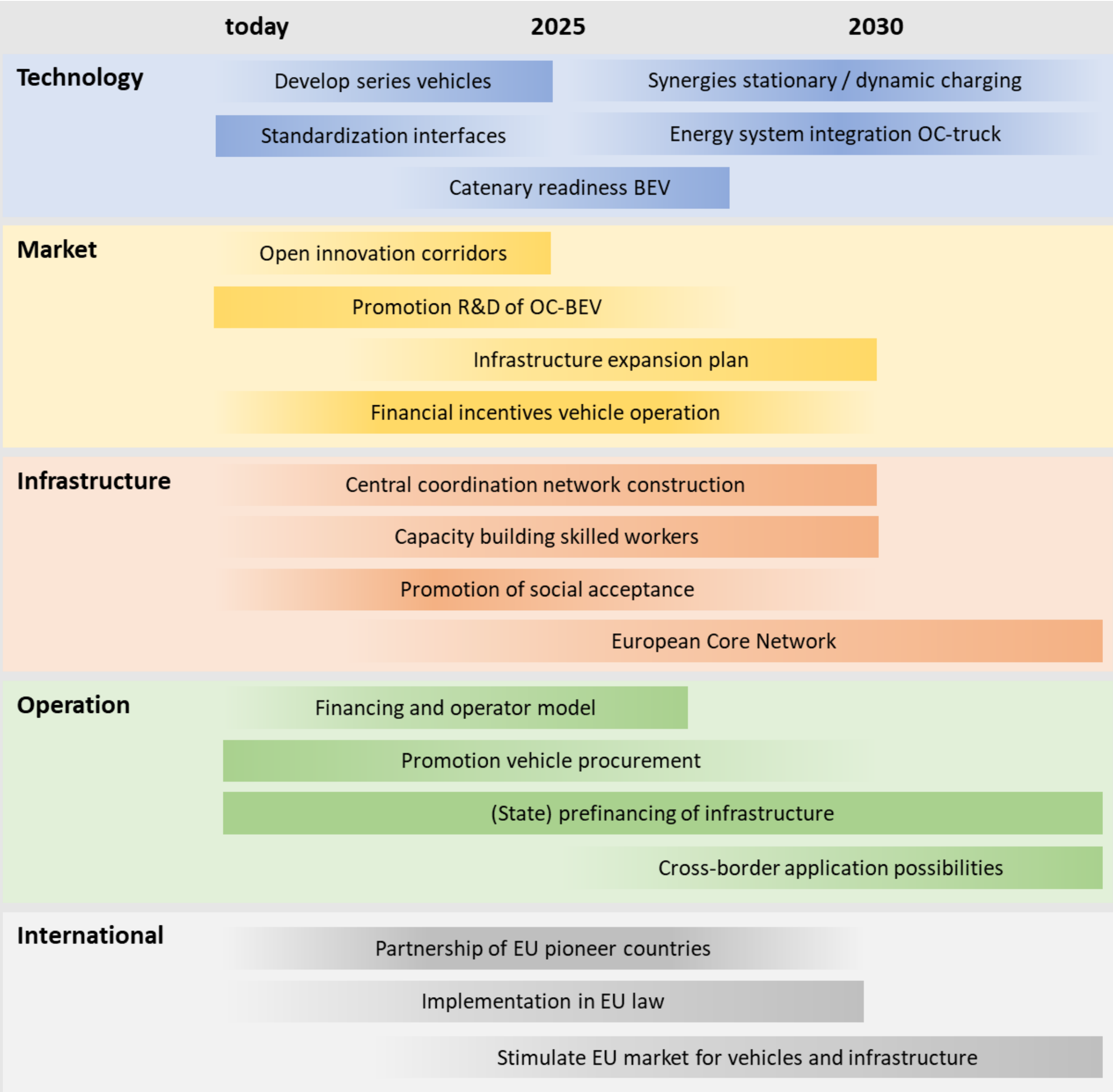
In Germany, battery electric (BEV), overhead catenary (OC-BEV) and fuel cell electric vehicles (FCEV) are considered the most promising alternative technologies. In the short to medium term, the options with direct electricity use have the greatest potential for greenhouse gas reduction. However, all vehicle technologies mentioned, as well as the energy supply infrastructure required for them, still need to make significant progress in order to be competitive and applicable in the mass market.

The following section summarises the necessary target states for the OC truck system and the action required to achieve them, so that the technology can make a substantial contribution to achieving the climate protection targets (for further details see (Mottschall et al. 2023)). In terms of time, the analyses are based on the specifications of the overarching climate protection targets and the German government's overall concept for climate-friendly commercial vehicles (BMVI 2020a). The years 2025 and 2030 are important targets: By 2025, a production-ready technology should be available to enable path decisions; and by 2030, alternative drive systems should already achieve a relevant market share that will enable these drive systems to dominate in subsequent years.

Five fields of action have been identified as particularly central to the successful further development of the OC-truck system and can be structured along the following main questions:

- Technology: What further technological development of the vehicle and infrastructure is required?
- Market: How do supply and demand for OC-trucks and the necessary infrastructure arise?
- Infrastructure construction: How can infrastructure construction succeed at the necessary speed?
- Operation: How can reliable and attractive operation of the O-truck system be achieved?
- International coordination: How can cross-border, European construction and operation of an overhead contact line network be ensured?

Figure 30: Action required for successful introduction of OC-trucks.



Source: Own illustration (Mottschall et al. 2023).

5.3.1 Technology

The OC-trucks currently used in the field trials are hybrid vehicles (OC-HEV) and are currently still prototypes, their technology readiness level (TRL) is at level 7. In the current third phase of the ELISA field trial on the highway A5, purely electric O-trucks (OC-BEV) will also be used. These are already being implemented on the basis of Scania's modular vehicle system and are closer to series production than the prototypes used to date. In the previous field tests with overhead contact line trucks, technical specifications were made on the vehicle side (current collectors and associated components) and on the infrastructure side in a dialog between the customer, infrastructure constructors and PAN/vehicle suppliers. The voltage level was nominally 600 V. In this way, it was possible to use components and design methods with which there is many years of experience in the public transport sector. However, it is foreseeable that this voltage level will not be able to ensure a safe, efficient and cost-optimised supply of all vehicles within a supply section in the event of a higher number of OC-trucks, which is why an increase in the voltage level is currently being prepared.

The technological maturity of OC-trucks must be advanced in the coming years to such an extent that they can be offered as mature series products on a mass market. The standardisation of central interfaces between components is essential for this and will facilitate the market entry of other manufacturers. Emerging synergies between overhead contact lines and stationary charging ("overhead contact line readiness" of BEVs) should be taken into account at an early stage in further technology development.

5.3.2 Market

The vehicle market for OC-trucks currently amounts to prototype models from Scania in transition from the 2nd to the 3rd development generation. In addition to the field trials in Germany, Scania has already equipped hybrid trucks with pantographs for a demonstration project in Sweden in 2016; the Volvo Group also provided a tractor unit with pantographs for a pilot project on overhead contact line systems in Los Angeles in 2017 (Siemens AG et al. 2016). To date, no competition exists for the pantograph or catenary-compatible vehicles. It is unclear whether additional manufacturer and supplier companies can be activated through the development of overhead line corridors or subnetworks. Market acceptance varies on the supply and demand side and can be determined by looking more closely at the vehicle manufacturers as well as the users. Infrastructure providers are also relevant for market acceptance, but apart from the willingness of the manufacturer Siemens, no further findings are currently available. Vehicle manufacturers can be divided into the group of companies involved in field trials and those not involved. The participating companies see OC-trucks as an option in the technology mix for decarbonising road freight transport. However, the strategic focus of these companies is mainly on battery-electric solutions with stationary charging. Among trucking companies, both differences and similarities are evident between companies participating in the field trials and those not participating. Freight forwarders already involved in trials with OC-trucks show a high level of acceptance and initiative in testing the technology. The OC-system from Siemens has the highest technical maturity for concepts for dynamic charging. In three field tests in Germany and one field test in Sweden, the system was tested in real road operation and is considered ready for the market. Currently, only a few kilometers of overhead line infrastructure with dedicated vehicle allocation are available.

In order to create trust among important stakeholders on the manufacturing and user side, long-term promotion of the technology and reliable and predictable expansion of the infrastructure are essential. This applies analogously to the emergence of a competitive market with a larger number of economic players. The implementation of the planned innovation corridors while ensuring the low-threshold participation of as many stakeholders as possible is an important next step.

5.3.3 Infrastructure

Analyses of the acceptance of residents and the affected local population were carried out in the field tests. Research results from *eWayBW* [16] (prior to construction of the facility) show that many participants have a critical view on the construction of the infrastructure, as impacts on traffic are suspected. In the ELISA project, research was conducted with road users. The measurement of driving behavior before and after the construction of the infrastructure shows that no difference in driving behavior can be detected among car drivers. The existing overhead contact line systems in the field tests were all approved for a limited period of time in order to avoid a planning approval procedure in the planning phase - in the sense of the fastest possible testing of the technology. At the EU level, Electric Road Systems (ERS), which in addition to overhead line options also include conductor rails embedded in the road or inductive systems, are listed in the annex to the Alternative Fuel Infrastructure Regulation (AFIR; successor to the AFID Directive), which is currently being revised. At this time, demand from overhead trucks is not included in network expansion planning either in terms of volume or regional or time distribution.

[16] https://ewaybw.de/de/ewaybw/

To ensure that expansion proceeds quickly, infrastructure expansion must be given high priority, coordinated at a central point, and interactions with important parallel developments (including power grid expansion and stationary charging) must be taken into account at an early stage. Issues of social acceptance must also be considered. Early European coordination and standardisation of the technology should be sought in view of the close interdependencies of freight transport.

5.3.4 Operation

A high level of acceptance of overhead contact line technology is evident among early users in the field trials. This is due to the practical trials. The suitability in logistical practice also appears to be given. The OC-trucks are currently being used in Germany on pilot routes in Hesse, Schleswig-Holstein and Baden-Wuerttemberg. The test deployment is limited in each case to a small area of operation with electrified route sections of up to five kilometres per direction of travel.[17] The test deployment is for research purposes; without funding for vehicles and infrastructure, commercial operation would not be possible today. From today's perspective, the use of OC-trucks in Germany is assessed in a number of studies as a long-term economically attractive alternative option to diesel vehicles (Nationale Plattform Zukunft der Mobilität 2020; Jöhrens et al. 2022; Hacker et al. 2020a). So far, the operation of the overhead contact line infrastructure has only been carried out in temporary operation in the field trials with few users and without an energy economic classification of the system. The operation of the overhead line infrastructure is the first time that the legal fields of energy and road law meet in this way.

A high level of technical and economic practicality is a basic prerequisite for acceptance of the technology among users. Economic incentives (e.g., long-term privileges in truck tolls) that make the use of OC-trucks by logistics companies economically advantageous at an early stage and uncomplicated use of the infrastructure are central to this. The operation of the overhead line infrastructure requires new types of cooperation between different players or the integration of their tasks (e.g., provision of electricity and infrastructure). In view of the importance of cross-border traffic, a concept for cross-border infrastructure use should be developed at an early stage.

5.3.5 International coordination

The close links between freight transport and the vehicle market in Europe and the location of important regulations at EU level underscore the importance of early European coordination of activities relating to OC-trucks. The further intensification of Germany's initiatives for international exchange and direct cooperation with interested neighbouring countries are important next steps in this regard. In the long term, the technology should be incorporated into European infrastructure planning.

During the stakeholder dialog accompanying the project, numerous stakeholders emphasised that a political decision in favour of the OC-truck system is a key prerequisite for accelerated and successful development of the technology.

[17] In August 2023, the ELISA test track in Hesse was extended by 7 km in direction to Darmstadt, so that currently 17 km of test track are available to date.

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