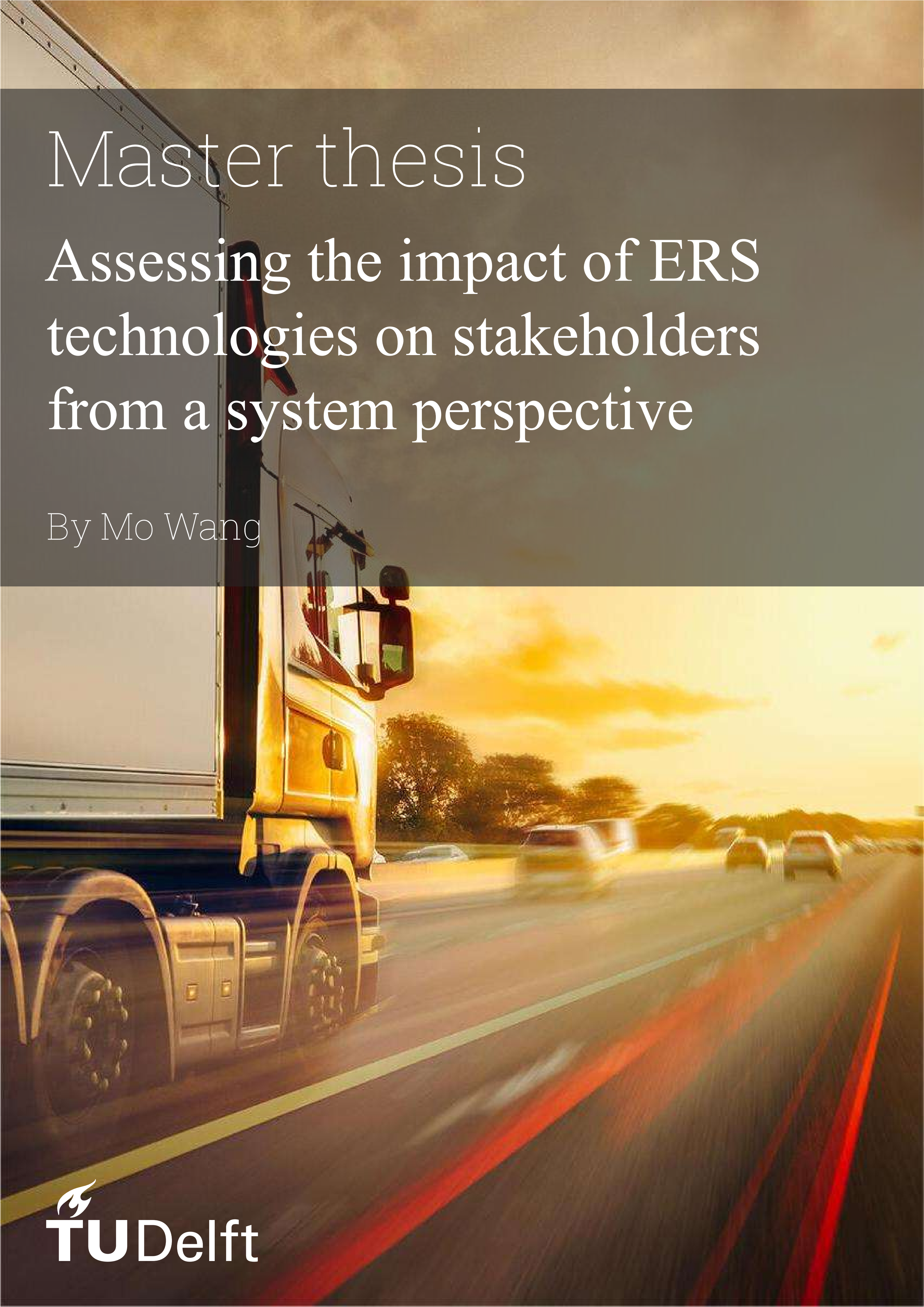


Master thesis

Assessing the impact of ERS technologies on stakeholders from a system perspective

By Mo Wang

TU Delft

Master Thesis

Assessing the impact of ERS technologies on stakeholders from a system perspective

by Mo Wang

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on the 30th of October 2023.

Student number:	5452163	
Project duration:	April 2023 – October 2023	
Thesis committee:	Prof. dr. ir. L.A. Tavasszy,	TPM, TU Delft
	Dr. ir. A.J. van Binsbergen,	CEG, TU Delft
	Dr. ir. M. Nogal Macho,	CEG, TU Delft

Preface

Around the time when the title of my thesis was still undecided, I had already begun to have ideas for the preface. Now, as I finish the final check of my report, finally it's time to express all the crap I've been accumulating over the past seven months. But my mum told me yesterday that it would be best to keep the whole report short so she could still try to read it patiently in an effort not to fall asleep too quickly. I had to choose not to show off my excellent writing skills in the preface because I hope that you, especially my mum, are patient enough to read what I've researched.

This thesis evaluates two developing ERS technologies in the context of the 2050 climate goals. With a pure passion for sustainability, I was bold and adventurous enough to use my shallow knowledge of freight transport to start exploring new technologies that I had never studied before. I did my best to come up with a result that was objective, realistic and had practical applications. I hope I did.

For the completion of this report, I would like to sincerely thank my graduation committee. I would like to thank Lori Tavasszy for his care and interest in this project. This included regularly sharing the latest developments in the field, taking me to relevant conferences, and sharing opportunities to talk to stakeholders, etc, without which I would not have been able to move forward. I would like to thank my first supervisor, Arjan van Binsbergen, who has been providing me with a lot of valuable and insightful feedback, inspiring me to take the next steps in my research. What's even rare is that after providing ideas, he told me several times that he respected my thoughts and decisions and I could choose not to take his advice. Encouraging me to equally and freely exchange ideas with someone far more knowledgeable than me. I would like to thank Maria Nogal Macho for her encouragement and recognition after each meeting and for taking the results seriously. She kept a close eye on the quality of the final report and marked even punctuation errors for me.

Last I would like to thank my family for all their support, always. And my friends, I'll talk to you in person. Also, I want to thank myself. I am an optimistic person, but I must admit that it has been a very tough two years. Thankfully, I have stayed true to myself and have always done what I thought was right. I hope I can stay happy, continue to grow and be inclusive.

Executive summary

In order to achieve the goals set by the ”European Green Deal” of reducing greenhouse gas emissions, it is imperative for heavy goods vehicles to transition towards becoming climate-neutral (Göhlich et al., 2021, Buysse and Miller, 2021). To address this challenge, the development of clean and efficient technologies for charging heavy goods vehicles is crucial.

A review of the existing literature indicates that Electric Road Systems (ERS) present a promising solution for sustainable mobility by alleviating the range anxiety associated with electric vehicles. Two primary ERS technologies have gained prominence: overhead conductive and in-road inductive systems. The former has been successfully implemented in pilot projects across various countries, demonstrating technical maturity, safety, and efficiency. Meanwhile, in-road inductive ERS offers advantages such as minimal visual impact and lower maintenance requirements. Both technologies hold the potential as options for sustainable transportation. However, their real-world viability remains uncertain, with two critical gaps to address.
First, there is a lack of clarity regarding the differential impact of these technologies on various stakeholders. The complexity of ERS, with its numerous subsystems and diverse stakeholder requirements, complicates their adoption. Second, most existing studies tend to focus on individual aspects and lack a holistic systems perspective. Although several studies have examined the feasibility of ERS from various perspectives, such as environmental impact, cost, technical feasibility, and energy efficiency, few have conducted comprehensive assessments, and even fewer have conducted in-depth assessments of individual ERS technologies.

Therefore, this study formulates a main research question: What are the comparative impacts of overhead conductive and in-road inductive ERS technologies on different stakeholders from a systemic perspective? The study primarily focuses on the dissemination phase in relation to pilot projects within specific corridors, selecting the Rotterdam and Antwerp corridors as study areas.

To comprehensively evaluate ERS technologies from a systems perspective, the Multi-Actor Multi-Criteria Analysis (MAMCA) method and together with the Design for Value (DfV) are employed to provide a multidimensional evaluation that captures the diverse impacts of the ERS technologies.

The successful promotion and implementation of ERS depend on effective collaboration and coordination among various stakeholder groups, each with distinct interests and priorities. Nine main stakeholder groups related to the dissemination phase are included in this study as shown below. Their values and value-based criteria are first identified through interviews.
- Regulatory authorities play a central role in expediting ERS project development, ensuring broad social acceptance, and contributing to long-term climate goals by reducing greenhouse gas emissions from heavy-duty vehicles.
- Infrastructure providers are responsible for the practical implementation of ERS technologies,

with a strong emphasis on safety, harmonization with existing road infrastructure, and efficient traffic flow. They must also manage investments effectively within budget constraints.
- ERS technology providers drive innovation, reduce greenhouse gas emissions, strive for commercial competitiveness, and seek to expand their market share within ERS projects.
- Service users stand to benefit from ERS technology through logistical efficiencies and cost savings, essential for maintaining their market leadership.
- Citizens are concerned about road safety and the impact of ERS projects on their living environments, emphasizing the importance of their active involvement in the process.
- Energy providers prioritize the stability of power consumption patterns, security of supply, and the effectiveness of their power distribution plans.
- Vehicle manufacturers aim to provide cost-effective e-mobility solutions while meeting market demand. They closely monitor factors such as vehicle investment costs, the availability of electric infrastructure, and the speed of return on investment.
- Drivers focus on the driving experience itself, including vehicle performance and the ease of operating electric trucks.
- The ERS operator may be a new role that will only emerge in the future during the large-scale implementation phase. Currently, in pilot projects, infrastructure providers are taking on the responsibilities of this role in parallel. This stakeholder group is also included in this study as they may have different interests and responsibilities that deserve further clarification.

A comprehensive framework comprising a diverse of indicators across value-based criteria is developed next step according to the literature and interviews. These indicators are categorized into four groups: technical, economic, environmental, and social, and serve as the foundation for the subsequent quantitative and qualitative evaluation. The result for each stakeholder group is summarised as follows.

- Based on the calculation results in chapter 5, it is evident that the overhead conductive system, while posing less direct negative effects on regulatory authorities, raises concerns for service users and the public due to visual and safety risks associated with exposed overhead infrastructure and traffic disruptions which have indirect impact for regulation authority. In contrast, in-road inductive technology faces a longer wait for large-scale deployment and introduces new safety issues related to electromagnetism.
- Both ERS technologies present challenges for infrastructure providers and ERS operators. The overhead conductive system struggles in extreme weather conditions, requires frequent and costly maintenance, and is less versatile in supporting diverse vehicles. In-road inductive technology faces limitations in energy transfer capacity, significant upfront investments, and emerging electromagnetic safety and maintenance issues.
- Technology providers, while supporting their respective technologies, grapple with marketing challenges and the need to accelerate technology maturity.
- Service users identify operational risks associated with the weather susceptibility of conduction technology but see promise in the economic viability of in-road induction technology and its alignment with their e-mobility goals.
- From the perspective of citizens, both technologies raise concerns, demanding solutions related to safety and traffic management.
- Energy providers may face power system stability issues with in-road induction, given its unpredictable energy consumption patterns.

- Vehicle manufacturers may require additional maintenance for the overhead conductive technology and could find inductive technology favourable if interoperability concerns are addressed.
- Drivers, like the general public, worry about safety and stability, particularly with the overhead conductive system in extreme weather, and the efficiency of energy transfer in inductive technology.

The calculations resulting from the evaluation of the indicators through the second interview are shared with the various stakeholder groups to validate the result and also identify a number of new concerns and observations that deepened the understanding of the current state of ERS implementation in reality.

In conclusion, some emerging concerns underscore the intricate dynamics at play in the ERS project, emphasizing the necessity of addressing standardization, energy stability, and infrastructure availability to facilitate the successful integration of ERS technologies and foster broader stakeholder participation in shaping the future of transportation.

From the researcher's perspective, critical evaluation indicators for future research on ERS technologies are selected based on their relevance to multiple stakeholder groups, significant performance differences between ERS technologies, data limitations, and expected evolution over time. These include safety issues impacting human health and traffic, which are paramount and affect all stakeholder groups. Data scarcity and evolving safety aspects add complexity. Years to deployment significantly affect four stakeholder groups, especially due to the rapid evolution of in-road inductive technology. Infrastructure and vehicle maintenance costs diverge significantly between ERS technologies, with in-road inductive technology offering lower maintenance costs. International synergies possibilities hinge on standardization and interoperability, calling for resolution in the future. Electricity supply patterns may pose future challenges, particularly for in-road induction technology's unpredictable charging patterns, impacting energy system stability.

Addressing these key indicators in future research will inform ERS technology development, accommodating diverse stakeholder needs and concerns.

Contents

List of abbreviations

GHG	Green house gases
ERS	Electric Road System
HGV	Heavy goods vehicle
TTW	Tank-to-wheel
WTW	Wheel-to-wheel
BWM	Best-Worst Method
TRL	Technology readiness level
YTD	Years to deployment
CPT	Conductive power transfer
WPT	Wireless power transfer
TA	Technology assessment
MAMCA	Multi-actor multi-criteria analysis
DfV	Design for Value
kWh	Kilowatt hour
MJ	Mega Joule
CO_2	Carbon dioxide
TCO	Total cost of ownership

Nomenclature

Q_{HGV}	Average number of HGVs on a workday in study area, unit
$Q_{R,A29}$	Number of HGVs in the right hand lane of the A29 on workday, unit
$Q_{L,A29}$	Number of HGVs in the left hand lane of the A29 on workday, unit
D	Total distance travelled by ERS-HGV on workday, unit
L	Length of the road from the Port of Rotterdam to Antwerp, km
$T_{workday}$	Number of workdays in a year, day
f_{region}	The share of fleet remaining in the Rotterdam area, %
$f_{foreign}$	The share of fleet crossing the broader, %
e	Energy transfer efficiency, %
E_{ERS}	The total TTW energy consumption on workday, Mwh
E_{HGV}	The TTW energy consumption of an HGV on a workday, Mwh
Ef	Emission parameter, ton/km or ton/kWh
Cf	Cost parameter, EUR/km or EUR/kWh

1

Introduction

1.1. Problem definition

The European Commission's "European Green Deal" has set a goal of reducing 55 % of greenhouse gases (GHG) by 2030 compared to the 2019/2020 levels and needs to achieve climate neutrality in 2050 (Göhlich et al., 2021). The transport sector accounts for almost a quarter of the EU's total GHG and also contributes to other pollution such as noise (Buysse and Miller, 2021). Therefore a 90 % reduction of emissions in the transport sector needs to be made in order to meet the final goal. Within the EU's transport sector, 30 % of GHG emissions are generated by heavy goods vehicles (HGV) as shown in Figure 1.1. This share will possibly be continually increasing with the growing freight transportation need.

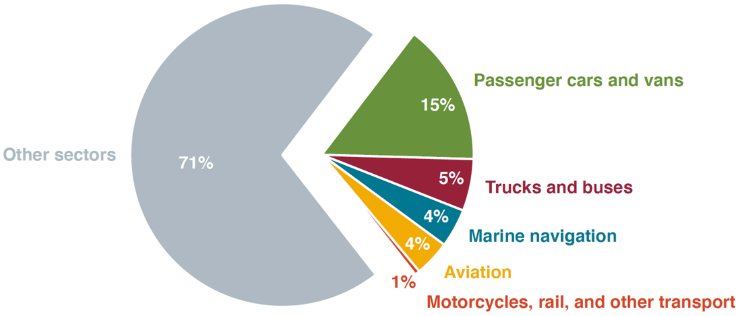


Figure 1.1: GHG Emissions in the EU (Buysse and Miller, 2021)

Therefore, promoting the development and adoption of clean and efficient technologies on HGV is necessary to achieve the environmental goal. One promising solution to decarbonization for transport is focusing on the use of electricity. Electric Road System (ERS), a branch of technologies for dynamic charging of electric vehicles, is considered a possible next-step solution for the future to reduce GHG emissions from the transportation sector. At the same time keeps a relatively higher energy efficiency and reduces the dependence on fossil fuels or batteries.

There are different types of ERS technologies in terms of charging options (conductive and inductive) and relative to the road surface (overhead, in-road, side) (Bateman et al., 2018). Overhead conductive Figure 1.2 and in-road inductive Figure 1.3 ERS are the two representative and competing technologies with high potential for decarbonization and already have the field tests in reality.

Figure 1.2: Overhead conductive ERS (Muelaner, 2020)

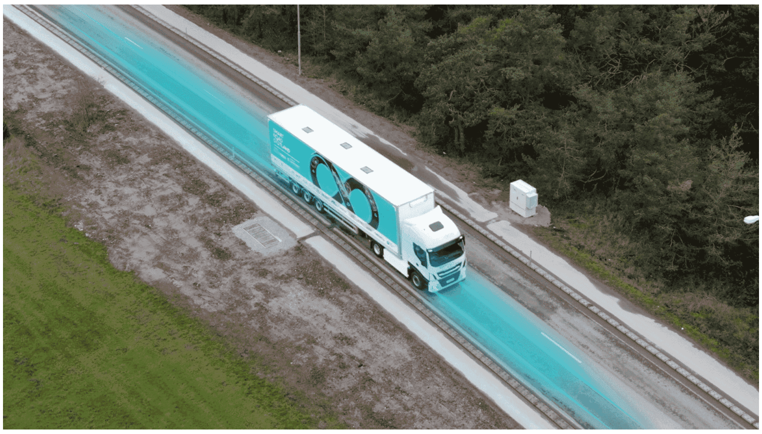


Figure 1.3: In-road inductive ERS (Cibean, 2022)

However, little is known about the real-life feasibility of either of these technologies, particularly as in-road inductive systems are a new technology under development. More research still needs to be done on what they will bring when applied in real life. Also, a more complex issue is that ERS is a system of systems. It contains several subsystems with complex interaction effects and these two competing technologies may have different consequences for each stakeholder group. In practice, the overhead conductive system is theoretically ready and several demonstration projects have been carried out since 2010, mainly in Sweden and Germany. The technology for in-road inductive systems has been slower to develop, with demonstration projects starting after a few years, and the operation of billing and payment systems is still in the testing phase. Both technologies could be potential options for road decarbonization.

However, there is a lack of experience when considering the possible impacts they may have on stakeholders and what roles and responsibilities stakeholders need to assume. To get more valuable insight into the implementation of the ERS system, all the related stakeholders within the ERS project have to be taken into account, especially in the current situation. The focus of this study is to evaluate, from a systemic perspective, the different impacts that the two technologies will have on all stakeholder groups, thereby providing insight into the decision-making process on which technology is preferred.

1.2. Research objectives

Firstly, at a macro level, the methodology of this study as a whole can be used as a comprehensive framework for evaluating other ERS technologies such as rail conduction considering the construction, operation and maintenance phases. Alternatively, it can be used to assess the impacts of future large-scale implementation phases of ERS technologies on the wider system, guiding future decision-making in the field.

Secondly, the study will focus on identifying and assessing in depth the impacts of the two different ERS technologies on various stakeholder groups from a system perspective. This will involve collecting relevant data and information on the technologies and selecting indicators to analyse the impacts of the technologies on the different stakeholders.

Finally, this study uses the corridor from the port of Rotterdam to Antwerp as a case study to demonstrate the research methodology and to provide insights and feasible recommendations for piloting an ERS project in this particular context. Real data needs to be collected, taking into account relevant factors such as environmental, social, and economic, to provide solutions on what impact technology will bring for various stakeholder groups .

1.3. Research questions

According to the background and objectives of this study, the following main research question can be formulated:

What are the comparative impacts of overhead conductive and in-road inductive ERS technologies on different stakeholders from a system perspective?

To systematically answer the research question, a series of sub-questions have to be answered.

- 1. What are the current state of ERS and its two competing technologies?

- 2. Who are the relevant stakeholders involved in an ERS project and what value-based criteria are held by them?

- 3. What are the indicators that should be taken into account to calculate the value-based criteria?

- 4. What are the impacts of overhead conductive and in-road inductive system on each stakeholder group?

In this study, only those factors where there are differences between the two technologies are analysed in detail, while factors where the impact of the two technologies is similar are not discussed. Also considering that the technology is currently in a rapid development phase, it is difficult to predict how it will actually perform in the full implementation phase in a few years' time. Therefore, the collection of stakeholder information and data related to the technology is mainly focused on the current pilot phase. As for other issues that may arise in the future, this study will only discuss important points in the overall analysis chapter to provide some insights for future research.

1.4. Methodology

1.4.1. Methodology review

Technology assessment (TA)

TA is the most common systematic method for scientifically investigating the conditions and consequences of technologies and expressing their social valuation (Rip, 2001). It can predict future developments in technology and their likely impacts, providing insights into relevant decision-making areas, and is a necessary approach to answering the main questions of this study.

Different types of TA methods can be used according to different technology, data type, and context. Commonly used methods include Life Cycle Analysis (LCA), which relies on ecological ideas on the environmental compatibility, Cost-Benefit Analysis (CBA) and Multi-Criteria Analysis (MCA), related to decision-making quantitative assessment (Grunwald, 2009).

CBA is a systematic method of estimating the advantages and disadvantages of different options and can be used to compare completed or potential courses of action, as well as to estimate or evaluate the value and cost of decisions, projects or policies (David et al., 2013). It is being widely used to assess transportation systems by using money as a unit to evaluate the system as a whole (Hoogmartens et al., 2014). Many studies on the feasibility of electric vehicles have used CBA. For example, research has been done to prove the usability and efficiency of CAB in the assessment of infrastructure investments impact (Chi and Bunker, 2021), and another research uses CBA to evaluate Autonomous Emergency Braking (AEB) technology to examine potential benefits (Fitri et al., 2021).

However, it has limitations on two aspects for the evaluation in this study. One is that the benefits and costs in a cost-benefit analysis are expressed in monetary terms and adjusted for the time value of money, however many of the non-market effects that are necessary to consider in this study are difficult to monetise. Another is that the distributional effects of the various stakeholder groups are difficult to represent.

LCA is a method for assessing the environmental impacts associated with all stages of the life cycle of a product, process, service, etc (Ilgin and Gupta, 2010). It also has been extensively used as a tool to assess the technology from a system perspective with a focus on evaluating sustainability performance. For example Ayodele and Mustapa (2020) using LCA to assess the competitiveness of electric vehicles in the early stages of production. Motuzienė et al. (2022) compare the impacts of different renewable energy technologies by LCA.

However, there are also two limitations to using LCA as the overall framework in this study. One of its limitations is that the current structure of LCA only allows for the identification and quantification of environmental indicators to analyse impacts, and does not allow for more references to sustainability and other non-environmental aspects (Jeswani et al., 2010). Another limitation is that LCA needs to take into account disposal and recycling-related stages, whereas for emerging ERS technologies there is no reference to relevant data in reality for the time being. Therefore the concept of the LCA methodology is only cited in the detailed environmental evaluation in section 5.3, where the environmental impacts involved in the entire life cycle are taken into account in the calculation process.

MCA is a form of system assessment that measures variables such as costs, time savings, and social and environmental impacts. It is suitable for making informed choices when faced with complex or conflicting factors or when no single best solution exists (Troldborg et al., 2014). The use scenario is consistent with the context of this study.

Based on the traditional MCA, the Multi-Actor Multi-Criteria Analysis approach (MAMCA) is proposed. This evaluation method focuses in particular on the inclusion of the different actors involved in the project, the so-called stakeholders. Talantsev (2017) use MAMCA to assess the different impacts of the UK's electric vehicle subsidy programme on nine stakeholders. Schutte et al. (2022) provide a value-focused MAMCA approach for the logistics design. They adapted the traditional MAMCA by changing the sequence of steps to make it better capture the value of different stakeholders. Research has shown that this is an approach that can be easily adapted to different technical and policy assessments.

According to Macharis et al. (2009), the general framework of MAMCA is alternatives identification, stakeholder analysis, criteria and weighting identification, indicator and measurement development, overall analysis and ranking, results and implementation. Best-worst method (BWM) is a method proposed by Rezaei (2016) that uses two pairwise comparison vectors to determine the weights of multi-criteria, ultimately enabling comparison between different alternatives. First, the decision maker determines the best (e.g., most desirable, most important) and the worst (e.g., least desirable, least important) criteria, and then compares the best criteria to the other criteria, and then compares the other criteria to the worst criteria. A nonlinear minimum model is then used to determine the weights such that the maximum absolute difference between the weight ratios and the corresponding comparisons is minimised.

The Design for Values (DfV) approach

During the evaluation process for this study, it is important to investigate stakeholder points of view. DfV approach can provide a perfect starting point. It is a methodology that helps translate values into requirements and provides guidance to articulate values (Van de Poel, 2013). Values usually refer to very general and abstract terms, and they are often too abstract to directly guide assessment projects. That is why it is essential to translate general values into one or more specific requirements. According to Van de Poel (2013), this requires a two-step process of translating general values into one or more general norms and translating those general norms into more specific requirements or indicators. This same idea applies well to this study.

A top-down approach is proposed to this process by Van de Poel (2013). The first step is to identify relevant values. Davis, Nathan, et al. (2015)'s study proposes 14 standard social science methods for values investigations. These methods include stakeholder analysis, value scenarios, value-oriented semi-structured interviews, value-oriented field deployments, and so on. Once a list of values has been made, the next step is to identify the proper response to the values, such as those criteria that need to be met to realise them, which need to be considered in this study. The next step is to translate the value-based criteria into more specific and measurable outcomes, in this study are the indicators that can be quantified.

1.4.2. Methodology of the thesis

To answer the research questions and evaluate the impacts of the two ERS technologies on different stakeholders, a structured method to incorporate the interests of each stakeholder group is developed according to the review of the methodology above. The overall framework as shown in Figure 1.4 is based on the general steps for MAMCA. Some adaptions are made according to this study's background of evaluating the two competing ERS technologies. For example, the steps from stakeholder analysis to measurement method development are inspired by the DfV method of identifying values, identifying value-based criteria and then identifying measurable indicators. Another adaption is in the overall analysis. The initial idea is to use the BWM to have the weighting of each criterion obtained during the second round of interviews with each stakeholder group and then to make a direct numerical comparison of the performance of the two technologies. However, the reality of the situation showed that there are obstacles to this idealised method. This is because stakeholders have less ERS-related experience and are unable to compare multiple criteria on behalf of their organisations based on their current understanding. Therefore, this study instead chose a semi-quantitative approach, using colour code to indicate stakeholder concerns as well as key impacts.
At last, a second round of stakeholder interviews is conducted for validation purposes. The results of the multi-criteria analysis will be presented in the interviews. Stakeholders' opinions are collected such as whether the results are in line with their previous guesses based on experience and whether new concerns have arisen.

For the first sub-question, the literature on ERS technologies and the relevant reports from the countries that have implemented ERS have been reviewed. Using keywords to search literature in Google Scholar, paying particular attention to articles published after 2015, and skimmed through the abstracts, introductions, and conclusions in order. Then select the useful papers and snowball backwards to view other related papers. On the other hand, check out the latest reports on ERS from Swedish and German institutes (e.g. RISE) for more information on their existing demonstration projects.
Subsequently, in addressing the second sub-question, the stakeholder analysis and the DfV method have been used. A series of value-oriented semi-structured interviews will be conducted with each stakeholder group. The objective of these interviews is to identify the values and also obtain information about their possible responsibility in an ERS project and their concerns about technology.
In order to answer the third sub-question, it is necessary to develop a set of evaluation indicators. Starting from the value-based criteria, indicators that can measure the criteria qualitatively or quantitatively are selected in two ways. One is derived directly from conversations with stakeholders during the interview process. The second is to use the evaluation indicators in the existing literature as a reference supplement and select indicators that reflect the criteria of the stakeholders, in case important factors are not covered.

The fourth sub-question is addressed through a calculation and analysis of both quantitative and qualitative indicators. The multi-criteria analysis will be employed for each stakeholder

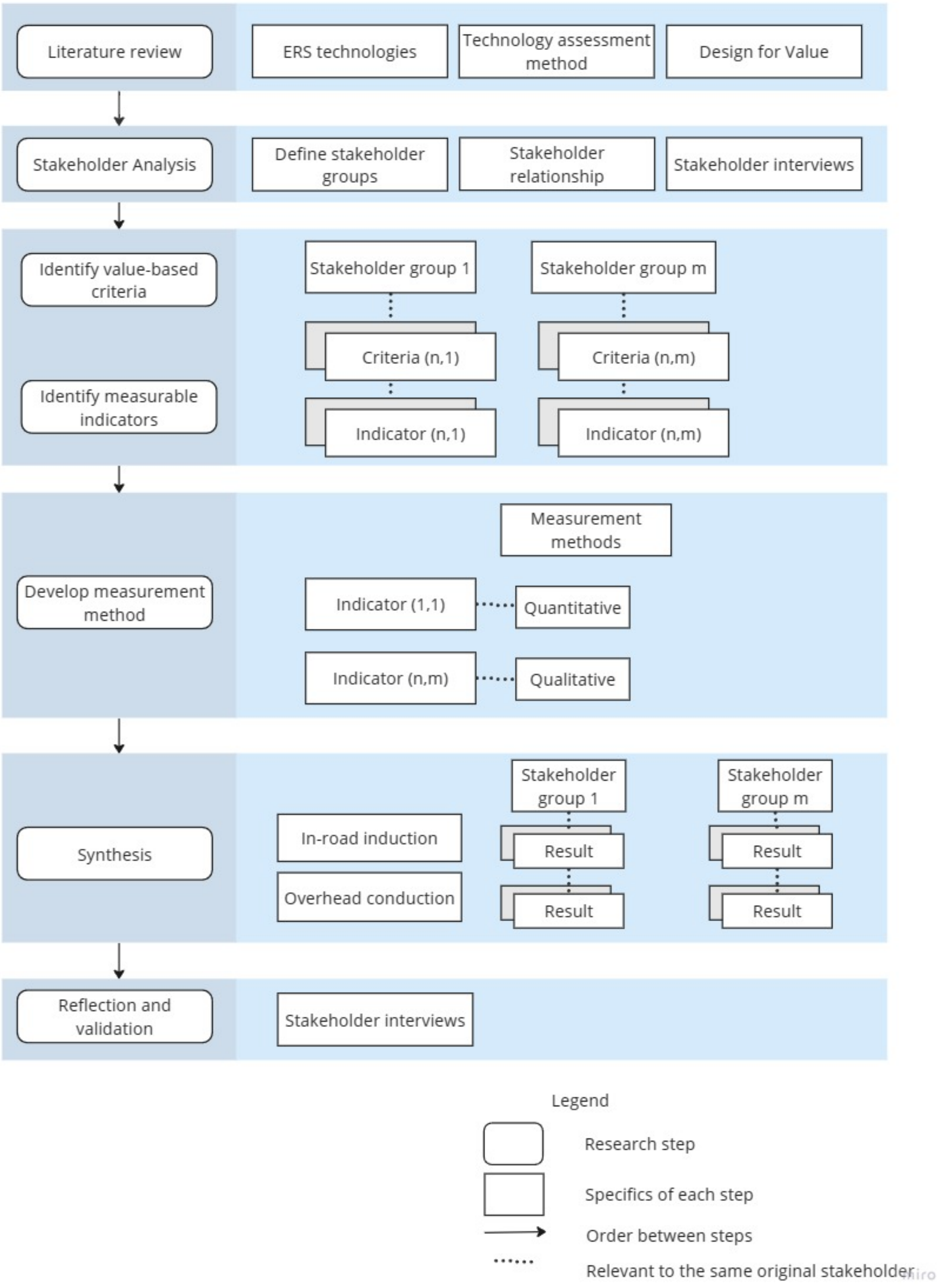


Figure 1.4: Framework

group. It is noteworthy that the weighting and ranking of criteria are not included in this study as the focus of this project is not to select the best-performing alternative but to sort out the impact of the different technologies on each stakeholder group.

1.5. Structure of the thesis

According to this research background, in chapter 2 the findings of the literature review on ERS technology are concluded. In Chapter 3, the first round of interviews and stakeholder analysis will be done to identify the value-based criteria held by them. In Chapters 4 and 5, evaluation indicators are developed and calculated. The results and validation of the MAMCA are provided with the second round of interviews in Chapter 6. Last, the main research question is answered in the conclusion stated in Chapter 7.

2

Literature Review

In this chapter, the current state of ERS will be summarised based on the literature and then focus on ERS projects and individual ERS technologies to identify their specific requirements.

2.1. ERS current situation

The studies found that ERS performs particularly well among the decarbonization solutions in terms of energy efficiency, WTW greenhouse gas emissions, and also reduces reliance on batteries (Ainalis et al., 2020; Widegren et al., 2022). Dynamic charging helps electric heavy goods vehicles (eHGV) require only small batteries, while the associated infrastructure can also be combined with other road infrastructure projects such as support sensing and communication of connected and autonomous vehicles and 5G network (Ainalis et al., 2020). ERS technology, especially overhead conductive systems which already have similar applications in trolley buses and train systems, are close to being technically mature, i.e. theoretically possible to put into practice. However, it is uncertain whether these different technologies are sufficiently feasible to operate in reality or even to roll out on a large scale.

Nevertheless, two biggest challenges exist: ERS consist of various subsystems, and each subsystem involves multiple stakeholders. They have their own needs and their future role or responsibilities are hard to identify (Gustavsson et al., 2019a). More importantly, in terms of technical implementation, both ERS technologies require investment in and adapting existing road infrastructure. It remains unclear what the different impacts of the two technologies will be from a systems perspective.

To address these uncertainties, many feasibility studies and field tests have emerged since 2010 to systematically examine ERS-related technologies and the impacts they will bring. There are more than 25 ERS development projects and demonstration projects in 5 EU countries with a total route length of about 60 km involving about 50 ERS HGV (Lehmann, 2023). The main projects of ERS, especially those of Siemens and Electreon in Europe, and their timetables are summarised in Figure 2.1.

With the development of ERS project in Sweden (2016), Germany (2019) and the United States of America (2017) (Almestrand Linné, 2020), the study of ERS has been developed by real-world projects instead of academic research. A large number of studies were conducted to

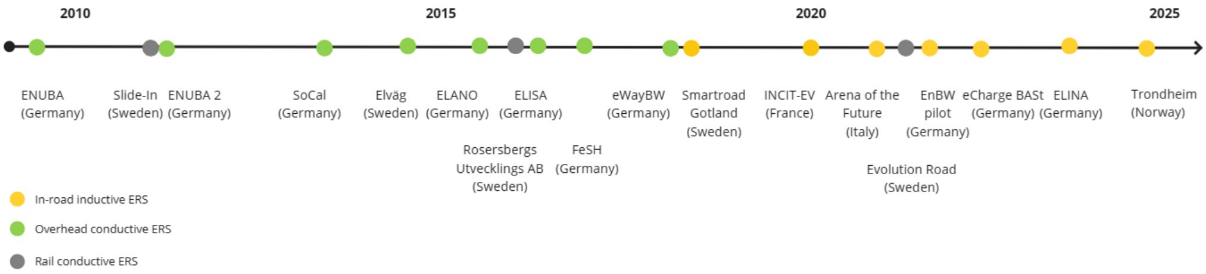


Figure 2.1: Timeline of trials with 3 alternative ERS technologies

evaluate the feasibility as well as the advantages and disadvantages of ERS implementation, with a focus on better understanding of individual aspects such as environmental (Shoman et al., 2022; Taljegard et al., 2017;Johnsson et al., 2020a; Johnsson et al., 2020b; Jelica et al., 2018), cost (Taljegard et al., 2017; Nordin et al., 2020; Ainalis et al., 2020; Andersson et al., 2019), operation strategy(Nordin et al., 2020), technical (Johnsson et al., 2020a), etc.

In the focus on environmental, Taljegard et al. (2017) evaluating the potential for mitigating CO_2 emissions to determine which classes of vehicles are most suitable for electrification to support the ERS project. Johnsson et al. (2020a) evaluate how ERS could impact the Swedish and German electricity systems by looking at the performance in the life-cycle GHG emissions since the long-term potential of ERS to reduce GHG emissions is important. Johnsson et al. (2020b) evaluate the performance on environmental aspects of ERS based on a case study on a potential corridor from Sweden via Denmark to Germany to illustrate the challenges and implementation strategies. Jelica et al. (2018) evaluate the energy demand and CO_2 mitigate potentials. The focus is on examining future scenarios and their impact on stakeholders and discussing future challenges.
Cost is also an important aspect to consider when talking about the implementation of ERS. Ainalis et al. (2020) calculate the associated costs of overhead conductive infrastructure to provide insight for the ERS implementation in the UK. Andersson et al. (2019) provide the forecast cost factor to implement both two technologies in Sweden. Aronietis and Vanelslander (2023) summarize the related cost with a background of Belgium. Nordin et al. (2020) evaluate the potential costs that the implementation of ERS could have on construction, maintenance, and operation processes in the US.
With a focus on the technology aspect, the study of Johnsson et al. (2020a) examines the performance of the Technology Readiness Level (TRL) and identifies the technical barriers that must be overcome. It assesses how ERS affects the power systems in Sweden and Germany.

All of these studies provide scientific solutions for ERS implementation by considering specific factors. However, these studies only focused on individual aspects and did not take a systems perspective to evaluate their combined impact. A large number of studies still compare ERS, especially overhead conductive solution, with conventional diesel vehicles or other alternatives, with few comparisons between different ERS technologies.

2.2. Life cycle of ERS project

The life cycle of a project on new technology consists of research and development, ascent, maturity and decline phase Commons (2022). It describes the business gains of a technology project through several phases. The lifespan depends on the characteristics of the technology.

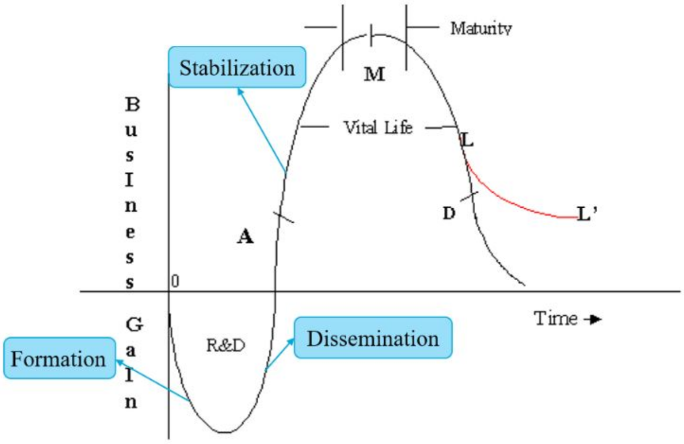


Figure 2.2: The life cycle of a technology project (Commons, 2022)

In the implementation of ERS, the subsystems and involved stakeholder groups can be different in each phase since not all stakeholders act in all phases and may develop over time. When considering the evolution of ERS technologies, corresponding phases also can be identified as shown in Figure 2.2. According to the European ERS Symposium in Berlin, three phases are introduced and they are characterized by different social actors and their changing interactions in changing networks (CollERS, 2023).

The formation phase includes the unstructured combination of actors, informal communication and the creation and application of technical systems. The dissemination phase includes the cooperation of strategic players, networking, and development of ERS prototypes and demonstration projects. The stabilisation phase is the next focus and includes the re-consolidation of socio-technical networks, the development of self-dynamic market needs, feedback loops from users and suppliers, leading design and a wider range of applications (CollERS, 2023). Currently, the EU is in the dissemination phase, with a number of achievements in the last decade, such as several demonstration projects, four standardization and approximately 60 km of ERS route length. Considering that most of the data and research are focused on the dissemination phase, these studies will use this phase as a background and analyse the different performance of technologies in a pilot project.

When looking at the dissemination phase in detail, where is the current progress, there are four distinct aspects that need to be considered when implementing the technology for the route. These four aspects are construction, operation, maintenance, and the final disposal (removal or reuse of construction materials) (Ortiz et al., 2009). In this study, the focus will be on the first three aspects. In this particular scenario, the corresponding subsystems and stakeholder groups will be identified in the following chapter.

2.3. Characteristics for different ERS technologies

In terms of charging methods, ERS can be divided into the conductive and inductive categories, and in terms of their relative relationship to the road surface, they can be divided into overhead, in-road and side (Bateman et al., 2018). Among these methods, three types of ERS technologies that are feasible in reality: in-road inductive, overhead conductive and conductive rail (Bateman et al., 2018) as shown in Figure 2.3.

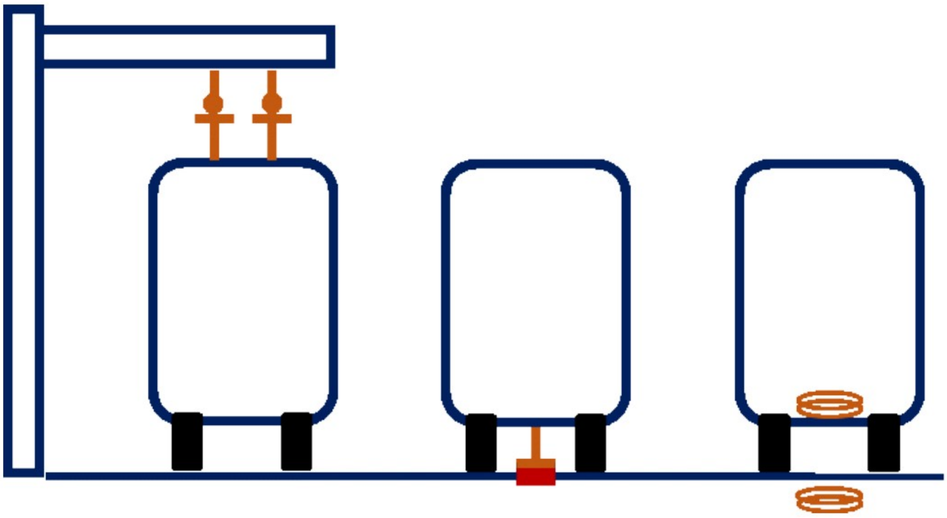


Figure 2.3: ERS technologies (Rijksoverheid, 2021)

In this research, the overhead conductive and in-road inductive technologies are the main focus because they are the two typical and controversial technologies that have already been implemented in reality with various studies. While the conductive rail posed higher inherent risks due to the presence of an exposed conductor on high-speed roads, as well as their potential impact on road maintenance activities(Bateman et al., 2018).

Overhead conductive technology

The overhead conductive ERS is essentially an evolution of the overhead rail and trolley system but with double cables and a more complex and vulnerable pantograph system. The power is transferred through the pantograph and supplies the vehicle's battery system (Bateman et al., 2018).

The overhead conduction system is based on the conductive power transfer (CPT) technology. The principle of CPT is that a support infrastructure outside the road boundary supports two overhead catenaries to transfer power to the pantograph mounted on top of a vehicle. The pantograph is capable of connecting and disconnecting from the overhead catenaries while running at a certain speed (200 kW at 90 % transfer efficiency allows 90 km/h) (Bateman et al., 2018). It is a physical connection between the infrastructure and the vehicle.

The German and Swedish governments were the first to agree on the implementation of the pilot conductive overhead ERS program. The Swedish government implemented the world's first trial of overhead conductive ERS technology on public roads, completing their project on the E16 outside Sandviken in 2016. The German government is implementing its ERS program at three major demonstration sites. France started their overhead conductive system in 2019 with a three-way partnership. Italy is also having their conductive project. (Federal Ministry for the Environment and Safety, 2018; Bateman et al., 2018)

Demonstration projects in Sweden and Germany have shown that this technology works in a range of real-world road infrastructure situations and that there are no technical barriers to large-scale replication. In addition, there are no significant health, safety, construction, or operational risks in reality. The main advantages mentioned in the literature of overhead conductive systems can be summarised as follows (Bateman et al., 2018 Ainalis et al., 2020):

- Technical mature
- Safe: High level of vehicle manoeuvrability
- Effective: the system has a higher potential to pay for itself and generate value
- Efficient transmission of electricity
- Experienced technicians on a similar system
- No impact on pavement structure

In-road inductive technology

The in-road inductive system is based on the in-motion wireless power transfer (WPT) technology, the principle of which is shown in Figure 2.4. The road (transmitter) and the vehicle (receiver) together form a loosely coupled transformer. Power from the road to a vehicle through the use of coils that create a varying magnetic field, inducing an electric current on pickup coils in the vehicle (Bateman et al., 2018). This technology was developed commercially available by KAIST in Korea in its bus system in 2009 and followed by multiple research in the State and demonstration projects in the EU (Choi et al., 2014)

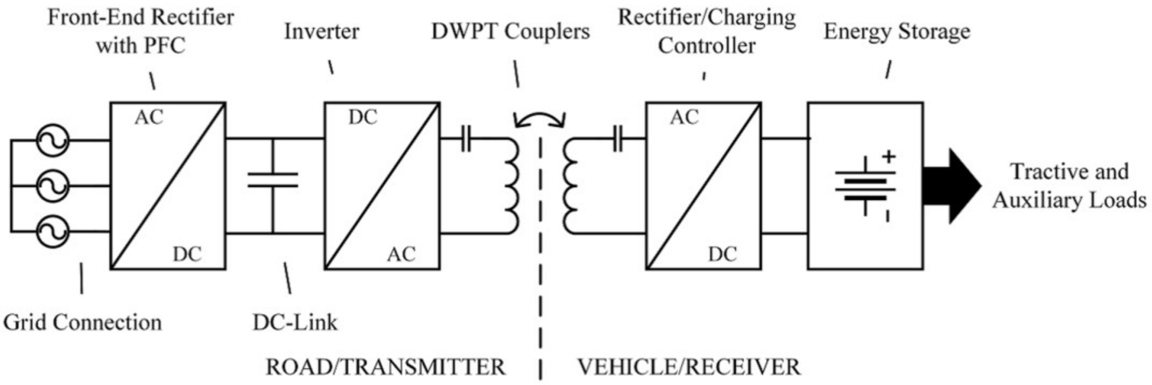


Figure 2.4: Principle of in-motion WPT system (Qiu et al., 2022)

The main advantages of the in-road inductive system can be summarised as follows (Bateman et al., 2018 Ainalis et al., 2020):

- Usable by more vehicle types

- Low visual impact
- No add-on technology with movable parts
- Less regular infrastructure maintenance required
- Less vulnerable to damage or vandalism

Requirements of ERS technology at different phases
The requirements for ERS technologies will be carried out within the context of several implementation phases. Most of the studies conclude the limitations and requirements in the construction, as well as operations and maintenance phases.

- Transition
  From a technical perspective, the transition of overhead conductive ERS technology can benefit from knowledge transfer from the railway sector. The main construction work such as overhead double cables and grid extension does not have an impact on the road surface. Almost all of the mounting of supporting infrastructure can be completed on the roadside, such as support poles, concrete foundations, safety barriers, etc (Nordin et al., 2020). While this approach is well-suited for open roads, may need some extra work for tunnels and bridges (Bateman et al., 2018).
  On the other hand, the installation of in-road inductive ERS technology requires modification of the road surface, which entails closing the road during the whole installation process.

- Operation
  In the case of overhead conductive technology, the operation phase requires the synchronization of overhead lines with the vehicle pick-up, which is influenced by the speed of the vehicle (Bateman et al., 2018). Drivers need to adapt their driving to connect to the overhead lines.
  The inductive system is most effective at speeds of 80-100km/h during operation (Bateman et al., 2018), as this achieves a better energy transition while keeping energy loss at a lower level. However, this speed range may not be suitable for passenger vehicles.

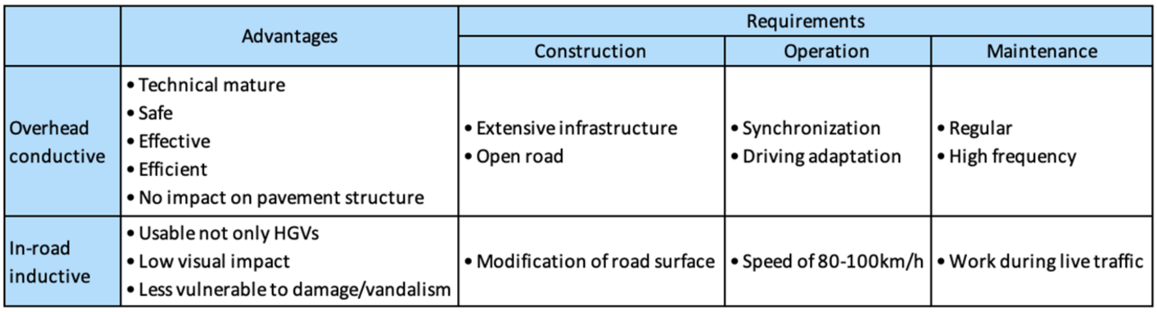
- Maintenance
  Regular maintenance is required for both ERS technologies. However, overhead conductive is more vulnerable to weather conditions due to its exposure. Maintenance of in-road inductive technology poses the risk of road surface failure due to embedded pads which require the workers to work during live traffic (Nordin et al., 2020). In addition, the maintenance of the road needs to be coordinated with the maintenance of the ERS infrastructure, which adds to the complexity.

2.4. Conclusion

In conclusion, the ERS has been recognized as a promising solution for sustainable mobility by overcoming the range of anxiety issues faced by electric vehicles. It is ready for real-life implementation and the ERS infrastructure can also be integrated with other road infrastructure projects.

Three main types of ERS technologies exist, namely in-road inductive, overhead conductive and rail conductive. Overhead conductive ERS technology has been implemented in pilot projects in multiple countries and has proven its technical maturity and effectiveness, as well as safety and efficiency. In-road inductive ERS technology has also shown good promise, with the advantages of low visual impact, less susceptibility to damage, and no need for regular infrastructure maintenance.

However, challenges exist in the complexity of the various subsystems and stakeholder requirements, as well as the pre-existing charging infrastructure and the significant investments required for various adaptions. Various studies have been conducted to assess the feasibility of implementing ERS from individual environmental, cost, technical or energy perspectives. It shows ERS implementation remains challenging, but its potential benefits make it a technology worth exploring and investing in for the future of sustainable transportation. A summary of the key findings from the existing literature is shown in Figure 2.5.



	Advantages	Requirements		
		Construction	Operation	Maintenance
Overhead conductive	• Technical mature • Safe • Effective • Efficient • No impact on pavement structure	• Extensive infrastructure • Open road	• Synchronization • Driving adaptation	• Regular • High frequency
In-road inductive	• Usable not only HGVs • Low visual impact • Less vulnerable to damage/vandalism	• Modification of road surface	• Speed of 80-100km/h	• Work during live traffic

Figure 2.5: Quick overview of key attributes of conductive and inductive ERS

2.5. Discussion

In general, many studies have investigated ERS nowadays, especially with the start of ERS implementation projects in Sweden and Germany. However, most of these studies focus on an individual perspective in their assessment of ERS impact. Such assessment still looks at the problem in a separate dimension, considering only the impact of individuals, rather than comprehensively assessing the impact of all stakeholders at the system level.

In addition, while a large number of technology assessment studies exist in related fields such as electric vehicles, very few studies have focused on technology assessment in the ERS field. Most of the studies only look at the overall ERS system as a solution and assess its feasibility at a high level, without looking in depth at the various technologies involved, such as conductive and inductive technologies. The assessment of different technologies can vary considerably.

These issues have not found a clear corresponding analysis in the literature as stated in section 2.1. Therefore the current gap lies in the lack of systematic assessment as well as the lack of detailed analyses at the level of specific technologies, which deserves continued reflection in future studies.

3

Stakeholder Analysis

This chapter will identify the subsystems of ERS technology according to a review of the relevant literature. Subsequently, the corresponding stakeholder groups involved in ERS projects, especially in the dissemination phase will be generated. An analysis of the interrelationships between these stakeholder groups will be done. Through value-based semi-structured interviews with experienced people from primary stakeholder groups, their possible roles and responsibilities in the context of ERS will be identified, along with an exploration of the values held by their respective organizations.

3.1. ERS subsystems identification

Gustavsson et al. (2019b)'s research identified that ERS consist of five different subsystems in the dissemination phase: energy supply, infrastructure, power transfer, road operation and vehicle. In this study, these five main sub-systems are used as a starting point to identify all stakeholders related to the two technologies. In addition to these, regulatory, technical and social actors will also be considered.

3.1.1. Energy supply

The energy supply system mainly consists of three components which are transmission, distribution and management (Gustavsson et al., 2019b). The transmission component includes the long-distance flow of electricity from the original source. Distribution is the flow of electricity through the grid to the transmission part of the electricity. The management component controls and balances the electricity.

3.1.2. Infrastructure

This sub-system consists of two main areas. One is the existing infrastructure that needs to be adapted, mainly road paving. There is a need for a transition from the current infrastructure to an infrastructure capable of supporting ERS technology. The other is the surrounding physical infrastructure that needs to be newly constructed, including barriers, auxiliary components, etc. Barriers relate to protective components in terms of safety and noise. Auxiliary components are road signs and other necessary roadside components.

3.1.3. Power transfer

The power transfer subsystem includes road power transfer, vehicle power transfer and control component (Gustavsson et al., 2019b). The road power transfer section consists of in-road or roadside equipment that detects vehicles using the service and controls the transmission of power. The vehicle power transfer can activate the power receiver, which is responsible for measuring the total energy transferred. The control component monitors the energy transfer in real-time.

3.1.4. Road operation

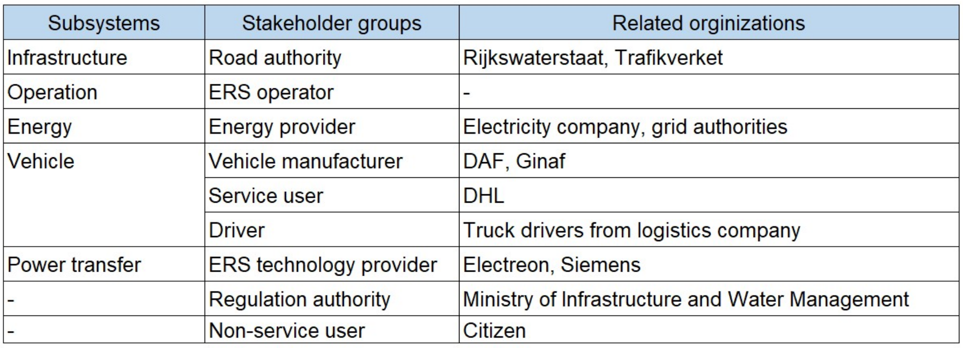
The road operation subsystem is a control centre that collects user information and processes payments and bills. This subsystem is not fully functional at the current phase, as ERS is not fully accessible to all members of the public on a large scale. The functionality will vary at the stabilization stage of technical maturity.

3.1.5. Vehicle

The vehicle subsystem converts the electricity from the power transfer subsystem into the energy needed to run the electric vehicle. In addition to the mechanical aspects of the vehicle, it also includes fleet management and vehicle positioning.

3.2. Stakeholder groups identification

Stakeholder groups associated with each subsystem will be identified according to these subsystems of ERS as shown in Figure 3.1. In addition to the stakeholder groups that are directly related to subsystems, two other indirect stakeholder groups are also considered in this study, which are the regulation authority and non-service user (citizen).



Subsystems	Stakeholder groups	Related orginizations
Infrastructure	Road authority	Rijkswaterstaat, Trafikverket
Operation	ERS operator	-
Energy	Energy provider	Electricity company, grid authorities
Vehicle	Vehicle manufacturer	DAF, Ginaf
	Service user	DHL
	Driver	Truck drivers from logistics company
Power transfer	ERS technology provider	Electreon, Siemens
-	Regulation authority	Ministry of Infrastructure and Water Management
-	Non-service user	Citizen

Figure 3.1: Stakeholder groups relevant to each subsystem

Infrastructure provider have a direct connection with the infrastructure subsystem, responsible for constructing, operating and maintaining the physical road infrastructure required to facilitate the ERS project. They are a very important stakeholder in this study because the two different technologies have different requirements for road construction.

ERS technology provider is responsible for the development of the overhead conductive and in-road inductive technologies, as well as the construction of supporting infrastructure and providing the power transfer solution. In the context of this research, all the data are collected with the assumption that the provider of overhead conduction technology is Siemens and the provider of in-road induction technology is Electreon.

ERS operator is associated with the operation subsystem and focuses on the operation and management of the ERS. They receive and process the request sent from the driver and finally forward it to the infrastructure subsystem. The operator is perhaps a future role and an important stakeholder for the next phase and can be seen as a new job opportunity that the implementation of ERS can bring. It can also be combined with the existing road operator instead of a separate role.
The existing cases in Germany and Sweden show that the current organisational structure of this operator is not clear and is for the time being a mixed operational structure (Bernecker et al., 2020). In the dissemination phase, the road authority will take the responsibility. Since it has a very important role in the future, this study will also include the ERS operator as a separate stakeholder group. However, there are not very suitable interviewees with experience in this field and their concerns will be identified through the literature.

Energy provider is responsible for the transmission, distribution and management of electricity to the system. Such stakeholders may include electricity suppliers, smart grid authorities and environmental authorities.
In the current context, they do not have a deep involvement in ERS projects and are more closely linked to technology providers to determine distribution plans.

Vehicle manufacturer is responsible for the development and manufacture of ERS-compatible electric vehicles and for the subsequent maintenance activities associated with the vehicles. Their work is highly dependent on the future market needs of the service users.

Service user can be freight forwarders providing end-to-end logistics, transport contractors, logistics company, etc. They purchase electric vehicles and electricity directly, use the ERS infrastructure and transmit information and data to the ERS operator.

Driver are the direct users of the electric vehicles. They drive the vehicle on the road and operate it to connect or disconnect from ERS infrastructure.

Regulation authority plays a crucial role, particularly during the initial stages of ERS implementation. They have the responsibility for assigning tasks to road authority and providing essential support to diverse stakeholder groups. Their support may include offering subsidies to facilitate the widespread adoption of ERS technologies.

Non-service user is citizens who are not directly related to the ERS subsystems, but whose views need to be taken into account. Because there is also the possibility of them being affected by the ERS project, especially for citizens who can drive. And they may be potentially affected by the additional infrastructure brought about by different technologies.

The relationship between stakeholder groups and their interest in joining the ERS project has been described in Figure 3.2 and Figure 3.3.
Regulation authority, infrastructure provider and ERS operator all have significant influence and interest in the project. They are the main stakeholders driving the roll-out of the ERS

project and deciding which technology to adopt. It is necessary to fully involve them during the ERS project studies. Citizens and service users are stakeholder groups with high influence but low interest. Their attitudes will largely influence the final decision. Therefore, their needs and concerns need to be carefully considered in order to satisfy them. Technology providers and vehicle manufacturers have a strong interest in the decision-making process for the roll-out of the ERS but have less influence. They own their technology and provide ERS solutions. Energy providers and drivers have less influence and interest, as they do not have much direct connection to the ERS project.

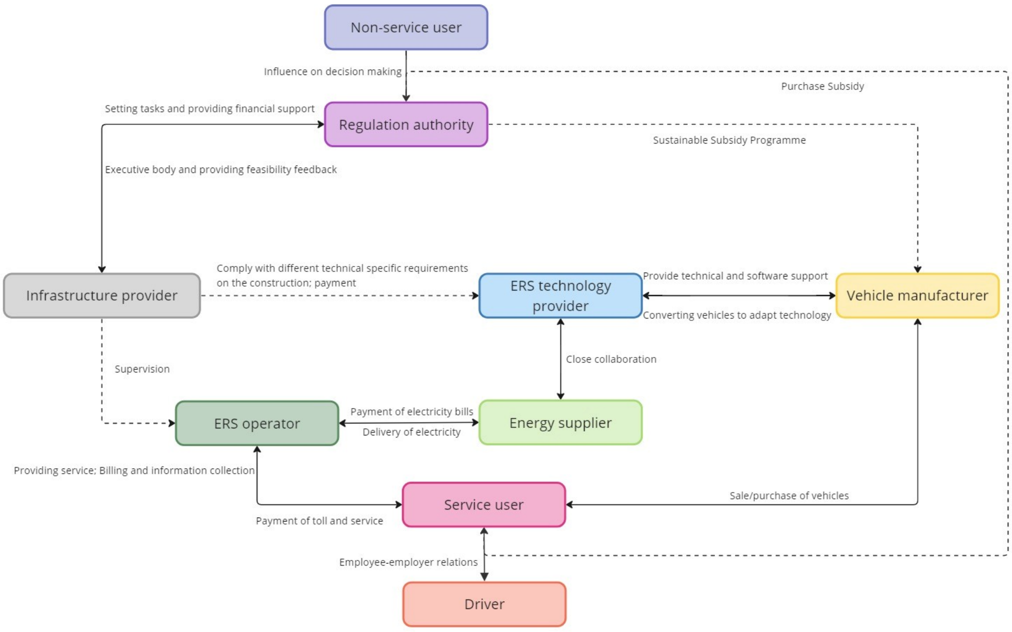


Figure 3.2: Stakeholder relationship analysis

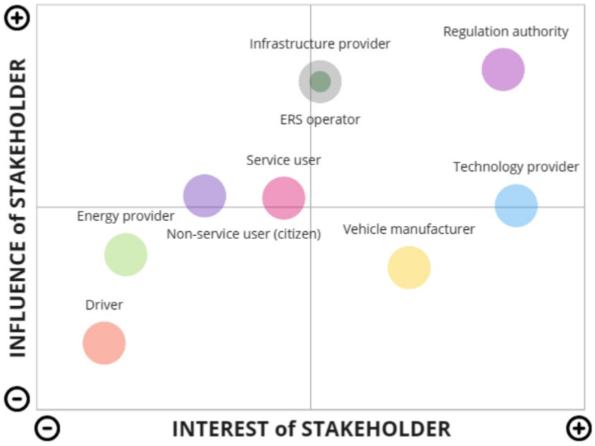


Figure 3.3: Stakeholder mapping

3.3. Stakeholder value-based criteria identification

Value-oriented semi-structured interviews will be conducted with stakeholders to determine their holding values, possible roles and responsibilities, and concerns about ERS technology. For each stakeholder group, there are several types of stakeholders. In this study, considering the limited time and resources, the interviews are conducted with example actors who already have experience in an ERS project or have direct connections in the case study project. The goal is at least to interview two organizations of each stakeholder group to get a more representative result.

Based on the results obtained, the values held by each stakeholder group and the value-based criteria will be identified.

3.3.1. Infrastructure provider: road authority

Trafikverket, the Swedish national road authority, have the ownership and responsibility for the country's comprehensive road infrastructure, including its construction, operation, and maintenance. Given the ongoing field projects in Sweden that have tested various technologies, engaging in an interview with Trafikverket is important to obtain practical insights regarding the implementation of ERS.

The interviewee, is the senior advisor within the organization, having experience in leading projects that analyze the ERS business model. Talking about the organisation's own interest, in addition to the sustainable development goals that need to be achieved, they focus on providing an efficient and safe transport system through the implementation of ERS. However, the interviewee showed a concern that most studies nowadays are positive about ERS technology and forget to consider it from a practical perspective, for example, many studies ignore the actual cost of the construction of vehicles.

Rijkswaterstaat is the road authority in the Netherlands, executive part of the Dutch Ministry of Infrastructure and Water Management. They are responsible for the design, construction, management and maintenance of the main infrastructure facilities in the Netherlands.

The interviewee is a senior advisor in the sustainable mobility department, working mainly with alternative fuels and infrastructure for heavy-duty vehicles. He was involved in the ERS project in 2020 from a technical point of view, mainly to carry out feasibility studies. He believes that ERS could be a cost-competitive technology in some cases in the Netherlands, but their organization has not yet decided whether to pilot it and which technology to use. In general, he feels that the overhead conductive system is the most developed technology and can be more easily applied in the Netherlands.

As a road authority, they want to maintain an efficient, electrified as well and sustainable transport environment by promoting ERS with a limited budget. Furthermore, he mentioned that when it comes to technology selection, they don't want to go for a technology that only one company could build, preferring to have a competitive business environment to deploy such technology. Their concerns about overhead conductive technology are mainly safety-related. Such as the possible impacts brought by the overhead lines and the performance of both technologies in specific environments.

3.3.2. ERS technology provider

Siemens Mobility is a technology company developing intelligent pantograph systems. It is the technology provider for overhead conductive systems and is also responsible for the construction of roadside infrastructure. Siemens Mobility has transferred its electrification as a technology from rail to road. They already have a lot of experience with rail systems and have a proven supply chain where they know how to work with all the components and can quickly build or fix system problems.

The interviewees are the Business Development Manager in the Netherlands and the Head of Business Development at eHighway in Germany, who has 11 years of experience in dynamic charging solutions.

From their perspectives, the primary advantage of their technology, coupled with their extensive experience, is that all the necessary infrastructure is constructed adjacent to the road, and the road occupation is limited to overnight periods. Moreover, most maintenance activities can be carried out next to the road.

By participating in the ERS project as a provider of overhead conductive technology, the interviewee's organization assumes a social responsibility to address climate change and growing urbanization, while also contributing to the digitization of mobility. Simultaneously, they strive to enhance efficiency in terms of energy, resources, and time, establish market leadership through technological advancements, and further expand their market.

Electreon is a leading provider of wireless charging solutions for electric vehicles and currently has 12 projects ongoing across the world. One of the interviewees is the Regional Director in Germany and another is the Regional Director for the Nordic region with more than 15 years of experience in the field of electric vehicle and road. He leads the Swedish Electric Roads research and innovation platform and has been the Swedish project leader for the Electric Roads collaboration between Sweden and Germany.

According to the interviewee's point of view, the primary benefit of an inductive system lies in no visible infrastructure, which eliminates the need for additional protection construction and reduces maintenance requirements. Additionally, this technology offers the advantage of serving as an applicable charging solution for various types of vehicles.

By participating in the ERS project as an in-road inductive technology provider, the organization aims to enhance its competitiveness and profitability in collaboration with its partners while accomplishing sustainable goals.

In conclusion, through their involvement as technology providers in the ERS project, Siemens Mobility and Electreon have a similar goal. These objectives include sustainability, as well as the desire to foster competitiveness and profitability.

3.3.3. Energy provider

Only one company responded to the invitation for an interview, so there may be other claims standing on the position of energy provider. This is a side effect of the relatively low interest of this stakeholder group in the ERS project.

VARO Energy is a prominent energy transition company that operates across the entire energy supply chain, prioritizing the acceleration of the energy transition towards achieving net-zero emissions. The interviewee from VARO Energy has extensive knowledge in the electricity market, with a 13-year background in e-mobility. While VARO Energy has been involved in smart charging projects, they have not yet participated in dynamic charging such as ERS.

During the interview, the interviewee expressed a critical attitude towards ERS technology, highlighting two primary concerns. Firstly, the earning model will raise issues for energy providers. Given the difficulties and costs associated with electric storage compared to traditional fuel, energy providers greatly value the pattern of electricity consumption. It is of great importance for them to know when and how much the vehicle going to charge which requires a very stable pattern of commercial fleets. However, in the case of ERS, especially with in-road inductive technology open to the public, vehicles have the flexibility to charge at varying times and locations, leading to an unpredictable consumption pattern that will bring more problems for the energy supplier's earning model. Secondly, the security of supply poses a challenge. In the liberalized electricity market of the Netherlands, commercial fleet managers prefer to maintain control over their own charging infrastructure to ensure a secure electricity supply. This private infrastructure is likely to persist until ERS becomes fully reliable and mature. In the early phase of ERS, it would face difficulty in competing with these established private charging facilities and the extra cost may exist.

Considering these concerns and the values held by VARO Energy, interviewees in general felt that there are challenges with both ERS technologies.

3.3.4. Vehicle manufacturer

DAF Trucks, a truck manufacturer and a leading player in the electric truck sector offers not only electric vehicles but also comprehensive solutions for zero-emission transportation. Their offerings include proven technologies, efficient charging systems, fleet management, and more. Within the context of the case study area, DAF Trucks has a market share of 32.5 %, making it a crucial stakeholder in the implementation of ERS in the Rotterdam-Antwerp corridor.

The interviewee from DAF Trucks is responsible for advanced technology, project management and technical external relations. The tasks included activities such as proof of concept and promoting advanced technology projects. Currently, they are collaborating with a university on a project involving overhead conductive systems, developing a vehicle that supports dynamic charging through an add-on system integrated with their standard battery electric vehicle. By the end of this year, these vehicles will be manufactured and delivered for field testing in the surrounding of Frankfurt. Although there are no ongoing projects related to inductive technology, the interviewee remains highly interested in exploring potential solutions for the future.

They have a significant focus on climate goals, investment costs, and the robustness of charging technologies. From DAF Trucks' perspective, another key consideration is achieving a quick return on investment, probably within two years, to ensure optimal operational efficiency for the company. Unlike governmental entities, DAF Trucks seeks a relatively swift payback period for their investments.

During the discussion, the respondent from DAF Trucks highlighted two specific risks associated with inductive solutions. First, there is concern about the power transfer efficiency due to potential air gaps between the truck and the coil. Second, adapting the vehicles to accommodate the induction system presents a challenge. DAF Trucks finds it relatively easier to modify vehicles using an add-on system rather than making modifications underneath the truck.

GINAF is a vehicle manufacturer that already has experience in vehicle construction and can support the in-road inductive system. The interviewee is the director of sales of electric vehicles and is also responsible for the supply chain. Based on experience, in addition to the factors already mentioned by DAF, she mentioned two other values that they take very seriously. The first is to provide the driver with easy and comfortable driving support. The other is good software compatibility between the vehicle and the ERS operating system. Since all the mechanical problems in vehicle manufacturing can be solved now, the next bottleneck for them is how to have a better connection in the software platform to avoid system failures or overheating. In addition, she mentioned that one of the very significant benefits of the electrification of the trucks brought by in-road inductive technology for their company is that they do not need to organize frequent and regular in-person inspections and maintenance, but focus on online inspections, saving a lot of maintenance costs.

3.3.5. Service user: Logistics company

DHL is known as the world's leading logistics company offering express delivery, parcel shipment, and courier solutions services, with annual parcel volume exceeding 1.8 billion. As one of Europe's prominent market players, they run the GoGreen program that focuses on reducing GHG and will continue to drive their operations towards zero logistics-related emissions in the future. They have a large number of trucks travelling daily from the Netherlands to Belgium, which makes DHL a very important potential service user for the ERS project.

The interviewee, a senior director of fleet and sustainability at DHL, focuses on the express dimension across the entire shipping network within Europe. To advance their sustainability objectives, DHL has already electrified their delivery vans and ground support equipment. However, the interviewee expresses concern regarding the present state of electric infrastructure and energy storage solutions, as these factors will impact DHL's decision on when to step into the related project. Standing on the company's aspect, it's interesting to see the potential of an ERS technology to provide cost reductions and enhance logistics efficiency, thereby keeping DHL's continued market leadership and operational continuity.

3.3.6. Driver

This collected information is based on a summary of a driver who has experience driving a truck on the eHighway in Germany. For the driver, the driving experience is the most important to them, for example, they want the electric truck to keep a fast speed on the slope, to be safe, to overtake and to keep the lane unobstructed. The time taken to successfully familiarise themselves with and operate the support ERS truck is also very important, which requires the operating steps to be very simple.

3.3.7. Regulation authority

The Ministry of Infrastructure and Water Management responsible for transport, water management, etc in the Netherlands, is also the initiator of the implementation of the ERS project. One of its priorities is to create an efficient transport network in a safe and sustainable environment and to achieve decarbonization goals. They play a crucial role in promoting and implementing the ERS program. The interviewee is in the position of dept. project leader Heavy Good Vehicles Tax and stakeholder manager tolling.

In the Netherlands, road users are subject to a fixed fee for road usage and a flexible fee based on CO2 emissions and distance travelled. The funds generated from these fees, approximately 300 million euros annually, are allocated towards enhancing sustainability within the transport sector and increasing the appeal of electric trucks.
The organization currently faces a challenge which is a ”chicken and egg” dilemma. To promote the implementation of ERS, there have to be electric vehicles and there has to be charging infrastructure. There’s a need for the Ministry on proactive measures to stimulate action among various stakeholders, such as introducing subsidies or rebates and establishing environmental targets.
The primary objective of the Ministry is to implement the ERS program aimed at reducing GHG in the heavy-duty vehicle segment. At the present stage, there is a strong desire to speed up the rollout of electric trucks and associated charging infrastructure, rather than awaiting further technological advancements. The Ministry also seeks to make a lasting contribution to climate goals while enhancing the overall quality of the living environment for all individuals.

3.3.8. Citizen (non-service user)

In a survey conducted by the Dutch Ministry of Infrastructure and Water Management, the attitudes and preferences of 1013 citizens towards ERS were collected by means of a questionnaire. The survey showed that concerns were focused on road safety. Citizens were keen to know how different technologies would affect road safety, and they expressed concern, for example, about the possible dangers posed by overhead line breaks.

Through the interviews, the values and responsibilities held by the various stakeholder groups are clear, and the criteria corresponding to these values could be used in the subsequent evaluation process of the two technologies. The multiple criteria that can be used for multiple actors are shown in Figure 3.4.

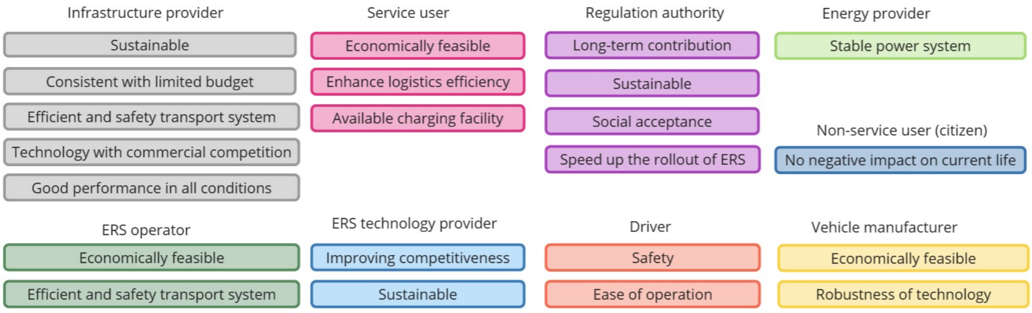


Figure 3.4: Summary of value-based criteria from stakeholder interviews

4

Performance indicators development

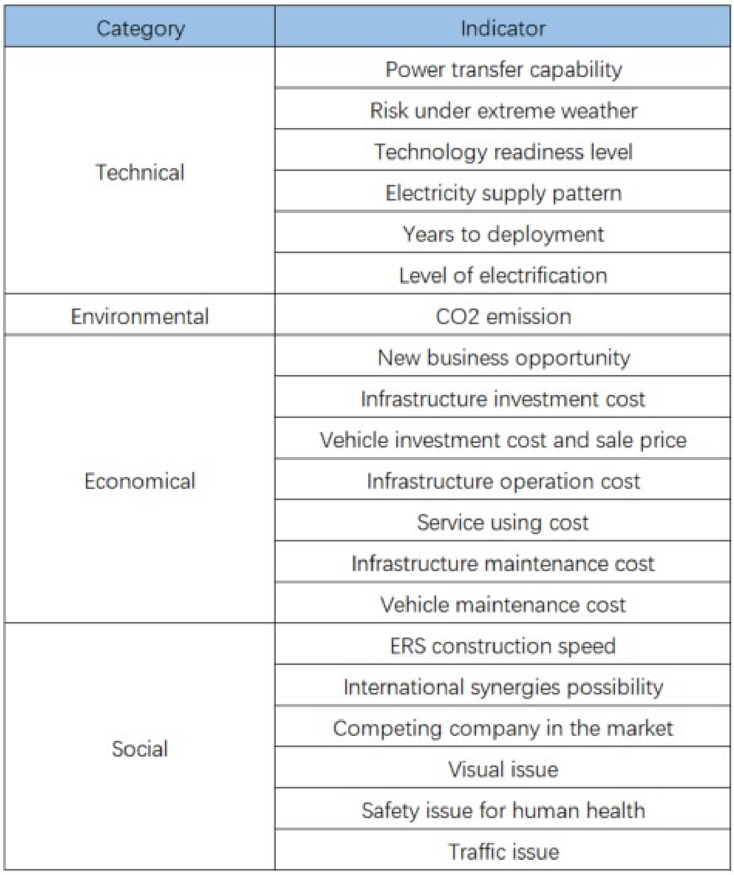
In this chapter, value-based criteria from the results of Chapter 3 will be used as a starting point for selecting relevant measurable indicators from the literature that can describe or evaluate the two different technologies. Indicators are linked to their associated criteria and quantitative or qualitative calculations are developed to assess the performance of each criterion.

Jöhrens et al. (2021)'s research develops a performance indicator framework that can serve as a toolbox for evaluating the feasibility of ERS projects. This indicator framework in four aspects will be used as a foundation in this study and together with a grid of 63 technology assessment indicators developed in France (2021). Other possible indicators mentioned from stakeholder interviews are also included. Note that because this study is the value-based generation of criteria and their evaluation indicators, some indicators need to be deleted first because it is needed to guarantee they are independent of each other in MAMCA. Only criteria and indicators that are independent of each other will be selected for comparison in this study.

The technical indicator includes the characteristics and important parameters of the technology itself, as well as technology-related issues that may arise during the implementation of the ERS project. The economic aspect focuses on the specific costs associated with vehicles and infrastructure for the quantitative analysis of economic feasibility, as well as the possible economic impacts of the ERS project. The environmental aspect focuses on CO_2 emission. The main goal of the implementation of the ERS is to reduce GHG emissions and at the same time decrease the dependence on batteries. The social aspect is mainly for the qualitative analysis, covering what kind of impact it might have on each citizen and the impact service users would have on the technology.

A total of 20 indicators are generated based on the value-based criteria and a complete framework of indicators used in this study is shown in Figure 4.1. Note that two technologies may perform differently on the same criteria due to different stakeholder positions. Therefore, in the subsequent process of calculating, the stakeholder groups associated with it are first identified, and then the calculation method and selected parameters are clarified from the perspective of these stakeholders.

The relationships between indicators and each stakeholder group are shown below. On the left are the value-based criteria for each stakeholder group, which derive from the results of the



Category	Indicator
Technical	Power transfer capability
	Risk under extreme weather
	Technology readiness level
	Electricity supply pattern
	Years to deployment
	Level of electrification
Environmental	CO2 emission
Economical	New business opportunity
	Infrastructure investment cost
	Vehicle investment cost and sale price
	Infrastructure operation cost
	Service using cost
	Infrastructure maintenance cost
	Vehicle maintenance cost
Social	ERS construction speed
	International synergies possibility
	Competing company in the market
	Visual issue
	Safety issue for human health
	Traffic issue

Figure 4.1: Summary of indicators

interviews. On the right side are measurable indicators that are used to assess the performance of the ERS technologies.

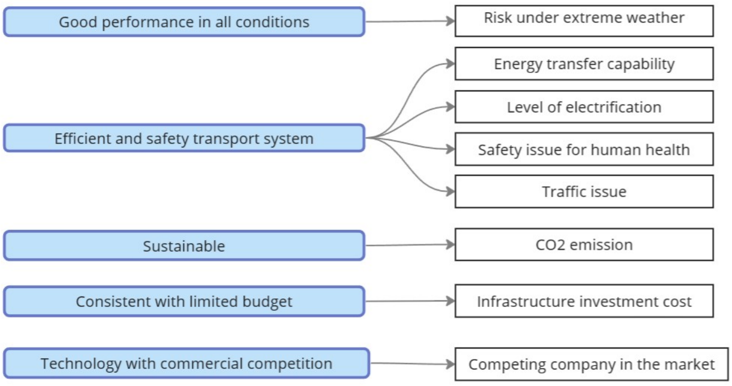


Figure 4.2: Criteria and indicators for infrastructure provider

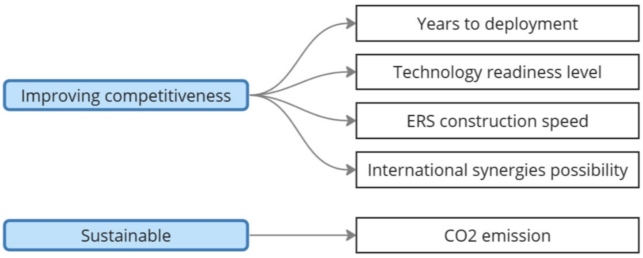


Figure 4.3: Criteria and indicators for technology provider

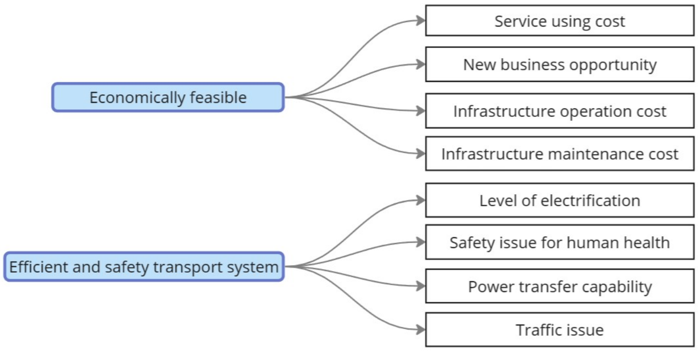


Figure 4.4: Criteria and indicators for ERS operator

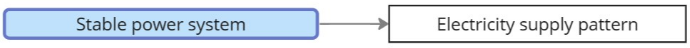


Figure 4.5: Criteria and indicators for energy provider

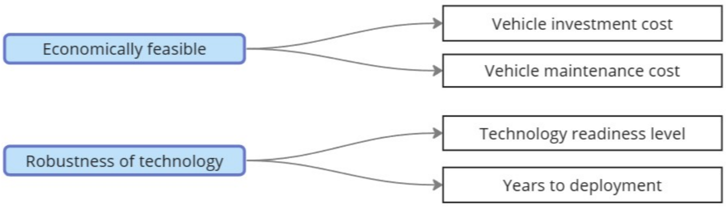


Figure 4.6: Criteria and indicators for vehicle manufacturer

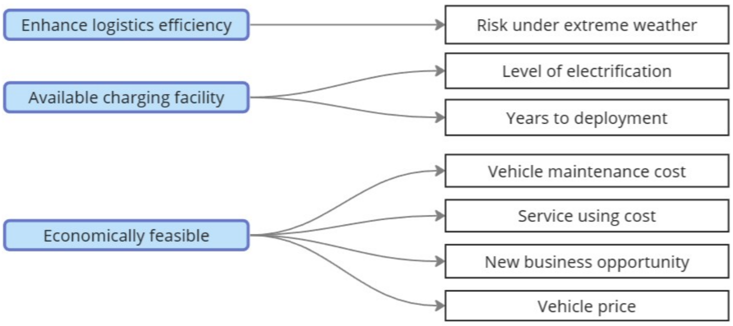


Figure 4.7: Criteria and indicators for service user

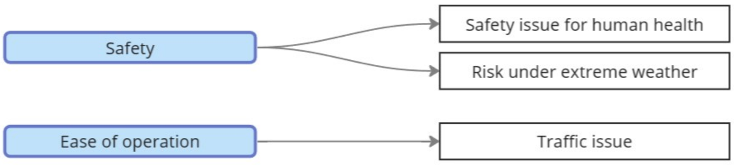


Figure 4.8: Criteria and indicators for driver

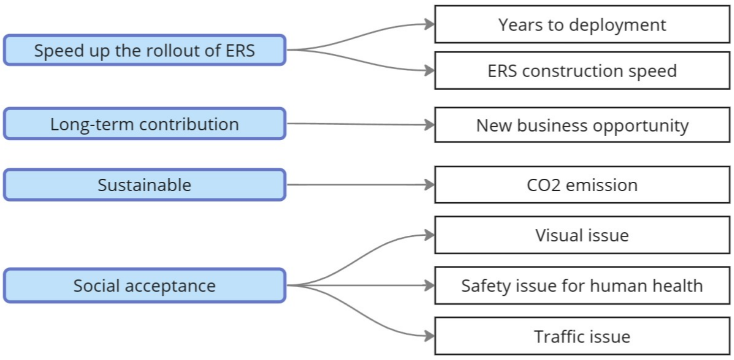


Figure 4.9: Criteria and indicators for regulation authority

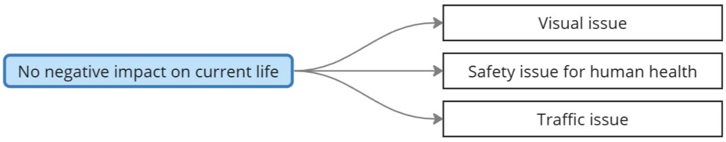


Figure 4.10: Criteria and indicators for citizen

5

Evaluation

For quantitative criteria, such as costs and emissions, this chapter will develop quantitative real data on the two technologies to compare their results. For qualitative criteria, evaluation methods and rules will be described. All calculations in this chapter are based on the pilot projects which belong to the dissemination phase and ERS technology has not been developed to a mature stage.

5.1. Assumption

As ERS technology development is in a rapidly evolving phase and it is difficult to predict changes over the next few years, the time context for calculating the criteria is the present year with 250 working days assumed. The location context is the corridor from the port of Rotterdam to Antwerp with a road length of 128 km. Some of the basic assumptions are described in this section, and other assumptions that are specific to a single criterion only are described in the calculations.

As the Netherlands is interested in implementing ERS on freight corridors and considering cooperation with road networks in neighbouring countries, the location of this study focuses on the main road corridors for HGV between metropolitan centres, ports and inland metropolises. In this case, a route between the ports of Rotterdam and Antwerp is chosen to implement the research and to discover the possible impacts of implementing the ERS. This is because this corridor connects the two major ports and is a very important and in-demand freight connection. As shown in Figure 5.1, this route includes the A29 and A4 in the Netherlands and the A12 in Belgium with a total length of around 128 km. The data on traffic patterns in 2022 is shown in Figure 5.2.

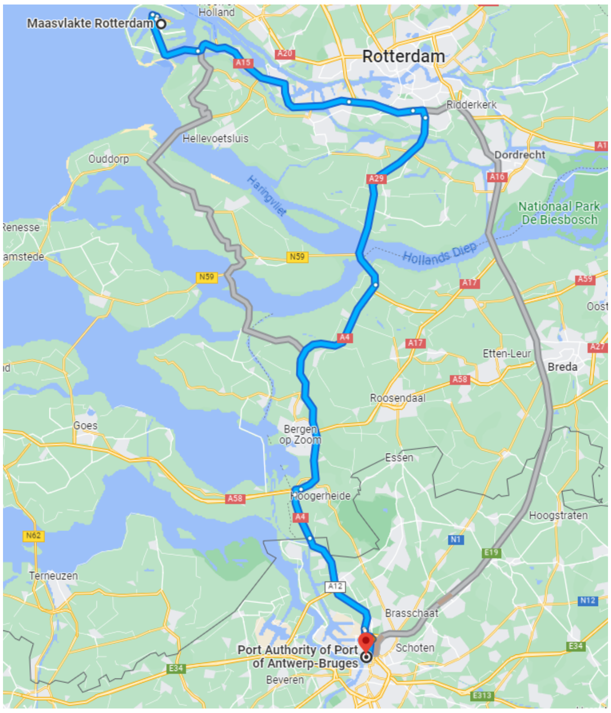
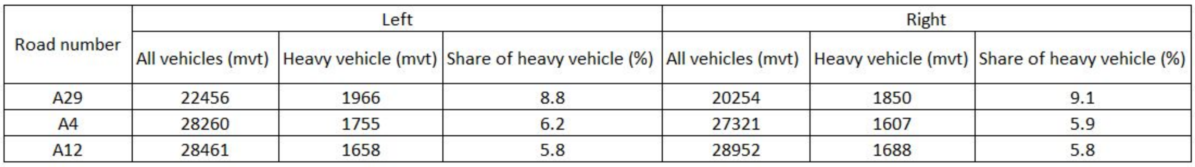


Figure 5.1: The corridor from the port of Rotterdam to Antwerp (Google Map)



Road number	Left			Right		
	All vehicles (mvt)	Heavy vehicle (mvt)	Share of heavy vehicle (%)	All vehicles (mvt)	Heavy vehicle (mvt)	Share of heavy vehicle (%)
A29	22456	1966	8.8	20254	1850	9.1
A4	28260	1755	6.2	27321	1607	5.9
A12	28461	1658	5.8	28952	1688	5.8

Figure 5.2: Intensity of vehicles in working day (Rijkswaterstaat, 2022)

Fleet characteristics

Different vehicles behave differently in terms of operational energy consumption and vehicle-related costs. The vehicle types considered in this study are based on eHGV with an electric motor of 350 kW, a battery of 100 kWh, and EURO VI emission standards with a cruising speed while driving.

Assume no modal shifts are made between road to rail or inland shipping in this case study. The daily number of HGVs is the average of roads A29, A4 and A12 for both directions. Based on the data in Figure 5.2 from INWEVA, the amount of HGV in a working day in 2022 is 3508 units in the corridor using the equation below. Assume the amount will remain constant between the different ERS technologies.

$$Q_{HGV} = \frac{Q_{R,A29} + Q_{R,A4} + Q_{R,A12} + Q_{L,A29} + Q_{L,A4} + Q_{L,A12}}{3} \tag{5.1}$$

Where Q is the daily traffic flow on a work day, the first bit of the subscript represents the direction and the second bit represents the road number, e.g. $Q_{R,A29}$ represents the number of HGVs per day in the right-hand direction on the A29 road.

In order to achieve the environmental goal, the share of eHGV needs to be at least 3% of the total fleet size (IEA, 2021). Therefore, the HGV that has the potential to support the ERS project in this case is assumed 105 units per day.

Travel distance

According to the data from the Port of Rotterdam, 40% of the journeys that leave the port by truck remain in the Rotterdam region, half are destined for the Dutch market and 10% cross the border (of Rotterdam, 2023). For the different driving characteristics above, make the assumptions in Table 5.1 for the distance of driving.

Table 5.1: Distance assumed driven on the corridor Rotterdam - Antwerp

	Region	Dutch or foreign country
Share of the fleet [%]	40	60
Distance assumed [km]	1/2L	L

Therefore, it can be assumed that the total distance driven by an ERS vehicle in a working day is 12083 km according to the formula below.

$$D = \frac{1}{2}L * f_{region} * Q_{eHGV} + L * f_{foreign} * Q_{eHGV} \tag{5.2}$$

Where L is the length of the road from the Port of Rotterdam to Antwerp, which is equal to 128 kilometres, and f is the proportion of the fleet that stays in the Rotterdam area or crosses the border.

Energy transfer efficiency

The energy transfer efficiency of the technology in this study specifically refers to the process of energy power from the substation through the ERS infrastructure to the vehicle, as there are differences in the performance of the two different technologies at this stage in the overall process.

According to Bateman et al. (2018) and France (2021), the current energy transfer efficiency for the two technologies are shown below. Normally the overhead conductive ERS can maintain at a level higher than 90% when taking into account 300kW of energy. When considering the provision of up to 500 kW of energy, this number will fluctuate considerably.

The in-road inductive systems are less efficient, mainly due to air gaps (Bateman et al., 2018). It can almost achieve 90% transfer efficiency when the air gap is between 85 to 100 mm when delivering 200 kW of power (Zhao et al., 2018). Normally, according to the latest report from the technology provider, their experiment shows that the energy transfer efficiency can maintain a level higher than 80% regardless of vehicle speed as shown in Figure 5.3.

$$e = \begin{cases} 80 - 97\% & \text{if } overhead\ conductive \\ 81 - 85\% & \text{if } in - road\ inductive \end{cases} \tag{5.3}$$

Therefore, in this research, the energy transfer efficiency assumes an average of 90% for the overhead conductive system and 83% for the in-road inductive system in the following calcu-

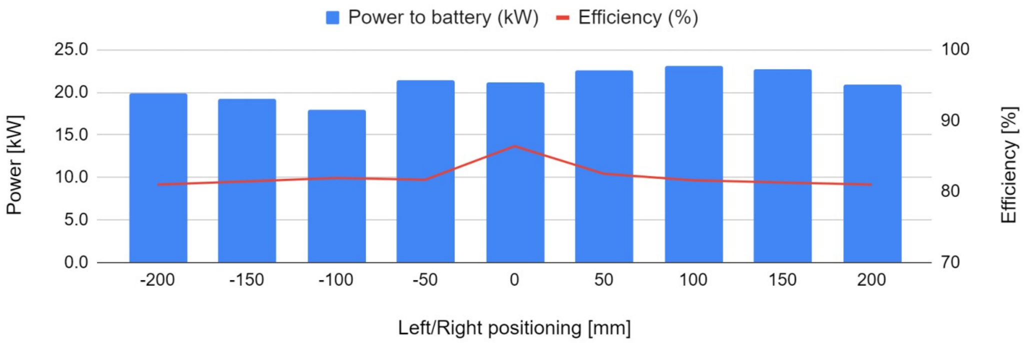


Figure 5.3: Energy transfer efficiency (experiment result from Electreon)

lation.

Energy consumption

The TTW energy consumption of long-haul articulated trucks in the Netherlands is about 4 MJ/km (TNO, 2023), which corresponds to 1 kWh/km. This means the supporting infrastructure for the two technologies needs to provide the required energy for the vehicle tank with their different energy transfer efficiency. Based on the equation below, the total energy consumption on a workday can be calculated as 11.1 - 13.4 MWh (average 12 MWh) for the overhead conduction system and 12.6 - 13.3 MWh (average 13 MWh) for the in-road induction system.

$$E_{ERS} = \frac{E_{veh} * D}{e} \tag{5.4}$$

Where E is the TTW energy consumption of the ERS system or an HGV in a workday, D is the total distance travelled by ERS-HGV in a workday, and e is the energy transfer efficiency.

Above is a detailed description of important assumptions. Figure 5.4 shows all the underlying assumptions involved in calculating indicators, including technical and case study aspects. Among these, energy transfer efficiency is the most critical assumption, which will greatly influence the results of calculations in terms of infrastructure operating costs and emissions.

5.2. Technical indicators calculation

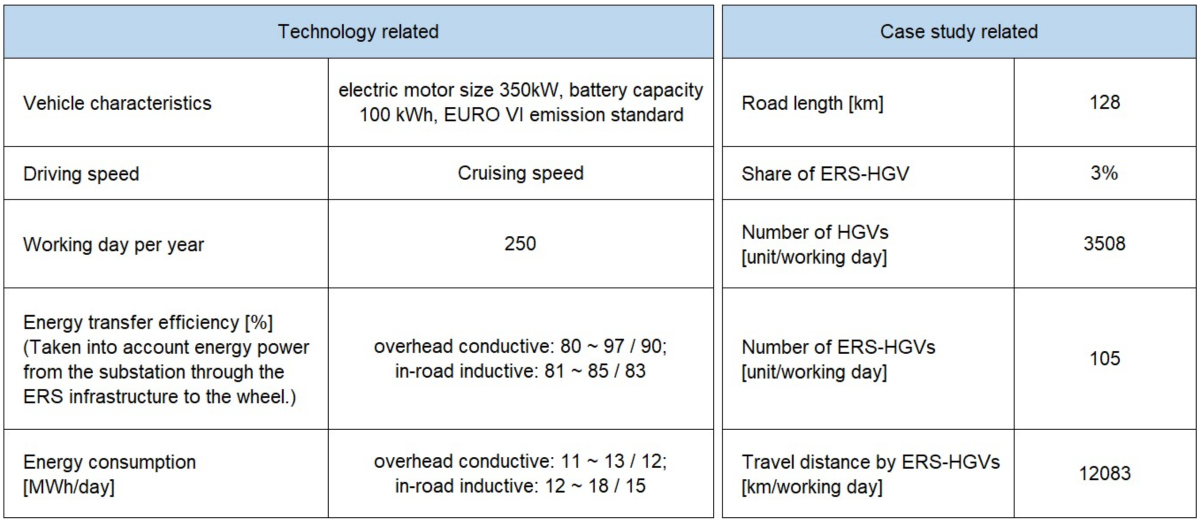
5.2.1. Level of electrification

Electrification of roads and vehicles has enabled electric vehicles to achieve unlimited range and longer run times using smaller batteries. The current electrification level of the two technologies for road and vehicle are summarized in Table 5.2.

- road electrification

Due to the nature of the technology, an overhead conductive system cannot cover the entire road, as the roadside infrastructure is affected by factors such as bridges and caves. Some road sections need to be powered by the vehicle's own battery. Catenaries are likely to be placed in limited locations which leads to partial electrification. Based on the interview with Siemens, electrification of 50% to 70% of the road is usually possible.

For an in-road inductive system, the electrified coverage of the road is theoretically independent of external conditions and can be laid on roads on a large scale with low charging power



Technology related	
Vehicle characteristics	electric motor size 350kW, battery capacity 100 kWh, EURO VI emission standard
Driving speed	Cruising speed
Working day per year	250
Energy transfer efficiency [%] (Taken into account energy power from the substation through the ERS infrastructure to the wheel.)	overhead conductive: 80 ~ 97 / 90; in-road inductive: 81 ~ 85 / 83
Energy consumption [MWh/day]	overhead conductive: 11 ~ 13 / 12; in-road inductive: 12 ~ 18 / 15

Case study related	
Road length [km]	128
Share of ERS-HGV	3%
Number of HGVs [unit/working day]	3508
Number of ERS-HGVs [unit/working day]	105
Travel distance by ERS-HGVs [km/working day]	12083

Figure 5.4: Overview of calculation assumption

Table 5.2: Level of electrification

		Overhead-conductive	In-road inductive	Source
Road electrification		50% - 70%	>70%	Interview
Vehicle electrification	Truck	100%	100%	Ajanovic and Haas, 2019
	Bus/Van/Car	-	100%	

requirements to achieve a higher level of road electrification. However, it should be noted that higher road coverage on the other hand may bring increasing infrastructure costs. So it is not always true that the advantage of a higher level of road electrification is more advantageous from a whole system perspective. There is a trade-off between the charging power system, the battery capacity and the level of road electrification.

- vehicle electrification

Both technologies can support the realization of zero-emission battery-powered electric vehicles, defined as 100% electrification (Ajanovic and Haas, 2019). However, due to the limited use of overhead conductive systems (the height of cables is around 5.15 meters), it can only provide a high level of electrification to trucks and has electrification limitations in other vehicle types. The in-road inductive technology already has a demonstration project for both trucks and buses. However, based on the current state of the art, vans and cars have not been tested in practice, partly because the commercial operating models are not yet well developed and the power capacity is also not able to support this more volatile mode of energy use.

5.2.2. Technology readiness level (TRL)

TRL is a method of estimating technology maturity at the start of a project based on Table 5.3. The TRL allows for a consistent and uniform discussion of the maturity of different ERS technologies.

Within CollERS2, a platform for the exchange of knowledge in the field of ERS, the TRL

Table 5.3: Technology Readiness Levels Summary (Mankins et al., 1995)

TRL	Definition
1	Basic principles observed and reported.
2	Technology concept and/or application formulated.
3	Analytical and experimental critical function and/or characteristic proof-of-concept.
4	Component and/or breadboard validation in laboratory environment.
5	Component and/or breadboard validation in relevant environment.
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space).
7	System prototype demonstration in a space environment.
8	Actual system completed and “flight qualified” through test and demonstration (ground or space).
9	Actual system “flight proven” through successful mission operations.

assessment for each technology has been discussed. Widegren et al. (2022) concluded the TRL assessment of the technology development of Siemens eHighway and Electreon projects according to the knowledge and experience of experts from Germany and Sweden. Information from interviews with ERS technology providers and vehicle manufacturers are also combined. Table 5.4 summarises the different TRLs for different ERS technologies taking into account different subsystems.

Table 5.4: TRL assessment

Technology Subsystem		Overhead conductive	In-road inductive	Source
Energy supply		TRL 8	TRL 7	Widegren et al., 2022 Mankins et al., 1995
Road infrastructure		TRL 7	TRL 6	
Power transfer		TRL 8	TRL 6	
Operation	Energy measurement	TRL 7	TRL 6	
	Vehicle identification	TRL 6	TRL 7	
	Billing & payment solution	TRL 6	TRL 4	
Vehicle	Truck	TRL 8	TRL 6	
	Bus	Not tested	TRL 7	
	Van/Car	N/A	TRL 6	

The TRL for overhead conductive systems ranges from 6 to 8, which is not surprising since the railway system is already well-established with this technology. It has a high TRL in all the subsystems except for vehicle recognition. The system may have problems identifying specific vehicles and rejecting vehicles that do not belong to its system.

The TRL for in-road inductive ERS is lower, ranging from 4 to 7. The subsystems associated with the mechanical engineering component of the demonstration project are relatively mature.

However, according to the interview with the vehicle manufacturer, the technology still does not provide a solution that can effectively support billing and payment in actual operation. It is worth noting, however, that the in-road inductive ESR has high TRL for different types of vehicles, so it could theoretically support all types of vehicles.

The latest information from the in-road inductive technology provider suggests that an overall TRL of 8 is now achievable and that the operational model in real scenarios no longer has any technical problems. However, due to the lack of supporting material, this TRL level has been undertaken.

5.2.3. Years to deployment (YTD)

Stakeholder estimates of the time (in years) for the future development of each technology to the point where it can be built at large-scale maturity are collected from the interview, and definitions of TRL in Table 5.3 are used as a consistent reference to guide stakeholder responses. Based on interviews and research from Bateman et al. (2018), the average YTD for overhead conductive ERS is 4 years and for in-road induction is 6 years. Researchers and regulators are generally optimistic about the YTD estimate for overhead conductive technology, which is 3.3 - 4.2 years, whereas technology providers and researchers are relatively optimistic about the YTD estimate for in-road induction, which is 6.4 - 6.5 years.

Overall, there is a general consensus among all stakeholders that mature deployment of in-road inductive ERS will take longer. Currently, the bottlenecks in in-road induction technology are the improvement of power transfer efficiency and compatibility with truck operating systems.

5.2.4. Risk under extreme weather

Strong winds and heavy rainfall

For the overhead conductive technology, accident hazards arise when ERS infrastructure is subjected to unstable wind loads and long-duration wind gusts. Research in Norway has shown that turbulence intensities of 20% and unsteady winds lasting more than 10 minutes can lead to a risk of catenary wire and pantograph deflection (Song et al., 2022). In the Netherlands catenary rail system, wind gusts greater than 19 m/s (about 15% of all days in the Netherlands) have a significant effect on the number of railway disruptions (Xia et al., 2013). Considering the windy weather conditions in the Netherlands, the wind resistance to which the overhead catenary and the pantograph over the truck will actually be subjected is a potential risk to the road system.

Considering the high winds in the Rotterdam port area and the harbour location, there is also a high risk of chloride-induced corrosion of the support infrastructure due to the sea winds.

For the in-road inductive system, the standing water caused by heavy rain hardly has a negative impact. This system is based on the principle of magnetic field WPT (Ampere’s law and Faraday’s law), and the characteristics such as efficiency of the transmission, and accuracy of the induction are theoretically unaffected by other common non-metallic materials such as air, water, etc., and can pass through these objects without interaction.

Another risk is the strong wind can also exert the vertical movements of trucks. In-road inductive solution provided by Electreon can support fluctuations of the lateral position of 30 cm to each side currently (France, 2021), therefore it is not stringent for drivers and can be accepted.

Lightning and thunderstorms

During 2022, Dutch railways reported 21 failures due to damage to overhead power lines (de Treinen, 2023a), mainly due to extreme weather such as lightning or storms. For the road system, the same overhead conductive technology may also pose the same problems.

Snow and ice

Snow or ice build-up on the conductors may affect the contact between the pantograph and the conductors, thus reducing efficiency. Similarly, in-road induction systems can also suffer from ice build-up leading to a larger air gap between the vehicle and the coil, thus reducing the efficiency of energy transfer. However, since this study focuses on the Rotterdam-Antwerp road, where snow and ice are rare, this factor is not a critical one.

In conclusion, the overhead conductive system is more likely to be affected by external geographical and meteorological factors.

5.2.5. Electricity supply pattern

For both technologies, the eHGV charging process in the study area is regular and predictable, as the fleet operation in this transport corridor is relatively stable. According to the interview with DHL, their fleets run between the ports of Rotterdam and Antwerp and are logistically planned, basically with fixed vehicles at fixed times of the day. This also means that for the electricity supply system, the unpredictability is much lower and the power characteristics can be predicted in advance based on the logistic planning of the logistics company.

However, the charging process for in-road induction systems is currently discontinuous. The charging process only occurs when the receiver passes through the induction coil. As shown in Figure 5.5, the induction coils are mounted on the road in a modular fashion, so the charging process to the battery varies in pulses. This will increase fluctuations in the power supply and also harm the battery.

In the future, when considering a wider range of vehicles, which in-road inductive systems can support, there is a problem. The greater volatility and more random behaviour of car drivers mean that it is difficult to accurately predict power demand in advance. When a large number of private cars at a certain point in time, such as on holidays, also use the ERS system for charging, this is a big challenge for the electricity supply system.

Therefore, the in-road inductive technology will bring a more fluctuating electricity consumption pattern in this criterion. The advantage of supporting multiple vehicle types is cut down by their attendant instability and unpredictable electricity usage patterns. The use of clustering patterns is very important to prevent stochastic.

5.2.6. Power transfer capability

The vehicles are assumed to be travelling at the maximum legal speed in Germany or Sweden on a road. The power transfer from the catenary line to the pantograph of the vehicle is theoretically possible up to a maximum of about 500 kW claimed by Siemens, with 300 kW already recorded in the current test project. In the test project for Electreon in-road inductive solution, it has been demonstrated that it is possible to transmit more than 150 kW of power,

Figure 5.5: Inductive coil of in-road inductive technology (photo from Electreon)

which is far less than that of another technology.

5.2.7. Technical indicators calculation result

In Figure 5.6, the results of all the indicators in the technical aspect have been summarized.

5.3. Environmental indicators calculation

5.3.1. CO_2 emission

Both technologies are in line with the decarbonization target and can achieve zero CO_2 emissions during vehicle operation. However, there are differences in the emissions performance of the two technologies on a system-wide basis, especially considering the full life cycle of the electricity and infrastructure. The calculation model and the data for the evaluation of CO_2 emission are shown below.

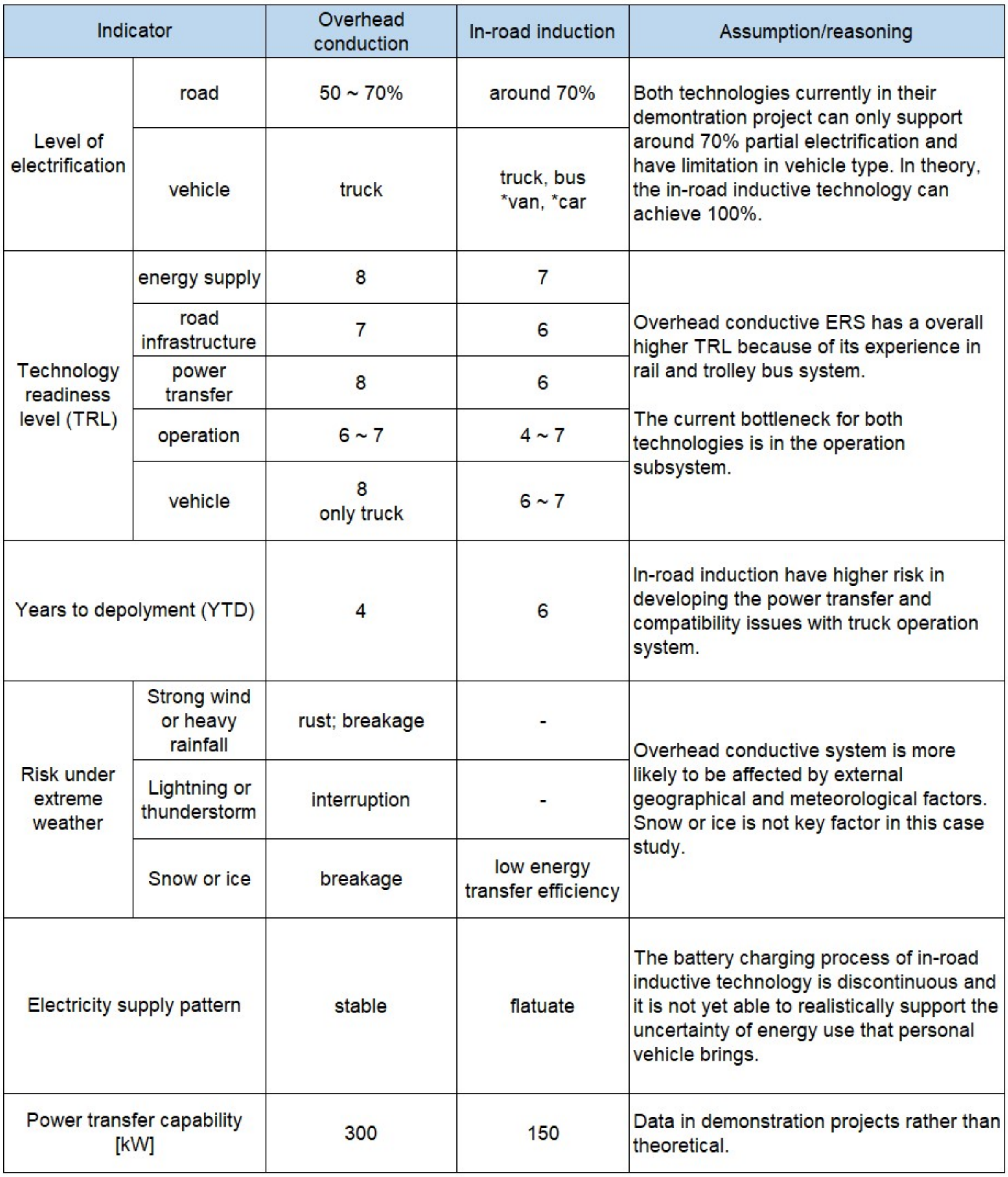
$$CO_{2ERS} = CO_{2construction} + CO_{2operation} + CO_{2maintenance} \tag{5.5}$$

It is assumed that the lifetime of the ERS road is 20 years and the functional unit (FU) of the road is 1km * 3.5m with 3 layers. Calculations are based on a full year. All the generic unit emission parameters are summarized in Figure A.1

- construction

In the construction phase, the emissions mainly include road adaption, infrastructure construction, raw material transportation and pavement.

The road adaption for in-road inductive ERS is the pre-cast concrete blocks containing the coils with dimensions of 0.67 × 0.07 m embedded in the road. 500 coils are needed in one kilometre (Balieu et al., 2019). Only the surface and the binder layer need to be reconstructed, which represents half of the road thickness. Figure 5.5 shows the construction work on the road surface. Therefore, the emissions data used in this study are half of the emissions from



Indicator		Overhead conduction	In-road induction	Assumption/reasoning
Level of electrification	road	50 ~ 70%	around 70%	Both technologies currently in their demontration project can only support around 70% partial electrification and have limitation in vehicle type. In theory, the in-road inductive technology can achieve 100%.
	vehicle	truck	truck, bus *van, *car	
Technology readiness level (TRL)	energy supply	8	7	Overhead conductive ERS has a overall higher TRL because of its experience in rail and trolley bus system. The current bottleneck for both technologies is in the operation subsystem.
	road infrastructure	7	6	
	power transfer	8	6	
	operation	6 ~ 7	4 ~ 7	
	vehicle	8 only truck	6 ~ 7	
Years to depolyment (YTD)		4	6	In-road induction have higher risk in developing the power transfer and compatibility issues with truck operation system.
Risk under extreme weather	Strong wind or heavy rainfall	rust; breakage	-	Overhead conductive system is more likely to be affected by external geographical and meteorological factors. Snow or ice is not key factor in this case study.
	Lightning or thunderstorm	interruption	-	
	Snow or ice	breakage	low energy transfer efficiency	
Electricity supply pattern		stable	flatuate	The battery charging process of in-road inductive technology is discontinuous and it is not yet able to realistically support the uncertainty of energy use that personal vehicle brings.
Power transfer capability [kW]		300	150	Data in demonstration projects rather than theoretical.

Figure 5.6: Evaluation result of technical indicators

conventional road construction (62.26 tons/km), and 31 tons/km.

The construction of ERS infrastructure of overhead conductive mainly includes the usage of pillars in steel spaced 50 m and copper cables. For the in-road inductive ERS, 500 coils in one FU is needed (Balieu et al., 2019) and a certain amount of concrete is needed to fill the road.

The transport and paving including the transport of the manufactured asphalt mixture from the plant to the construction site at temperatures between 110 and 120 degrees Celsius and the pavement construction process.

$$CO_{2construction} = L * [Ef_{road} + \sum_{m \in M} (Ef_{infra_m}) + Ef_{tran}] \tag{5.6}$$

Where Ef is the emission parameter.
According to the formula, the calculated CO_2 emission in this phase is 10112 tons for overhead conductive ERS and 11264 tons for in-road inductive ERS.

Figure 5.7: Infrastructure preview of overhead conductive technology (photo from Siemens)

- operation

The operational phase consists mainly of emissions from production processes used to generate electricity for vehicle operation.
Based on the generation capacity projected for the Netherlands in 2015, electricity for EV charging would largely be generated using natural gas. The CO2 emission estimates for electricity generation from natural gas is around 486 g/kWh (de Treinen, 2023b).

$$CO_{2operation} = Ef_{elec} * E_{ERS} * T_{workday} \tag{5.7}$$

where Ef_{elec} is the emission factor during electricity generation, E_{ERS} is the energy consumption of an ERS-HGV in a work day, $T_{workday}$ is the number of working days in a year, which is equal to 250 days in this study.

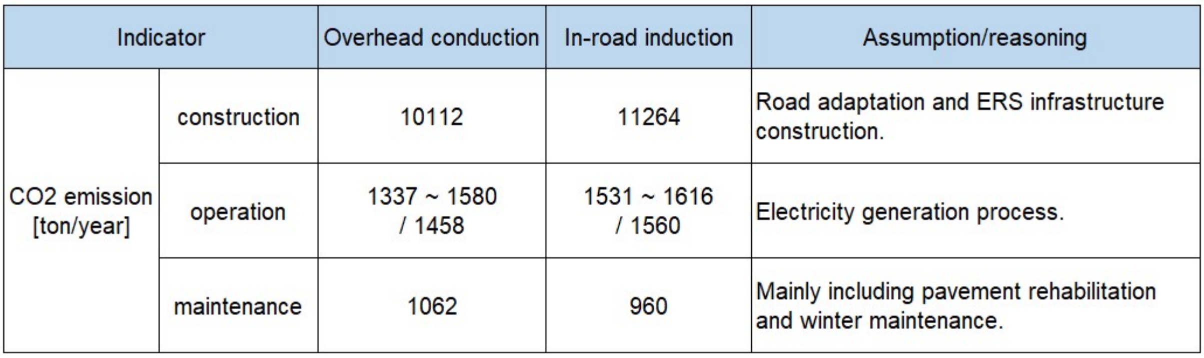
Based on the formula above, the related emission in the operation phase is from 1336.5 to 1579.5 tons for overhead conductive ERS and from 1458 to 2187 tons for in-road inductive ERS.

- maintenance

$$CO_{2maintenance} = L * Ef_{mnt} \tag{5.8}$$

The maintenance phase in this study considers pavement rehabilitation as well as maintenance to prevent premature pavement damage. It is difficult to accurately predict the rehabilitation needs for a specific type of road as the long-term behaviour of the pavement depends on many factors such as loading, temperature, humidity, etc. It is assumed that the top layer of the road will require the replacement of the surface 3 times and the replacement of the entire pavement 1 time during its lifetime of 20 years. And winter maintenance is assumed to be 10 times per year.
The emissions from these two technologies for this period are 1062.4 tons and 960 tons, respectively. In-road inductive ERS have less emission because the coils are embedded in the road surface, which reduces the amount of infrastructure maintenance.

Therefore, the total average life cycle CO_2 emission for overhead conductive ERS is 12632.4 tons which is lower than 14046.5 tons from the in-road inductive system. The emissions on each life cycle phase are summarised in Figure 5.8.



Indicator		Overhead conduction	In-road induction	Assumption/reasoning
CO2 emission [ton/year]	construction	10112	11264	Road adaptation and ERS infrastructure construction.
	operation	1337 ~ 1580 / 1458	1531 ~ 1616 / 1560	Electricity generation process.
	maintenance	1062	960	Mainly including pavement rehabilitation and winter maintenance.

Figure 5.8: Evaluation result of environmental indicators

5.4. Economic indicators calculation

Since ERS are a relatively new concept that has not been tested on a large scale over a long period of time, it is difficult to accurately calculate the cost of operating and maintaining such systems. The data used in this study is based on studies of ERS projects in Sweden (where there are test projects for both technologies), the UK and the States, other similar projects such as rail and trolley bus as well as interviews. Actual costs for future development are likely to differ from these early assessments, but the evaluation in this section is reasonable for projects implemented at the current stage.

5.4.1. Infrastructure investment cost

The infrastructure investment cost includes mainly two parts. One is the grid extension. Assuming that the degree of road electrification and the number of substations (one every ten kilometres) are the same for both technologies, then the cost factor for grid extension is the same for both technologies (Andersson et al., 2019).
Another part is the cost of power transmission. The cost of overhead conductive ERS including the contact wire, re-tensioning device, road-side supporting infrastructure (axial or lateral), etc, as shown in Figure 5.9. The power transmission of in-road inductive ERS mainly includes the cost of road adaption, primary coils and ferrite cores embedded in the road. The elements

under the road have a life span of 20 years stated by the interviewee. The main construction work on the energy transmission part of this technology can be seen in Figure 5.10 and the detailed pavement work can be seen in Figure 5.11.

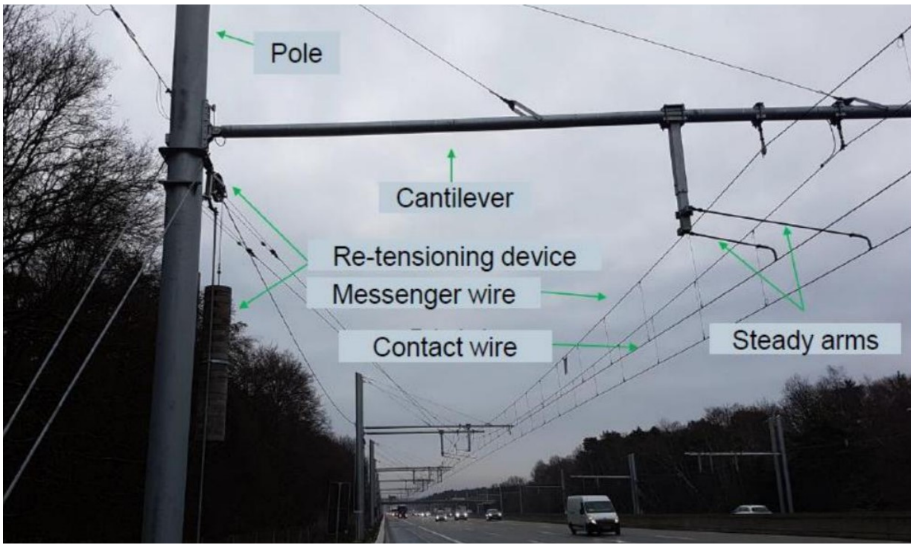


Figure 5.9: Overhead conductive system supporting infrastructure (photo from Siemens)

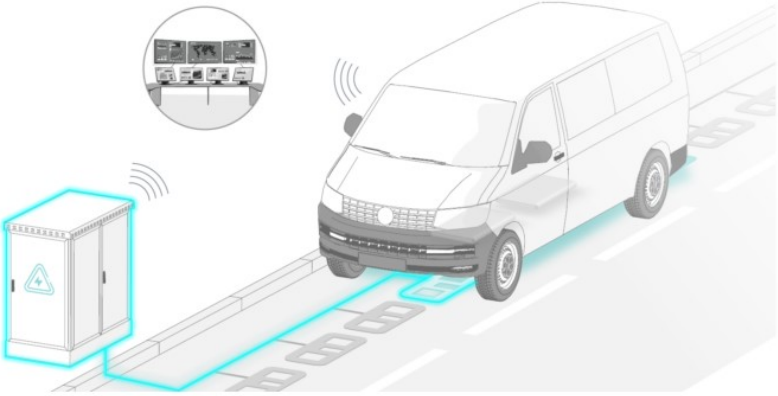


Figure 5.10: Schematic of power transmission structure (photo from Electreon)

The Swedish study (Andersson et al., 2019) presents a range of construction costs including grid extension and power transmission, which will be used as a basic reference for this study. Aronietis and Vanelslander (2023)'s research in Belgium shows that the cost of overhead infrastructure was calculated to be within the range of 1.2 M euro/km when the traffic volume of heavy trucks is 1000-6000 vehicles. And the data from Ainalis et al. (2020) in the UK confirms the reasonableness of the range. Electreon company provided that the construction cost for their technology is 0.6 M euro/km which is a much lower number, consider that this

Figure 5.11: Pavement construction (photo from Electreon)

is proposed by the technology company, the data will not be used in this research. Therefore, the cost parameters used in this research are summarized in Figure A.2

Using the formula below, the construction cost is 102.4 - 153.6 M EUR for the overhead conductive system and 115.2 - 384 M EUR for the in-road inductive system.

$$Investment\ cost_{infra} = (Cf_{power} + Cf_{grid}) * L \tag{5.9}$$

where Cf is the cost parameter, and L is the road length.

5.4.2. Infrastructure operation cost

The operation cost for the infrastructure is the criteria only valued by the ERS operator. From their perspective, the infrastructure operation cost mainly includes the electric power and electricity grid charges to be paid by the ERS operator when managing the electric road. According to Andersson et al. (2019), the cost parameter is the same for both technologies. Using the average energy consumption calculated in Figure 5.4, 180 - 420 k EUR and 195 - 455 k EUR are calculated as the infrastructure operation cost.

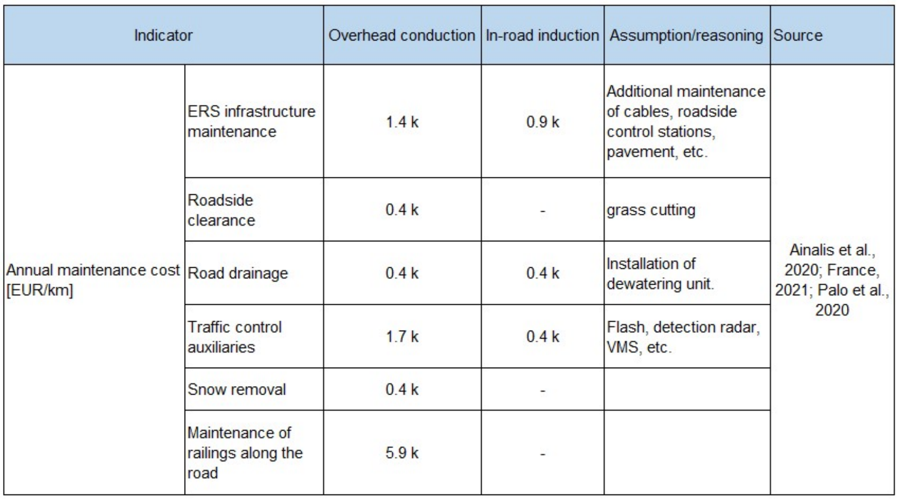
$$Operation\ cost_{infra} = Cf_o * E_{ERS} * T_{workday} \tag{5.10}$$

where E_{ERS} is the energy consumption, E_{ERS} is the energy consumption of an ERS-HGV in a workday, $T_{workday}$ is the number of working days in a year, which is equal to 250 days in this study.

5.4.3. Infrastructure maintenance cost

Most of the existing research uses the 1.5% - 2% of investment cost to calculate the maintenance cost (Ainalis et al., 2020, Andersson et al., 2019) and state there is no big difference between these two technologies. However, during interviews, road authorities felt that most studies underestimated the maintenance costs of overhead conductor systems. Therefore, in this study, more detailed data need to be collected to calculate maintenance costs.
Taking into account the tasks required for ERS roads throughout the year, the related costs are summarized as Figure 5.12. The in-road inductive system almost has no need for extra maintenance. And also has no negative impact on the pavement itself, The interviewee said that

they currently doing an experiment and the result shows even the heaviest trucks travelling on pavements fitted with an in-road inductive system can have a service life of up to 40 years. And there is no impact on the life of the pavement itself.



Indicator		Overhead conduction	In-road induction	Assumption/reasoning	Source
Annual maintenance cost [EUR/km]	ERS infrastructure maintenance	1.4 k	0.9 k	Additional maintenance of cables, roadside control stations, pavement, etc.	Ainalis et al., 2020; France, 2021; Palo et al., 2020
	Roadside clearance	0.4 k	-	grass cutting	
	Road drainage	0.4 k	0.4 k	Installation of dewatering unit.	
	Traffic control auxiliaries	1.7 k	0.4 k	Flash, detection radar, VMS, etc.	
	Snow removal	0.4 k	-		
	Maintenance of railings along the road	5.9 k	-		

Figure 5.12: Infrastructure maintenance cost

5.4.4. Vehicle investment cost and sale price

The vehicle investment cost with conduction and induction system is very close, between 12000-152000 euros, about 10-15 % higher than diesel (Zhao et al., 2018, Qiu et al., 2022, Andersson et al., 2019). An example from Zhao et al. (2018) shows that the vehicle investment cost for the overhead conductive system is around 130k EUR and 131k EUR for the in-road inductive system. The main difference of this result is the wireless charging receiver embedded in the vehicle is more expensive than the active pantograph and converter.

According to Karlström et al. (2019), the retail price equivalent parameter in the EU can be assumed as 1.48, and the purchase price is around 192k euros for overhead conductive and 194k euros for in-road inductive vehicles if there is no subsidy.

5.4.5. Vehicle maintenance cost

Vehicles with in-road inductive systems require less routine inspection of the energy receivers, online monitoring is also feasible. Overhead conductive vehicles would require in-person routine inspections by staff, which would incur a higher cost for vehicle maintenance of 0.05 EUR per km. And the unit maintenance cost for in-road inductive technology is 0.04 EUR.
Based on the formula, the vehicle maintenance costs are 134.4k and 107.5k, respectively.

$$Maintenance\ cost_{veh} = Cf_{veh-m} * D * T_{workday} \tag{5.11}$$

5.4.6. Service using cost

The cost paid by service users for using ERS road may be done in a variety of ways, such as based on electricity consumption, length of use, or a fixed-price subscription. In interviews, service users indicated that they would only consider joining the ERS project if the cost was the same or lower than the current diesel price. Ainalis et al. (2020)'s research has also shown this. Therefore for simplicity, the ERS road using cost is assumed to be equal to the diesel fuel when calculating this criteria. It is a reasonable assumption that the price for using the electric road approaches but not exceed the effective price for an alternative fuel. According to Ainalis et al. (2020), diesel price is at 1.8 EUR/L, and the average fuel economy for HGV is 35.8 L per 100 km, equivalent to 0.6 EUR/km.

$$Annual\ using\ cost = Cf_{using} * D * T_{workday} \tag{5.12}$$

$$Cf_{using} = Cf_{diesel} = 0.6\ EUR/km \tag{5.13}$$

5.4.7. New business opportunity

This criterion is generated from the value held by the technology provider, service user and regulation authority.

- Technology provider

In addition to trucks, in-road induction technology can support other types of vehicles. As shown in the TRL assessment Table 5.4, this technology could theoretically support dynamic charging of buses, vans, and private vehicles very well. This means the potential market size for in-road inductive technology is huge. When the technology matures, it could be a universal solution that will truly reduce the carbon footprint of the transportation sector in a significant way.

- Service user

The service users in this study are mainly logistics companies with fleets in the corridor from the Port of Rotterdam to Antwerp. The Dutch government is willing to subsidise entrepreneurs who purchase electric trucks (van Infrastructuur en Waterstaat, 2022a). This means that service users are unlikely to pay additional higher costs for the use of ERS vehicles and infrastructure compared to the current situation with diesel trucks. Considering that electricity is cheaper than diesel, both technologies offer the future possibility of lower fleet operating costs for service users.

The in-road inductive technology has the extra advantage of supporting other types of logistics vehicles operating on this road, which can help the service user quickly shift to e-mobility.

- Regulation authority

The reality of the ERS project rollout may be that there are fewer users and relatively low electricity demand at the beginning, and as the infrastructure matures, the level of road electrification gradually increases, the number of ERS users increases, and the market share of EVs increases accordingly. The overhead conductive system can better support this pattern. According to the interviews, Siemens's solution can provide lower power (e.g., 0.25-0.5 MW per km per direction) in the initial phase, which can be accommodated by a 5 MW substation every 10 km. On a 10 km stretch, this could supply up to 10 trucks in each direction. At a later stage, when the number of users increases, the power can be increased according to the specific demand, e.g. a 5 MW substation can be built every 2.5 km. This is a cost-effective approach for both low and high demand and is flexible and scalable in construction. The in-road inductive technology is less able to cope with such phased expansion as the power capability is

closely linked to the design of the coils embedded in the road surface (Qiu et al., 2022), which is usually determined at the start of the project, and subsequent adaptation may require more work.
Therefore the overhead conductive technology can bring more flexibility and less complexity in the future development standing on the regulation authority side.

Another opportunity presented by the two technologies is jobs. ERS Operator is now a vacancy and it is not clear which organisation is responsible for it. This could be new job opportunities in the future. Rijksoverheid (2021) shows the electrification of roads will create a workload of 1.7 persons per kilometre, which means that the 128-kilometre project under study could create 218 new job opportunities.

5.4.8. Economic indicators calculation result

In Figure 5.13, the results of all the indicators in the economic aspect have been summarized.

5.5. Social indicators calculation

5.5.1. ERS construction speed

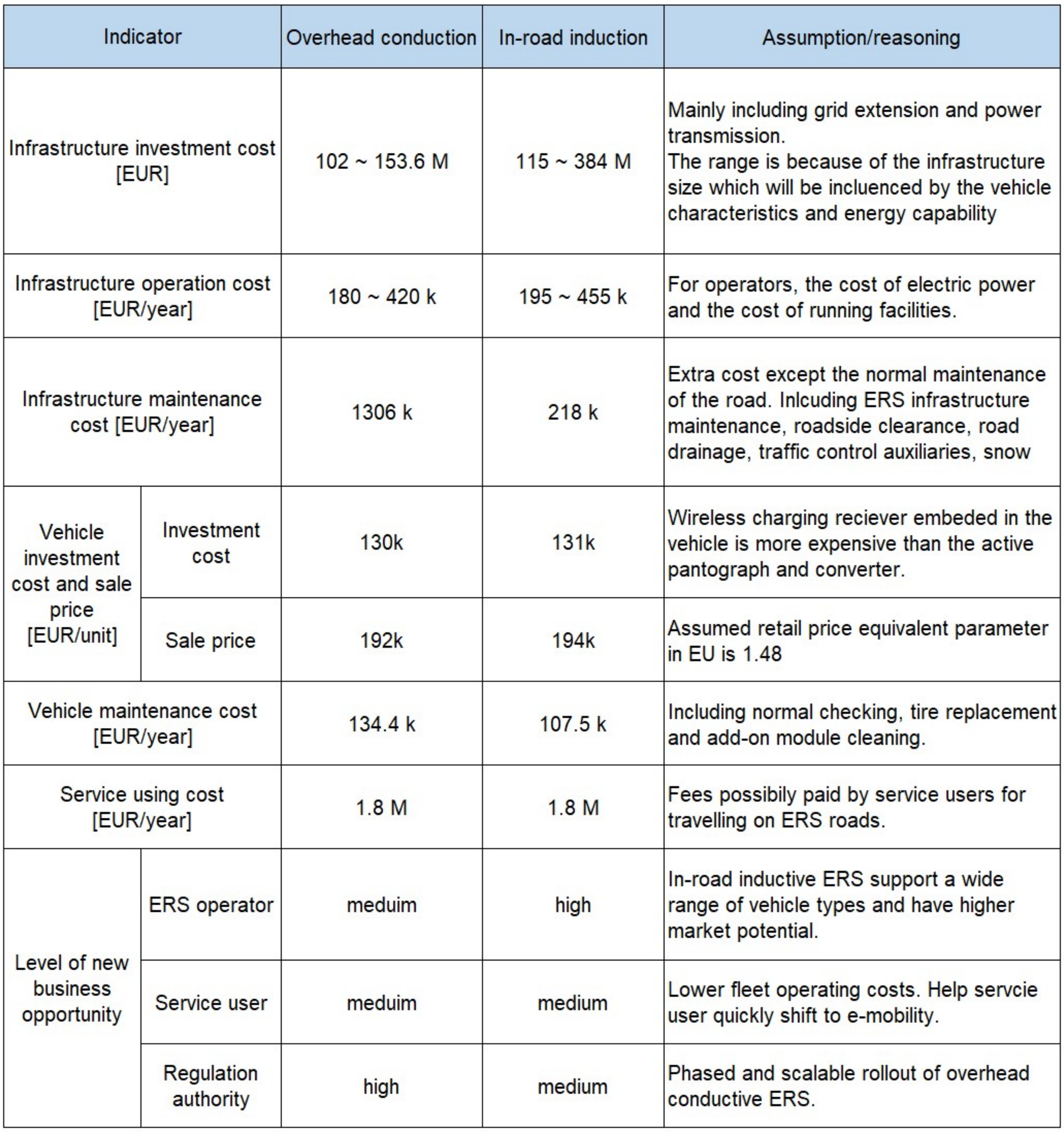
The 2km overhead conductive ERS project on E16 in Sweden took a total of 11 months from the investment decision in June 2015 to the first operational test in May 2016. Germany's conductor programme of three major pilots, including A5, BAB1 and B462, each had a planning phase of roughly one year and construction around 9 months, with electrified sections of between 6 and 10 km (Ainalis et al., 2020). The average rate of overhead conductive ERS construction is approximately 1 month per km.

Using Electreon's three most recent induction projects as a reference, the average construction speed can be estimated. Smartroad Gotland, Sweden 1.65 kilometres, the total time from construction to ready for operation is six months (2019.9 - early 2021). Arena of the Future project, Italy 1.05 kilometres is three months (2021.9 - 2021.12). eCharge BASt, Germany 100 metres is four months (early 2022 - mid 2022). Therefore, for their truck project, the average construction speed is 3 months per km.

However, the speed of road closure construction is a more important indicator, as it will have a significant impact on the transport system. Both technologies require in-road installation, but the exact speed is unknown. A common assumption is that in-road induction systems have more road adaptation work and therefore require more time.

5.5.2. International synergies possibility

The current potential for international synergies between the two technologies is difficult to judge, as the ERS project is in the pilot phase and countries have not decided which technology will be selected in the end. Neighbouring Belgium does not yet have a pilot project and is currently in the research phase. Germany currently has three overhead conductive projects and one inductive pilot project for vans.
Regardless of the technology, a big challenge if international synergy is to be achieved is interoperability, i.e. the ability of different ERS systems to power different types of vehicles. Currently, neither technology is interoperable in terms of efficient power transfer from the grid



Indicator		Overhead conduction	In-road induction	Assumption/reasoning
Infrastructure investment cost [EUR]		102 ~ 153.6 M	115 ~ 384 M	Mainly including grid extension and power transmission. The range is because of the infrastructure size which will be incluenced by the vehicle characteristics and energy capability
Infrastructure operation cost [EUR/year]		180 ~ 420 k	195 ~ 455 k	For operators, the cost of electric power and the cost of running facilities.
Infrastructure maintenance cost [EUR/year]		1306 k	218 k	Extra cost except the normal maintenance of the road. Inlcuding ERS infrastructure maintenance, roadside clearance, road drainage, traffic control auxiliaries, snow
Vehicle investment cost and sale price [EUR/unit]	Investment cost	130k	131k	Wireless charging reciever embeded in the vehicle is more expensive than the active pantograph and converter.
	Sale price	192k	194k	Assumed retail price equivalent parameter in EU is 1.48
Vehicle maintenance cost [EUR/year]		134.4 k	107.5 k	Including normal checking, tire replacement and add-on module cleaning.
Service using cost [EUR/year]		1.8 M	1.8 M	Fees possibily paid by service users for travelling on ERS roads.
Level of new business opportunity	ERS operator	meduim	high	In-road inductive ERS support a wide range of vehicle types and have higher market potential.
	Service user	meduim	medium	Lower fleet operating costs. Help servcie user quickly shift to e-mobility.
	Regulation authority	high	medium	Phased and scalable rollout of overhead conductive ERS.

Figure 5.13: Evaluation result of economic indicators

to the ERS infrastructure to the vehicle, and there are currently no standards or regulations that provide clear guidance for achieving interoperability.

5.5.3. Visual issue

The exposed infrastructure of overhead conductive ERS will have a visual impact on all the road users and affect the aesthetics of the road. Figure 5.14 is an example picture taken by a road user in 2020 when travelling on a eHighway project in Germany. For in-road inductive technology, all transmitters are embedded in the road. This does not have any visual impact. However, this is not a serious problem, and according to a survey by the Dutch ministry, most road users find the visual impact of catenary wires above the road acceptable if these can provide more convenience for their travelling.

Figure 5.14: Visual impact (photo provided by road user)

5.5.4. Safety issue for human health

Both technologies will present an additional risk of electrocution. In addition, there are safety risks associated with exposed wires of the conductive system, such as being caught accidentally, falling due to mechanical failure or bad weather, the intervention of the rescue helicopter on the motorway, etc. Although this is not currently happening in real life, the possibility of such hazards cannot be ruled out.

In addition to this, in-road inductive ERS may pose an additional electromagnetic risk to service users in the future. Research shows that the electromagnetism generated by the system in the current pilot project is compliant and does not pose a risk to personal health (ICT, 2013). However, the electromagnetic data is currently undocumented and has yet to be quantified. And when transmission power becomes higher in the future, the corresponding electromagnetic fields may become a risk to the service user's safety.

5.5.5. Traffic issue

- driver

Both technologies support connecting and disconnecting automatically with the system but have requirements for driving speed.

The overhead conductive system maintains sufficient power at speeds of up to 90-100 km/h and at a maximum gradient of 4.5% for reliable performance (France, 2021).

The in-road inductive system has higher requirements on driving speeds, as exemplified by the inductive charging-enabled trucks produced by GINAF, which tend to overload the system's operation when speeds are too high, thus creating a safety risk. Interviews revealed that the main reason for this is the low compatibility between the infrastructure software system and the vehicle software system, which is still undergoing further testing and development. In addition, this technology is less tolerant of lateral deflections and therefore requires a higher degree of driving smoothness. A noteworthy risk is the likelihood of increased road damage if heavy goods vehicles travel more or less exactly on a given track.

- citizen

Overhead conductive systems with exposed infrastructure are more sensitive to weather and surrounding conditions and therefore require more frequent maintenance work. For example, in 2019, the ERS lane of the A5 motorway in Germany was closed for over an hour due to an object being caught in an overhead line. During this time, the power supply to the motorway overhead line needed to be cut off and wait for the fire brigade to arrive to remove the object. This led to a traffic congestion of up to 10 kilometres.

Figure 5.15: Traffic problem brought by the overhead line

In-road inductive systems may require less frequent maintenance, but when problems do occur, maintenance can take longer because much of the infrastructure is under the roadway. The construction will require temporary road closures during the installation of in-road equipment, which will have an impact on local traffic. The current speed of installation of in-road equipment is approximately 1-2 km per 2 days (Bateman et al., 2018).

In addition, both technologies have requirements for lateral vehicle deflection to maintain efficient energy transfer. However, when most of the vehicles are travelling along the same trajectory in the lanes, it will increase the risk of additional damage to the road surface and reduce the life of the road.

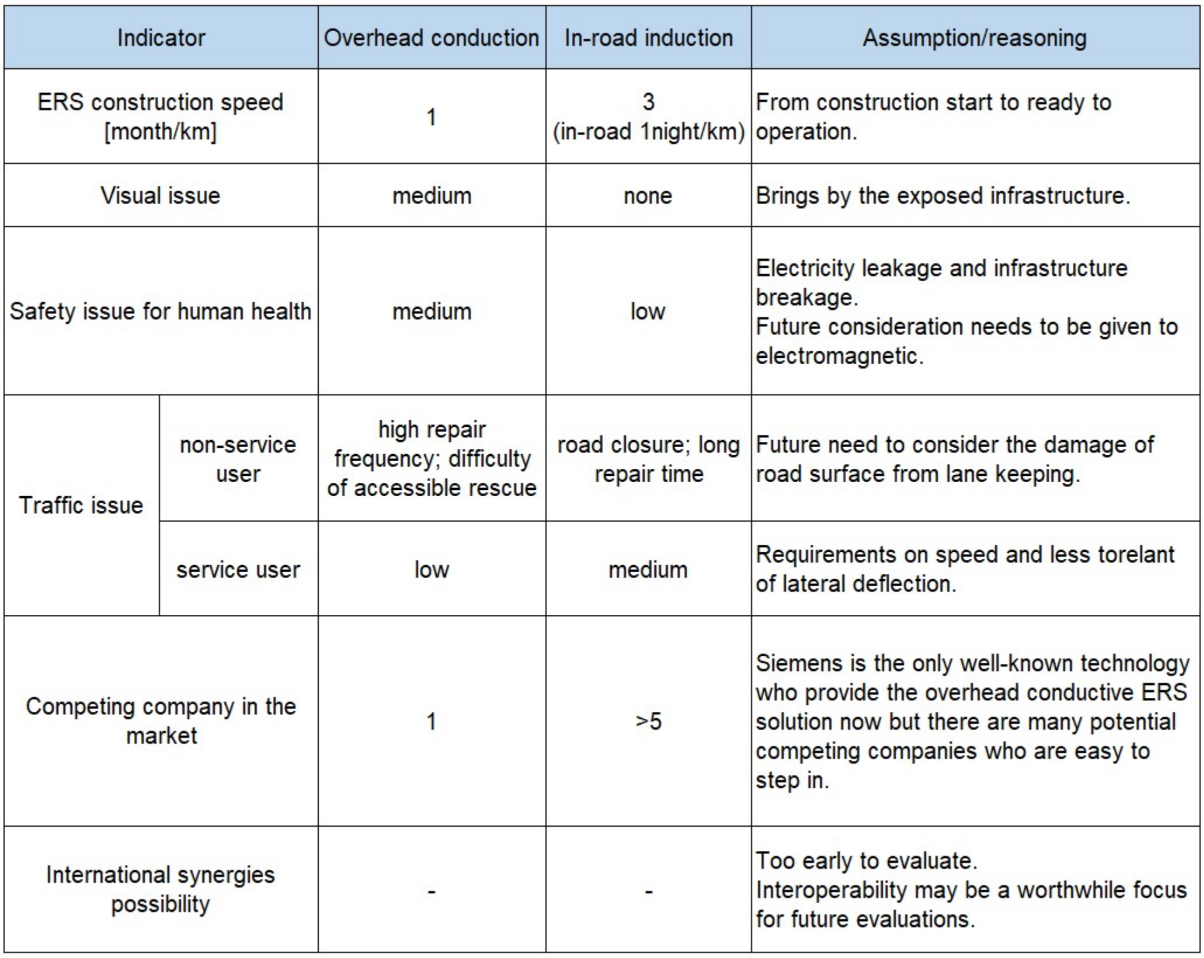
5.5.6. Competing company in the market

Siemens is the only well-known technology company that offers overhead conductive solutions, as they have extensive experience in applying the technology in the railway sector and can easily adapt it to the road. However, many companies have experience in this technology considering the existing rail and trolley bus system. It is very easy for them to come into the electric road market in the next step.

More than five companies are currently working on in-road inductive technology and already have their own demonstration projects. Examples include Electreon, which is the company of interest in this study, Olev in South Korea, Bombardier Primove in Germany, and WAVE in the United States, etc. With many companies developing the technology, there are lots of competitors in the market in the future.

5.5.7. Social indicators calculation result

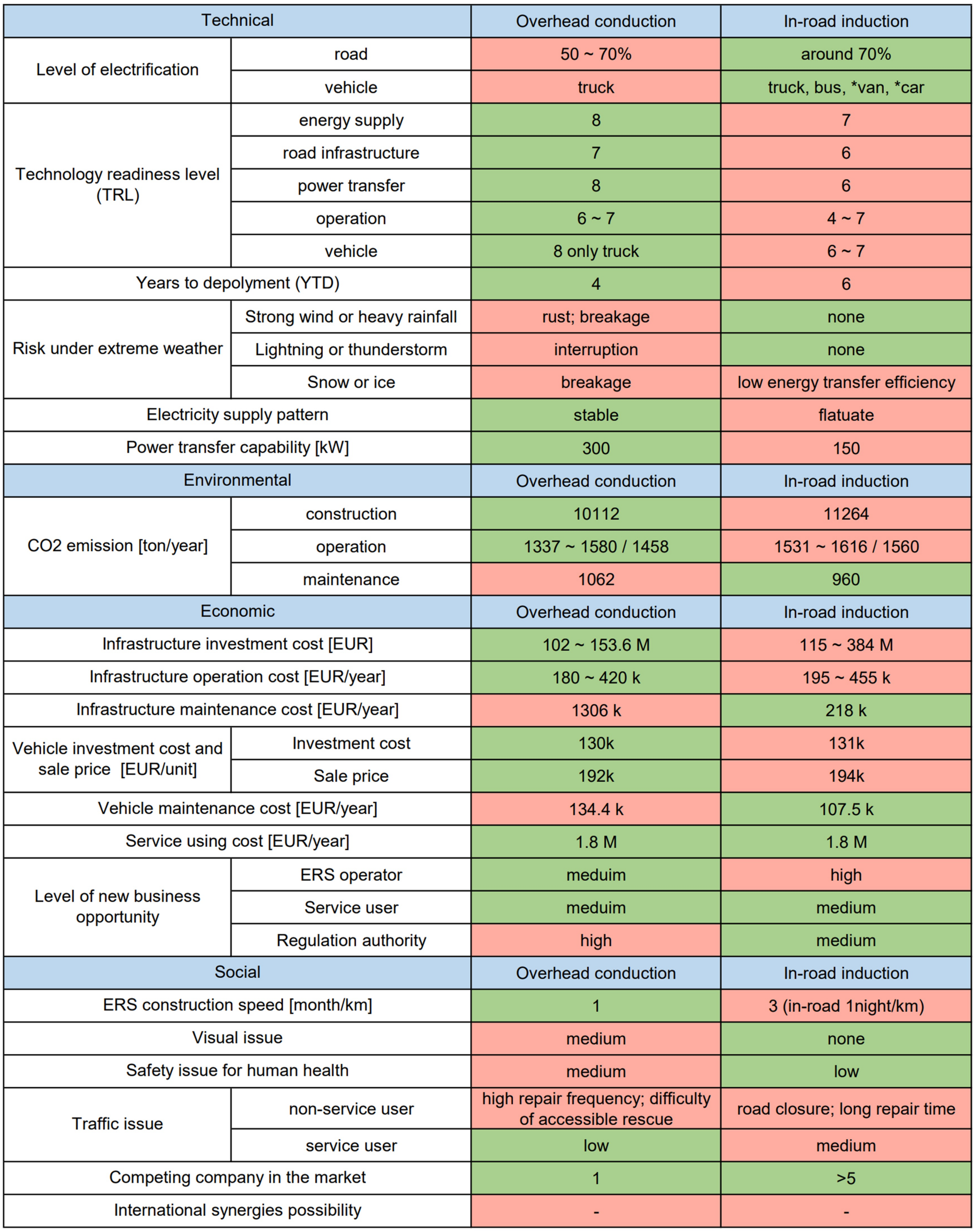
In Figure 5.16, the results of all the indicators in the social aspect have been summarized.



Indicator		Overhead conduction	In-road induction	Assumption/reasoning
ERS construction speed [month/km]		1	3 (in-road 1night/km)	From construction start to ready to operation.
Visual issue		medium	none	Brings by the exposed infrastructure.
Safety issue for human health		medium	low	Electricity leakage and infrastructure breakage. Future consideration needs to be given to electromagnetic.
Traffic issue	non-service user	high repair frequency; difficulty of accessible rescue	road closure; long repair time	Future need to consider the damage of road surface from lane keeping.
	service user	low	medium	Requirements on speed and less torelant of lateral deflection.
Competing company in the market		1	>5	Siemens is the only well-known technology who provide the overhead conductive ERS solution now but there are many potential competing companies who are easy to step in.
International synergies possibility		-	-	Too early to evaluate. Interoperability may be a worthwhile focus for future evaluations.

Figure 5.16: Evaluation result of social indicators

In summary, the performance of the two technologies on all indicators is shown in Figure 5.17. Green colour indicates better performance compared to the other technology and red colour indicates worse performance. Please note that this preliminary comparison is based only on the objective calculations in this chapter and is not connected to each stakeholder group. Judgements where subjective opinions exist, such as the impacts that stakeholders value more and the extent of the gap between the two technologies, are not included. This will be further analysed in the next chapter.



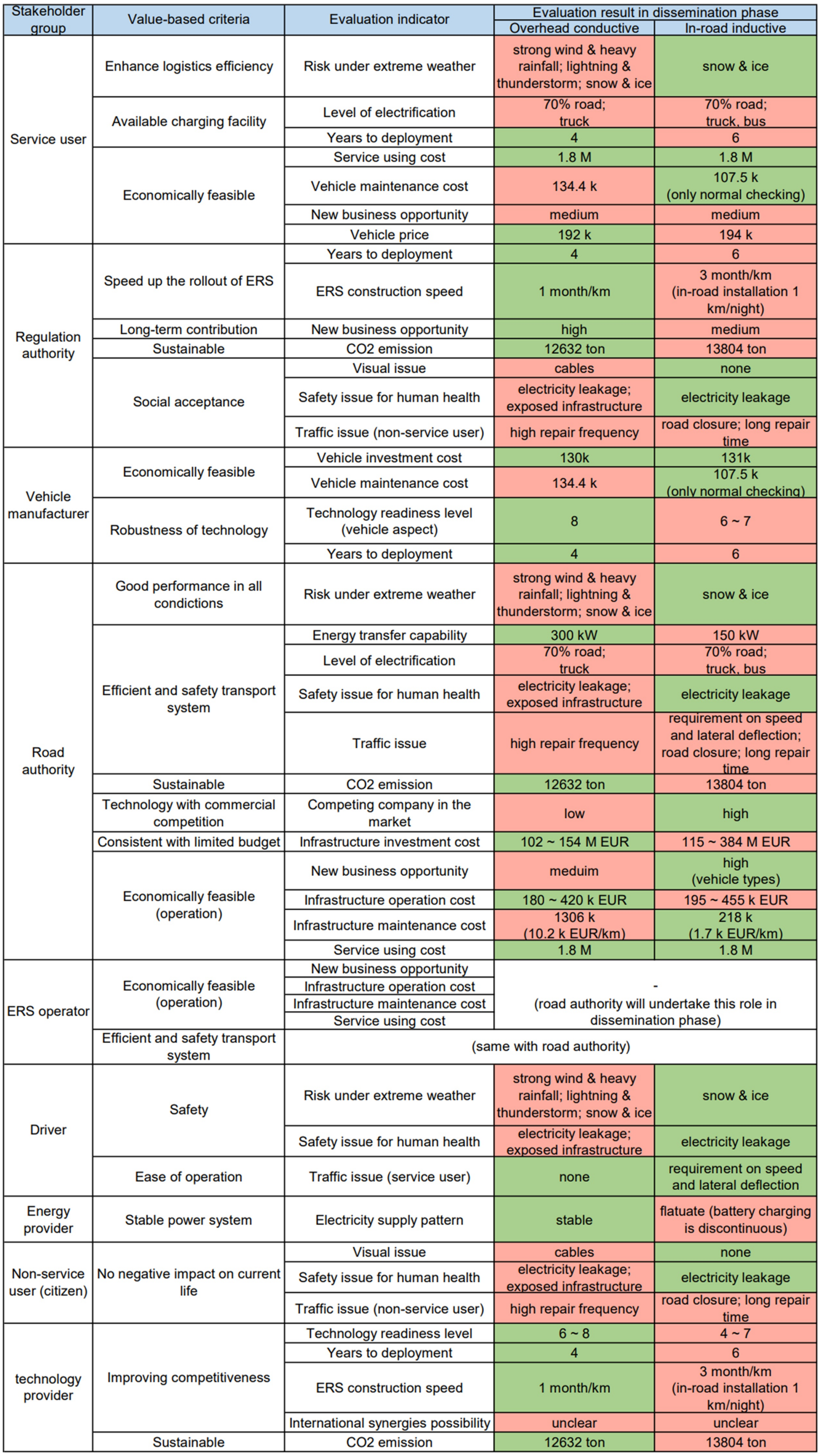
Technical		Overhead conduction	In-road induction
Level of electrification	road	50 ~ 70%	around 70%
	vehicle	truck	truck, bus, *van, *car
Technology readiness level (TRL)	energy supply	8	7
	road infrastructure	7	6
	power transfer	8	6
	operation	6 ~ 7	4 ~ 7
	vehicle	8 only truck	6 ~ 7
Years to depolyment (YTD)		4	6
Risk under extreme weather	Strong wind or heavy rainfall	rust; breakage	none
	Lightning or thunderstorm	interruption	none
	Snow or ice	breakage	low energy transfer efficiency
Electricity supply pattern		stable	flatuate
Power transfer capability [kW]		300	150
Environmental		Overhead conduction	In-road induction
CO2 emission [ton/year]	construction	10112	11264
	operation	1337 ~ 1580 / 1458	1531 ~ 1616 / 1560
	maintenance	1062	960
Economic		Overhead conduction	In-road induction
Infrastructure investment cost [EUR]		102 ~ 153.6 M	115 ~ 384 M
Infrastructure operation cost [EUR/year]		180 ~ 420 k	195 ~ 455 k
Infrastructure maintenance cost [EUR/year]		1306 k	218 k
Vehicle investment cost and sale price [EUR/unit]	Investment cost	130k	131k
	Sale price	192k	194k
Vehicle maintenance cost [EUR/year]		134.4 k	107.5 k
Service using cost [EUR/year]		1.8 M	1.8 M
Level of new business opportunity	ERS operator	meduim	high
	Service user	meduim	medium
	Regulation authority	high	medium
Social		Overhead conduction	In-road induction
ERS construction speed [month/km]		1	3 (in-road 1night/km)
Visual issue		medium	none
Safety issue for human health		medium	low
Traffic issue	non-service user	high repair frequency; difficulty of accessible rescue	road closure; long repair time
	service user	low	medium
Competing company in the market		1	>5
International synergies possibility		-	-

Figure 5.17: Preliminary comparison of all indicators
(green indicates relatively good performance and red indicates relatively poor performance)

6

Synthesis

The chapter begins by using value-based criteria as a bridge to match indicator evaluation results with their relevant stakeholder groups. Then for each stakeholder group, discuss the impact of ERS technologies during the dissemination and stabilisation phases in section 6.1. Here the data for the dissemination phase are the results of chapter 5, and the performance of the future stabilisation phase is mainly derived from the content of the interviews with the technology providers and projections of the technology's development in the literature. As explained in subsection 1.4.2, instead of giving weight, the second round of interviews focuses on presenting the results of the analyses, getting feedback for validation, and checking whether new issues are raised. Nine interviewees from all stakeholder groups participated, except for drivers, whose possible responses were predicted by the vehicle manufacturer and logistics company. After the single stakeholder impact analyses, the key indicators will be selected in section 6.2, standing in the researcher's perspective.



Stakeholder group	Value-based criteria	Evaluation indicator	Evaluation result in dissemination phase	
			Overhead conductive	In-road inductive
Service user	Enhance logistics efficiency	Risk under extreme weather	strong wind & heavy rainfall; lightning & thunderstorm; snow & ice	snow & ice
	Available charging facility	Level of electrification	70% road; truck	70% road; truck, bus
		Years to deployment	4	6
	Economically feasible	Service using cost	1.8 M	1.8 M
		Vehicle maintenance cost	134.4 k	107.5 k (only normal checking)
		New business opportunity	medium	medium
		Vehicle price	192 k	194 k
Regulation authority	Speed up the rollout of ERS	Years to deployment	4	6
		ERS construction speed	1 month/km	3 month/km (in-road installation 1 km/night)
	Long-term contribution	New business opportunity	high	medium
	Sustainable	CO2 emission	12632 ton	13804 ton
	Social acceptance	Visual issue	cables	none
		Safety issue for human health	electricity leakage; exposed infrastructure	electricity leakage
		Traffic issue (non-service user)	high repair frequency	road closure; long repair time
Vehicle manufacturer	Economically feasible	Vehicle investment cost	130k	131k
		Vehicle maintenance cost	134.4 k	107.5 k (only normal checking)
	Robustness of technology	Technology readiness level (vehicle aspect)	8	6 ~ 7
		Years to deployment	4	6
Road authority	Good performance in all condictions	Risk under extreme weather	strong wind & heavy rainfall; lightning & thunderstorm; snow & ice	snow & ice
	Efficient and safety transport system	Energy transfer capability	300 kW	150 kW
		Level of electrification	70% road; truck	70% road; truck, bus
		Safety issue for human health	electricity leakage; exposed infrastructure	electricity leakage
		Traffic issue	high repair frequency	requirement on speed and lateral deflection; road closure; long repair time
	Sustainable	CO2 emission	12632 ton	13804 ton
	Technology with commercial competition	Competing company in the market	low	high
	Consistent with limited budget	Infrastructure investment cost	102 ~ 154 M EUR	115 ~ 384 M EUR
	Economically feasible (operation)	New business opportunity	meduim	high (vehicle types)
		Infrastructure operation cost	180 ~ 420 k EUR	195 ~ 455 k EUR
		Infrastructure maintenance cost	1306 k (10.2 k EUR/km)	218 k (1.7 k EUR/km)
		Service using cost	1.8 M	1.8 M
ERS operator	Economically feasible (operation)	New business opportunity	- (road authority will undertake this role in dissemination phase)	
		Infrastructure operation cost		
		Infrastructure maintenance cost		
		Service using cost		
	Efficient and safety transport system	(same with road authority)		
Driver	Safety	Risk under extreme weather	strong wind & heavy rainfall; lightning & thunderstorm; snow & ice	snow & ice
		Safety issue for human health	electricity leakage; exposed infrastructure	electricity leakage
	Ease of operation	Traffic issue (service user)	none	requirement on speed and lateral deflection
Energy provider	Stable power system	Electricity supply pattern	stable	flatuate (battery charging is discontinuous)
Non-service user (citizen)	No negative impact on current life	Visual issue	cables	none
		Safety issue for human health	electricity leakage; exposed infrastructure	electricity leakage
		Traffic issue (non-service user)	high repair frequency	road closure; long repair time
technology provider	Improving competitiveness	Technology readiness level	6 ~ 8	4 ~ 7
		Years to deployment	4	6
		ERS construction speed	1 month/km	3 month/km (in-road installation 1 km/night)
		International synergies possibility	unclear	unclear
	Sustainable	CO2 emission	12632 ton	13804 ton

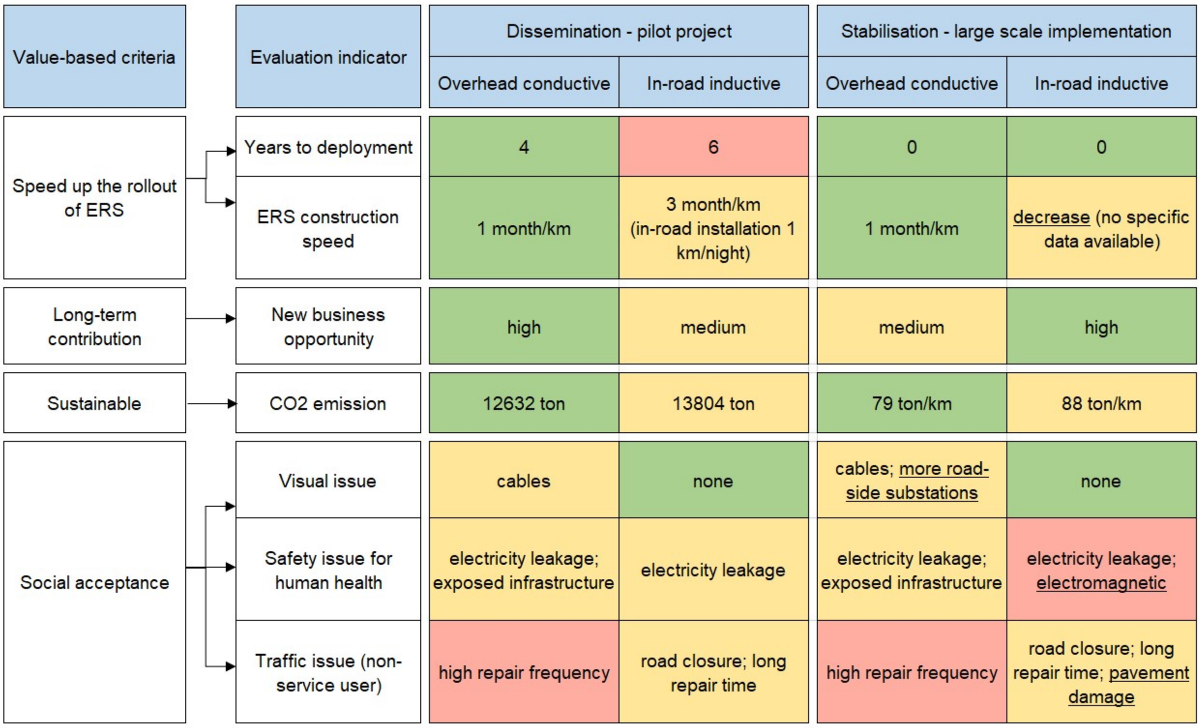
Figure 6.1: Synthesis of the impact of ERS technology on all stakeholder groups

6.1. The impact for each stakeholder group

This section will discuss the different impacts that each of the two technologies may have on each of the nine stakeholder groups. The focus of the discussion is not simply to judge which technology is better, as some of the results are difficult to compare, but to discuss the full range of possible impacts. The discussion focuses on the differences in the impacts, which means that if the two technologies perform similarly on an indicator, this indicator will not be analysed in detail here.

Each subsection will have a table that summarises the performance of the two technologies on each indicator at different stages. The left two columns show the value-based criteria and associated measurable indicators for each stakeholder group. The middle two columns are the results of the dissemination phase evaluation calculated in chapter 5. The right two columns are insights into the future stabilisation phase of the two technologies obtained from the second round of stakeholder interviews and the literature. The green colour means that the technology has an absolute advantage on the indicator, and the red colour means that it is a no-go performance for this stakeholder group and will have a very negative impact. The yellow colour indicates that the technology performs poorly and is still problematic, but the stakeholder interviews indicate that it is acceptable.

6.1.1. Regulation authority



Value-based criteria	Evaluation indicator	Dissemination - pilot project		Stabilisation - large scale implementation	
		Overhead conductive	In-road inductive	Overhead conductive	In-road inductive
Speed up the rollout of ERS	Years to deployment	4	6	0	0
	ERS construction speed	1 month/km	3 month/km (in-road installation 1 km/night)	1 month/km	decrease (no specific data available)
Long-term contribution	New business opportunity	high	medium	medium	high
Sustainable	CO2 emission	12632 ton	13804 ton	79 ton/km	88 ton/km
Social acceptance	Visual issue	cables	none	cables; more road-side substations	none
	Safety issue for human health	electricity leakage; exposed infrastructure	electricity leakage	electricity leakage; exposed infrastructure	electricity leakage; electromagnetic
	Traffic issue (non-service user)	high repair frequency	road closure; long repair time	high repair frequency	road closure; long repair time; pavement damage

Figure 6.2: Result of the impact evaluation on regulation authority (green indicates better performance, yellow indicates a negative but acceptable impact, red indicates critical negative impacts)

For the regulation authority, irrespective of the period, overhead conductive technology will allow them to roll out ERS projects faster than in-road inductive ERS and with less risk to meet pressing environmental goals.

Currently, the technology readiness of the conductive system is at a higher level and the deployment time for large-scale rollout is significantly shorter than that of in-road induction technology. The pace of construction is also faster due to the experience gained on the railway side. For example, technology companies such as Siemens already have a very mature raw material supply chain and extensive experience in emergency response.
The speed of implementation of in-road inductive technology is less predictable and more uncertain. There are issues such as energy transfer for the technology to work in reality, and the estimated deployment time is six years. This gap between the two technologies will be reduced in the future as the technology matures, but it is still inevitable that induction technology will require more time for road construction.

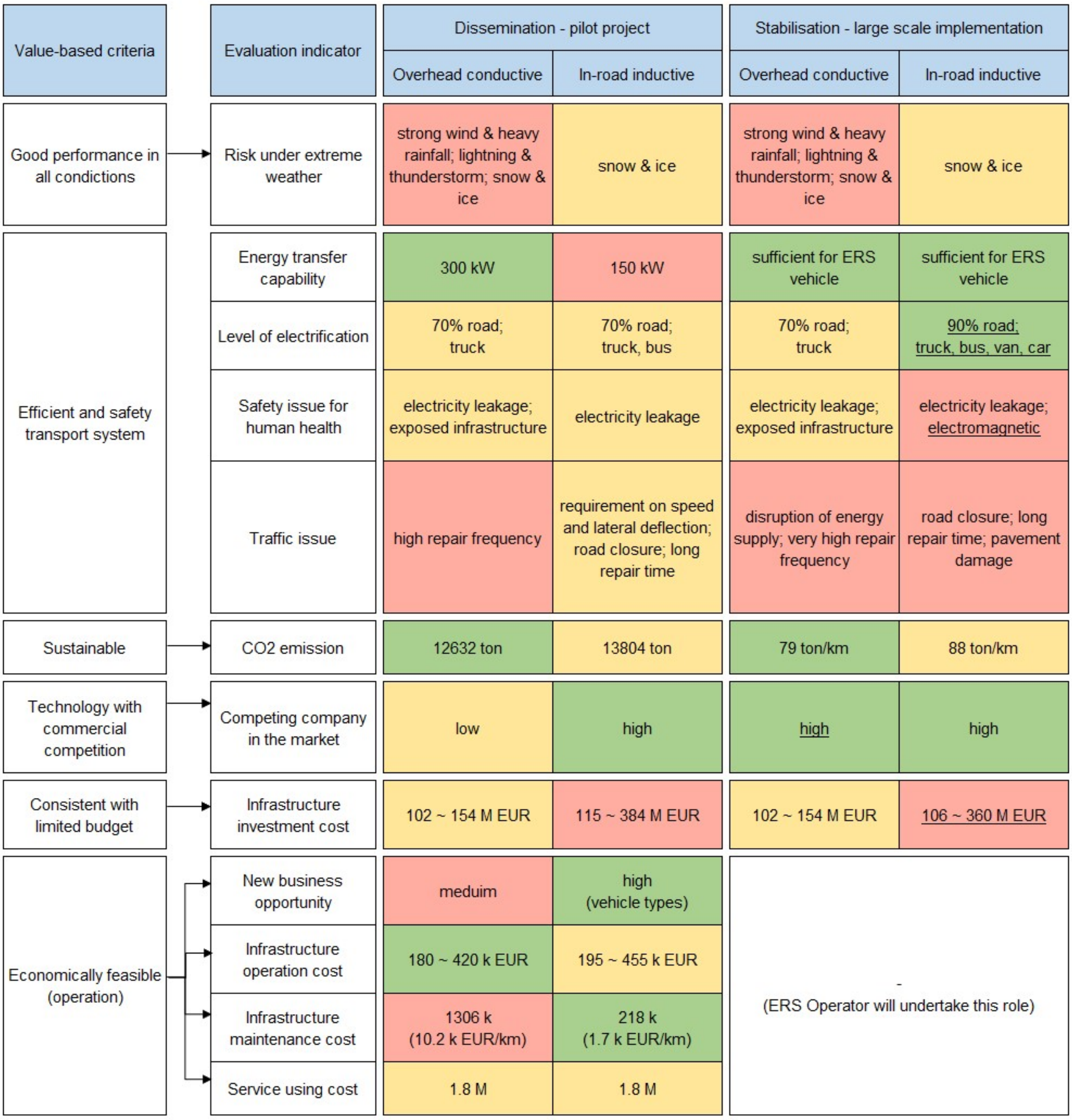
Currently, overhead conductive technology can easily support a phased scale-up of ERS infrastructure, with the flexibility to adjust to the amount of demand during the initial implementation phase. Both technologies are also effective and not too far apart in supporting environmental goals to effectively reduce emissions during transportation over the long term, with overhead conductive technology performing better in terms of whole-life emissions.
But when both technologies are fully mature, in-road induction technology presents more opportunities because it can theoretically support a wider range of vehicle types and has already been proven in pilot projects. It has the potential to become a universal solution for achieving zero emissions from road traffic. In addition to this, both technologies have the potential to create more jobs, such as the current vacancies for ERS operators.

The impact on citizens is also a very important factor that the regulation authority must consider. For different ERS technologies, there will be different direct impacts on citizens in three ways, thus responding to the level of social acceptance and therefore having an indirect impact on regulation authority. For a detailed analysis of the direct impacts, please refer to subsection 6.1.6. In summary, the overhead conductive system will negatively affect citizens who will be travelling on the road but are not users of the ERS service in several visual, safety and traffic aspects. The inductive system, on the other hand, has performed well in the pilot phase but may face serious safety (electromagnetic) issues in the future as it is scaled up, creating new concerns for the public.

6.1.2. Infrastructure provider - road authority

In the pilot phase, based on the experience in Sweden and Germany, both the role of the infrastructure provider and ERS operator can be assumed by the road authority due to the small number of service users in the field experiment. Therefore the analyses in this section for the pilot phase will merge the two stakeholders. Of these, only the economically feasible technology as it matures is something that needs to be considered separately for ERS operators in the future, which will be discussed separately in subsection 6.1.3. The others will be merged and analysed together in this section.

Here are six criteria that can be used to assess the impact on this stakeholder, both indirectly and directly. Indirect impacts arise because the road authority has a responsibility to provide a favourable road environment for ERS service users and the public. Therefore, factors that have a direct negative impact on them are also taken into account by the road authority which are the first two rows in Figure 6.3. Direct impacts include mainly financial and environmental factors



Value-based criteria	Evaluation indicator	Dissemination - pilot project		Stabilisation - large scale implementation	
		Overhead conductive	In-road inductive	Overhead conductive	In-road inductive
Good performance in all condictions	Risk under extreme weather	strong wind & heavy rainfall; lightning & thunderstorm; snow & ice	snow & ice	strong wind & heavy rainfall; lightning & thunderstorm; snow & ice	snow & ice
Efficient and safety transport system	Energy transfer capability	300 kW	150 kW	sufficient for ERS vehicle	sufficient for ERS vehicle
	Level of electrification	70% road; truck	70% road; truck, bus	70% road; truck	90% road; truck, bus, van, car
	Safety issue for human health	electricity leakage; exposed infrastructure	electricity leakage	electricity leakage; exposed infrastructure	electricity leakage; electromagnetic
	Traffic issue	high repair frequency	requirement on speed and lateral deflection; road closure; long repair time	disruption of energy supply; very high repair frequency	road closure; long repair time; pavement damage
Sustainable	CO2 emission	12632 ton	13804 ton	79 ton/km	88 ton/km
Technology with commercial competition	Competing company in the market	low	high	high	high
Consistent with limited budget	Infrastructure investment cost	102 ~ 154 M EUR	115 ~ 384 M EUR	102 ~ 154 M EUR	106 ~ 360 M EUR
Economically feasible (operation)	New business opportunity	meduim	high (vehicle types)	- (ERS Operator will undertake this role)	
	Infrastructure operation cost	180 ~ 420 k EUR	195 ~ 455 k EUR		
	Infrastructure maintenance cost	1306 k (10.2 k EUR/km)	218 k (1.7 k EUR/km)		
	Service using cost	1.8 M	1.8 M		

Figure 6.3: Result of the impact evaluation on road authority and ERS operator

related to the overall ERS construction and operation which are the last four rows in Figure 6.3.

- Indirect

As for indirect impacts, specific analyses can be found in subsection 6.1.6 and subsection 6.1.5, i.e. stakeholder groups that have direct impacts.

These include two main aspects, one being the need for the technology to ensure good performance under all conditions, especially in extreme weather. The higher risks associated with overhead conductive systems will result in additional emergencies and are more likely to disrupt operations.

Next is the impact that these technologies may have on an efficient and safe transport system. The overhead conductive system can provide a higher capacity to support larger amounts of trucks running on the road. However, it is less electrified and faces additional safety issues from exposed infrastructure. These issues with overhead conductive systems will remain in the future as the technology matures. Induction systems will have sufficient transmission capacity and higher electrification coverage in the future, but with that comes new electromagnetic risks.

- Direct
Three aspects have a direct impact, one is a sustainable objective. Both technologies can reduce carbon dioxide emissions to a large extent and contribute to environmental goals.

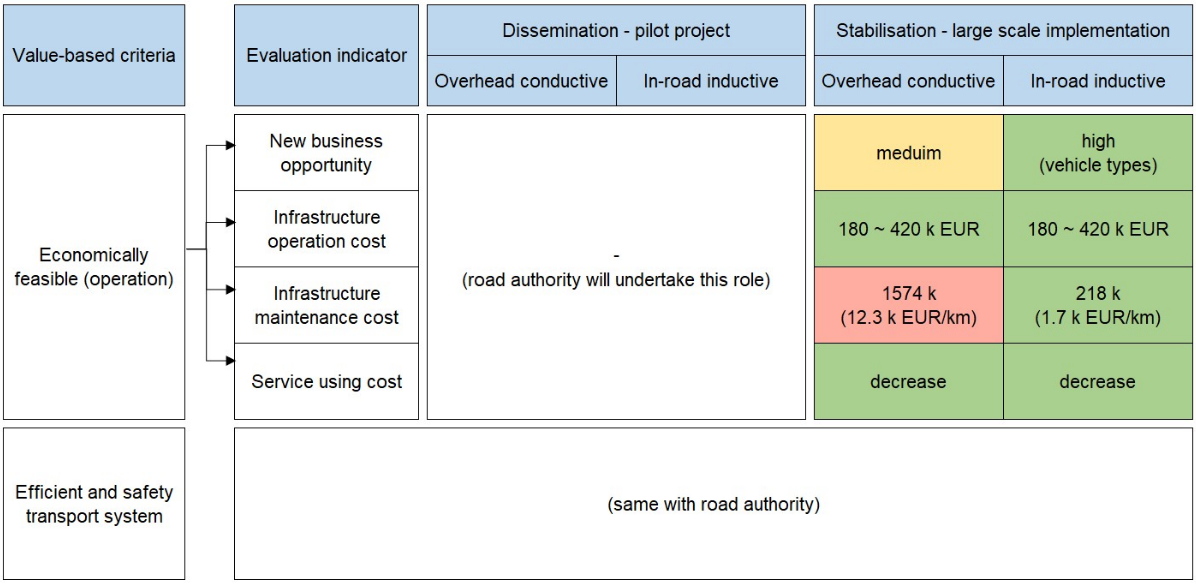
What's more, in-road inductive technology has more competition in the current ERS market companies and this trend will continue in the future as well. Many companies have experience with overhead conductive technology applied to railways. It is relatively easy for them to quickly join the road ERS programme. Therefore both technologies are highly price-competitive in the market.

The last one is the economic worries in investment, operation and maintenance costs. During the construction of the pilot phase, in-road inductive technology required a higher cost of infrastructure investment. The main reason for this is the need to rebuild the upper two layers of the road surface. Although investment cost will gradually decrease in the future as it is scaled up, the cost will still be higher than for the overhead system due to the difference in raw materials as well as the amount of construction work.
During operation, in-road induction technology will incur more energy consumption due to the current low efficiency of energy transfer. In the future, the efficiency has the potential to increase to a higher level as the technology matures, and the cost of the two technologies during operation may be equalised.
However, in terms of maintenance, the in-road induction infrastructure requires little additional maintenance effort and has a much lower cost overall.
In addition, it is undeniable that there is still a great market potential for induction technology in different vehicle types, which will bring more new business opportunities in the future. However, there is still a great deal of uncertainty as to whether there is sufficient demand and whether this demand can be successfully translated into actual revenue.

In the second round of interviews, stakeholders raised new concerns about the standardisation of the technology, as there is no detailed standardisation for either technology at this stage. Which technology can be standardised more quickly in the future may also be an important reference for their decision. For the time being, they still believe that funding and the technology itself will have the greatest impact and that the overhead conductive system meets the requirements in this regard, saves investment costs and provides better support to the transport system.

6.1.3. ERS operator (only in stabilisation phase)

As described in subsection 6.1.2, the impact of providing an efficient and safe transport system for the ERS operator is the same as with the infrastructure provider. And since the ERS operator is a new role only when the technology is mature that can support large-scale implementation, the economic impact in this section only considers the stabilisation phase in the future.



Value-based criteria	Evaluation indicator	Dissemination - pilot project		Stabilisation - large scale implementation	
		Overhead conductive	In-road inductive	Overhead conductive	In-road inductive
Economically feasible (operation)	New business opportunity	- (road authority will undertake this role)		meduim	high (vehicle types)
	Infrastructure operation cost			180 ~ 420 k EUR	180 ~ 420 k EUR
	Infrastructure maintenance cost			1574 k (12.3 k EUR/km)	218 k (1.7 k EUR/km)
	Service using cost			decrease	decrease
Efficient and safety transport system	(same with road authority)				

Figure 6.4: Result of the impact evaluation on ERS operator

The operation cost and service use cost will decrease accordingly in the future with the assumption that both technologies can achieve a 95% energy transfer efficiency. The business opportunity and maintenance cost have no big difference compared with a pilot project, in-road induction technology will almost bring no extra difficulty during future operation and maintenance according to the interview with the technology provider.

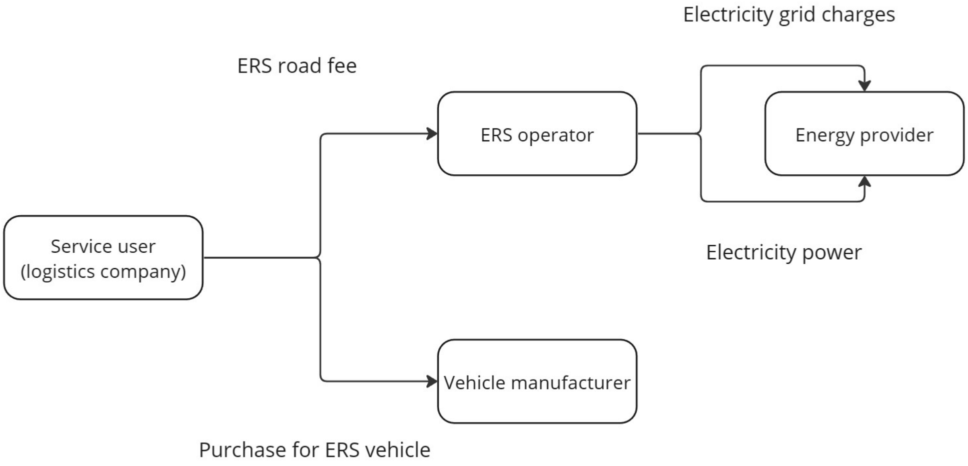


Figure 6.5: Possible payment model for the operational phase

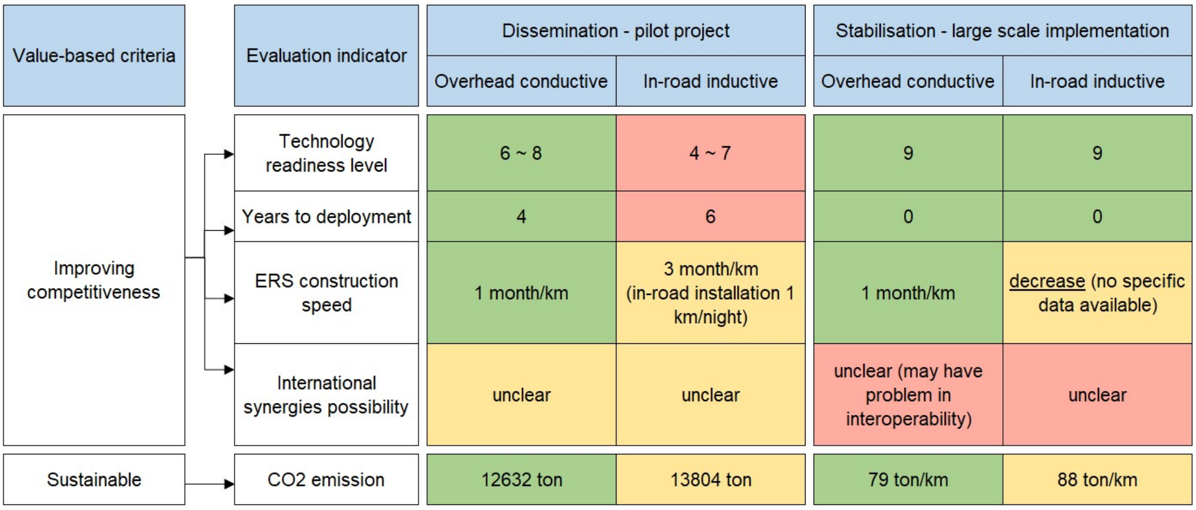
For the ERS operator, a possible payment model for the future operation of an ERS project can be defined in Figure 6.5. There might be a fixed subscription fee and a variable transmission fee to be paid to the energy provider, which in this study is the same figure as the infrastructure operating cost. And there's another cost of the infrastructure annual maintenance. The income is the ERS road using the cost paid by the service user. If only consider the single road in the study without taking into account the economy of scale, and assuming that the fleet size and annual operation and maintenance cost remain constant, the fastest payback period for the overhead conductive system is even longer than that of inductive system. In the future, if a larger fleet size and large scale of implementation are considered, the gap between the payback period will even increase accordingly considering the more expensive operation and maintenance cost of the conductive system.

$$Payback\ period = \frac{Initial\ investment}{Annual\ cash\ flow} \tag{6.1}$$

$$Payback\ period = \frac{Investment\ cost_{infra}}{Annual\ using\ cost - Operation\ cost_{infra} - Maintenance\ cost_{infra}} \tag{6.2}$$

6.1.4. Technology provider

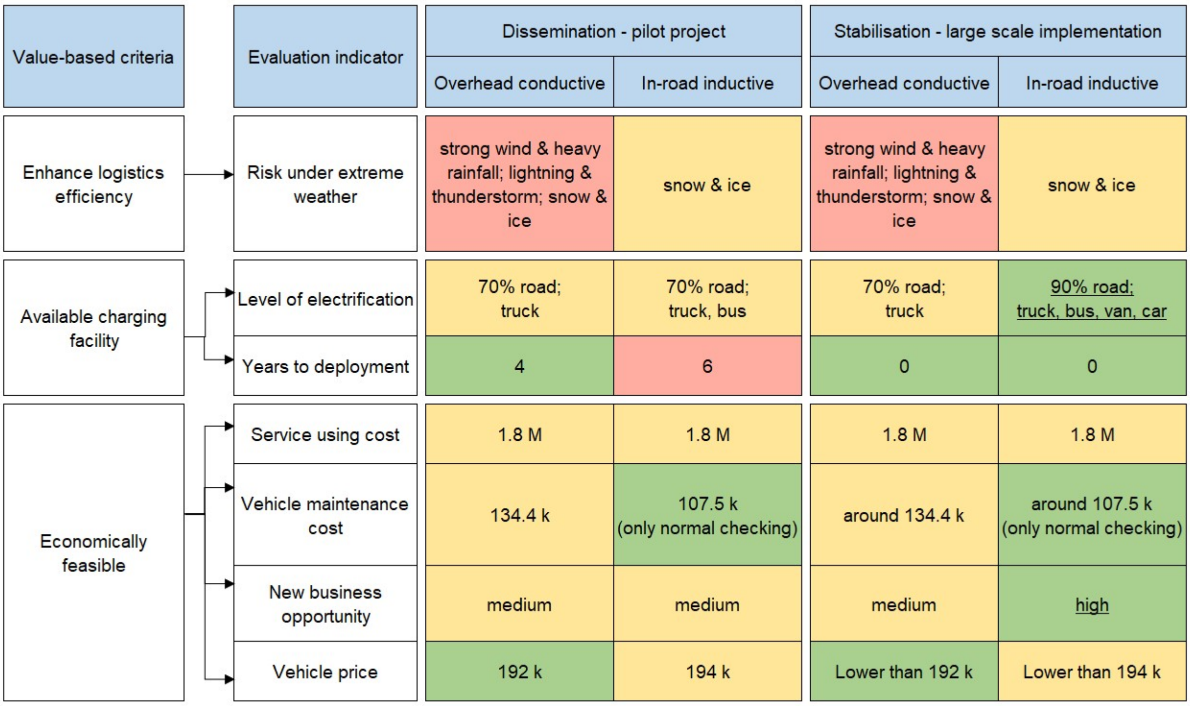
The technology provider is somewhat unique as they already have their position, i.e., they support their company's technology. Promoting their company's technology leads to more business opportunities. So there would not be much added value in analysing what different impact ERS technologies would have on this stakeholder group. Overall, as shown in Figure 6.6, it is clear that overhead conductive technology has less to worry about when considering the criteria that are important to technology providers, while in-road induction technology is generally still at a technically immature stage. Effort is still required to reach a satisfactory level for this stakeholder group.
What's more, in the overall analysis of technology providers, the main related work is to conduct a second round of interviews to confirm the validity of the data and to gain a deeper understanding of the possible development trends of the standards in the future stabilisation phase, as well as to obtain an update on the latest developments. The collection of this information is analysed in terms of its impact on other stakeholder groups.



Value-based criteria	Evaluation indicator	Dissemination - pilot project		Stabilisation - large scale implementation	
		Overhead conductive	In-road inductive	Overhead conductive	In-road inductive
Improving competitiveness	Technology readiness level	6 ~ 8	4 ~ 7	9	9
	Years to deployment	4	6	0	0
	ERS construction speed	1 month/km	3 month/km (in-road installation 1 km/night)	1 month/km	decrease (no specific data available)
	International synergies possibility	unclear	unclear	unclear (may have problem in interoperability)	unclear
Sustainable	CO2 emission	12632 ton	13804 ton	79 ton/km	88 ton/km

Figure 6.6: Result of the impact evaluation on technology provider

6.1.5. Service user



Value-based criteria	Evaluation indicator	Dissemination - pilot project		Stabilisation - large scale implementation	
		Overhead conductive	In-road inductive	Overhead conductive	In-road inductive
Enhance logistics efficiency	Risk under extreme weather	strong wind & heavy rainfall; lightning & thunderstorm; snow & ice	snow & ice	strong wind & heavy rainfall; lightning & thunderstorm; snow & ice	snow & ice
Available charging facility	Level of electrification	70% road; truck	70% road; truck, bus	70% road; truck	90% road; truck, bus, van, car
	Years to deployment	4	6	0	0
Economically feasible	Service using cost	1.8 M	1.8 M	1.8 M	1.8 M
	Vehicle maintenance cost	134.4 k	107.5 k (only normal checking)	around 134.4 k	around 107.5 k (only normal checking)
	New business opportunity	medium	medium	medium	high
	Vehicle price	192 k	194 k	Lower than 192 k	Lower than 194 k

Figure 6.7: Result of the impact evaluation on service user

For the service users, there are three main areas of impact from technology, all of which can have a significant impact on stakeholder attitudes.

The first is logistics efficiency. Since the main goal of this stakeholder is to deliver products to customers in a timely and intact manner, any risk that would affect its logistics process would have a significant negative impact. The overhead conductive system is potentially even more risky, both now and in the future. It is more likely to be disrupted in weather conditions, leading to cable repairs, signal interruptions and other issues affecting the normal movement of trucks on the road. Once the infrastructure fails to support dynamic charging, the service user will also need to pay for this problem.

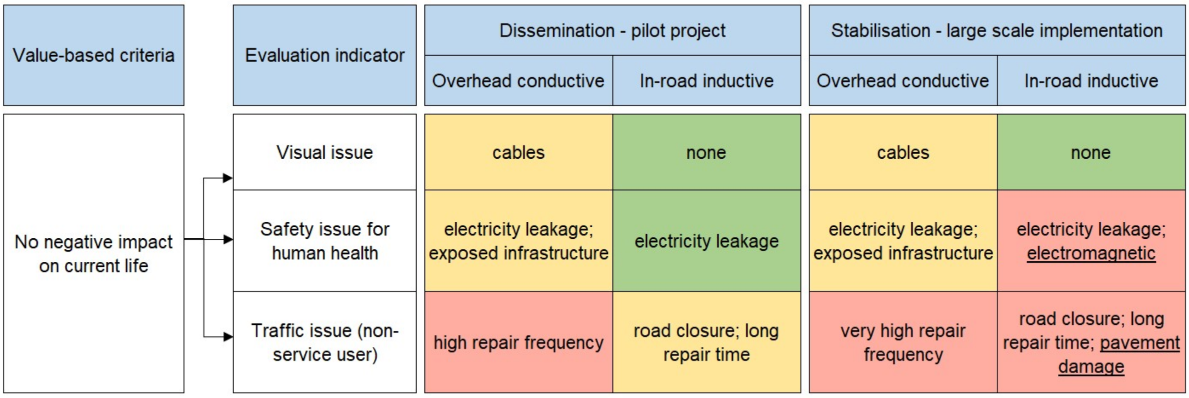
Another important factor for service users is available charging facilities. It only makes sense for this stakeholder group to acquire ERS vehicles for operational testing if the supporting infrastructure is ready. Otherwise, they have no interest in participating in ERS projects. Looking at the pilot projects, the fact that conduction technology is more mature and takes less time to deploy means that the supporting infrastructure can be ready sooner. But in the future, when there will be no difference in deployment time between the two technologies, in-road inductive technology can provide a high-level electrified road system environment while supporting a wide range of vehicle electrification. A service user's truck or van can travel on the ERS road and can be charged throughout the road. These are advantages that an overhead conductive system cannot offer.

What's more, they are the company that needs to have profit to support the operation. The economically feasible is also an important aspect. Considering the possible subsidy from the

government to encourage the use of ERS road, the estimated cost of using the ERS service will not have much difference.
The main difference in the annual cash flow regarding the two technologies is the cost of vehicle purchase and maintenance. In-road inductive vehicles almost do not need extra maintenance. However the purchasing cost is more expensive, this might be the only drawback the inductive technology may have in the future for service users.
In addition to this, in-road inductive technology has the higher potential to lead to further business opportunities. Service users will inevitably be faced with a future in which they consider reducing emissions throughout the transport process (including trucks, vans or cars) on which they provide their services. This technology could fully support the future shift of their business to e-mobility.

In a second round of interviews with the people from DHL, they did see the potential for an in-road inductive system to support a wider range of vehicles as the biggest advantage for logistics companies. Especially at the moment they are facing the internal target of a rapid shift to e-mobility, not only for trucks but also for delivery small vans. At this stage, they are very interested in the future development of in-road inductive technology.

6.1.6. Non-service user: citizen



Value-based criteria	Evaluation indicator	Dissemination - pilot project		Stabilisation - large scale implementation	
		Overhead conductive	In-road inductive	Overhead conductive	In-road inductive
No negative impact on current life	Visual issue	cables	none	cables	none
	Safety issue for human health	electricity leakage; exposed infrastructure	electricity leakage	electricity leakage; exposed infrastructure	electricity leakage; electromagnetic
	Traffic issue (non-service user)	high repair frequency	road closure; long repair time	very high repair frequency	road closure; long repair time; pavement damage

Figure 6.8: Result of the impact evaluation on non-service user

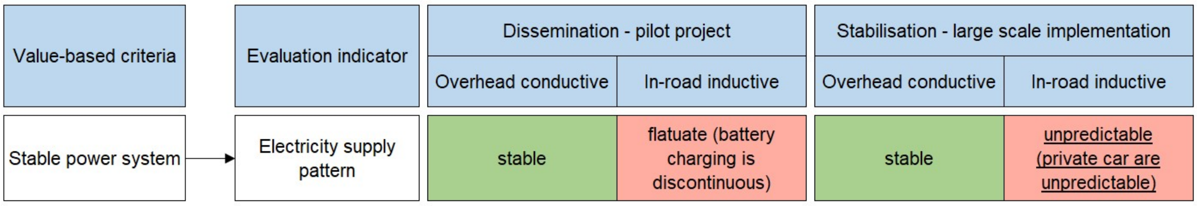
There are three types of impacts the ERS project will bring to citizens.

First is the visual impact. It must be admitted that overhead cables over the entire road and poles 50 metres apart on the side of the road do not look aesthetically pleasing. A questionnaire conducted by the Dutch Ministry on the attitude of the public towards the visual impact of overhead technology showed that the majority of the public in the Netherlands does not consider this to be a major problem as long as it provides a better transport system. Therefore, this risk is acceptable to society in this case study.

Apart from visual risks, safety risks for the human body are more worthy of consideration. Currently, overhead conductive systems face a more risky situation with their exposed infrastructure. In the future, the magnetic field generated during the charging process may become a problem. As power capabilities and transmission efficiencies increase, electromagnetism is likely to pose unforeseen dangers. High electromagnetism can hurt human health, which will affect society's acceptance of the technology. There is no data yet to prove that the technology will perfectly address this safety risk in the future.

The third is on the traffic aspect. For the overhead conductive system, the high frequency of repair work can result in temporary road closures, creating difficulties for traffic flow. And based on the experience of the railway, this type of situation could be a problem.
The risks of in-road induction technology are mainly because of the closure of roads during the construction period. This may cause a certain amount of traffic stress and inconvenience. Data provided by Electreon show that 1 kilometre of road closure work can be completed overnight. If this is the case then the impact is acceptable. However, the repair work will require a very long time and will influence the road pavement.
In the stabilisation phase, one new risk of in-road inductive technology in the operational phase is lateral tolerance. To achieve higher transfer efficiency and better connectivity of the system, vehicles may need an automated lane-keeping system to maintain a very limited amount of lateral movement. The consequent concentration of travelling along the same trajectory is harmful to the road surface and reduces its lifetime.

6.1.7. Energy provider



Value-based criteria	Evaluation indicator	Dissemination - pilot project		Stabilisation - large scale implementation	
		Overhead conductive	In-road inductive	Overhead conductive	In-road inductive
Stable power system →	Electricity supply pattern	stable	flatuate (battery charging is discontinuous)	stable	unpredictable (private car are unpredictable)

Figure 6.9: Result of the impact evaluation on energy provider

For energy provider, their only concern is which technology will make it easy to maintain a stable power system. Since either technology creates opportunities for the development of new market segments and brings in new customers with new demand patterns, they are not too concerned about economic and market considerations.

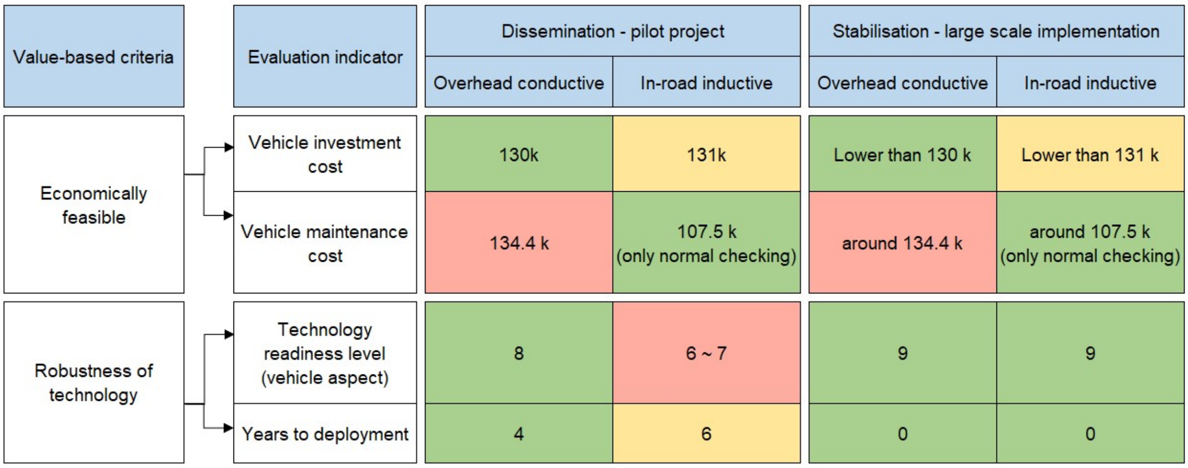
In the pilot project, the power supply patterns for both technologies are predictable and controllable. Because the pilot projects are mostly located on roads with high demand for electrified roads, there are stable ERS users. Moreover, the users are logistics companies in partnership who have relatively stable and planned fleet operation schedules. Taking this characteristic into account, the energy supply has not encountered any problems at this stage.

In the future, however, this could become a serious problem, especially for in-road inductive solutions. As the technology matures, the number of ERS service users will increase accordingly, including some small private transport vehicles. Charging patterns for all the trucks on the road are difficult to predict. The power system needs to be prepared for peak times when most trucks are charging simultaneously at the same time.
During the interviews with Siemens, they also see this problem in the future. They don't think that vehicles can run on ERS road alone. On-board batteries are necessary to avoid emergen-

cies. Therefore, they believe that the energy supply during peak hours can be kept within safe limits by the ERS operator. The trucks can maintain their normal operation by using batteries during this period.
The in-road inductive system will face a tougher situation. As it can support a wider range of vehicle types, the uncertainty will increase accordingly. Charging patterns for private cars will be more unpredictable, and energy use will fluctuate more dramatically. One possible solution to avoid this, says the technology company, is to offer a membership service. Member users have priority for charging at all times. The ESR operator would refuse charging requests from certain regular users when excessive power demand threatens the stability of the system.

During the interview, energy suppliers agreed that both technologies would equally challenge the stabilisation of the power system. And they see the reasonableness and necessity of the two possible solutions offered by the technology provider. They also believe that floating pricing is also a solution worth exploring further. However, they recognised that they have no direct contact with the end users in the ERS project. As a direct result of this, they are not deeply involved, and that pricing strategy is a more important issue for ERS operators to address. They are not currently putting extra effort into doing research in this area.

6.1.8. Vehicle manufacturer



Value-based criteria	Evaluation indicator	Dissemination - pilot project		Stabilisation - large scale implementation	
		Overhead conductive	In-road inductive	Overhead conductive	In-road inductive
Economically feasible	Vehicle investment cost	130k	131k	Lower than 130 k	Lower than 131 k
	Vehicle maintenance cost	134.4 k	107.5 k (only normal checking)	around 134.4 k	around 107.5 k (only normal checking)
Robustness of technology	Technology readiness level (vehicle aspect)	8	6 ~ 7	9	9
	Years to deployment	4	6	0	0

Figure 6.10: Result of the impact evaluation on vehicle manufacturer

For the vehicle manufacturers, the economic feasibility of the two technologies does not differ significantly. Based on the possible future payment model shown in Figure 6.5, the payback period could be achieved in about eight months, taking into account the vehicle investment and annual cash flow including the payment of the vehicle from the service user and the cost of the vehicle maintenance. As shown in the right two columns in Figure 6.10, in the future, the investment cost of both technologies will become lower as the economic of scale and also the development of technology (data are assumptions according to the experience from the interviewees). While the cost of an overhead conductive system is still at a lower level since the raw material is cheaper and the vehicle software system is easier.
One point worth noting is the difference in maintenance between the two technologies. The in-road technology does not require additional maintenance work on the vehicle, only routine vehicle inspections. The rest of the maintenance is mainly about software checks and updates,

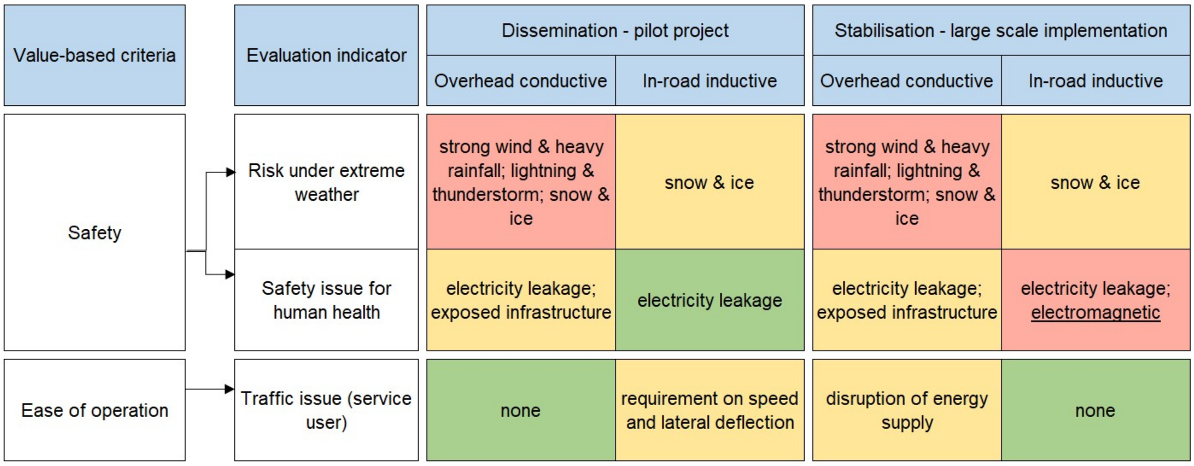
which can be done online at a very low cost. Since both technologies are not difficult to build in ERS vehicles, the economic investment will not change significantly in the future.
Both of these technologies can open up opportunities for the sale of new vehicles. There is also an opportunity to participate in and establish the new electric road market at an early stage, making ERS technology the standard and gaining a potential competitive advantage from it.

In terms of the robustness of the technology, overhead conductive systems are less risky in the pilot phase. This is because the vehicle subsystem TRL of overhead conductive is higher, up to level 8. Whereas the inducting has a lower TRL of 6 for trucks and 7 for buses, they need to continue to be tested in real-life operations and refine the business model. Deployment times are less predictable.

In the future, in-road inductive technology may be more advantageous for vehicle manufacturers. When the technology is mature and standardised, ERS vehicles will be built and operated without problems. The focus may then shift to the maintenance phase, where in-road systems are more advantageous.

Interviewees agree with this result and think that at this stage TRL is a key factor when they decide which technology to start investing in. They feel that in general at this stage trucks with pantographs are less difficult to build and less risky to develop than inductive trucks. Whereas maintaining worn pantographs is probably the biggest drawback of overhead conductive systems, their anticipated future maintenance is to be charged per distance travelled.
But more importantly, the supporting infrastructure is the main driver of which technology they choose to develop. This is closely linked to decisions made by governments and road authorities.

6.1.9. Driver



Value-based criteria	Evaluation indicator	Dissemination - pilot project		Stabilisation - large scale implementation	
		Overhead conductive	In-road inductive	Overhead conductive	In-road inductive
Safety	Risk under extreme weather	strong wind & heavy rainfall; lightning & thunderstorm; snow & ice	snow & ice	strong wind & heavy rainfall; lightning & thunderstorm; snow & ice	snow & ice
	Safety issue for human health	electricity leakage; exposed infrastructure	electricity leakage	electricity leakage; exposed infrastructure	electricity leakage; electromagnetic
Ease of operation	Traffic issue (service user)	none	requirement on speed and lateral deflection	disruption of energy supply	none

Figure 6.11: Result of the impact evaluation on driver

As direct users of ERS vehicles, drivers are most concerned about safety. Two main types of risks could lead to safety problems for this stakeholder. On the one hand, the dangers posed to drivers indirectly by the weather-driven nature of the infrastructure. On the other hand, the possible impacts of the technology directly on the health of drivers, similar to the situation for

non-service user subsection 6.1.6.
The first is the risk of operating in extreme weather. This factor has shown to be more problematic with overhead conductive systems, both in pilot projects and in future large-scale implementations. For example, concerning railway systems, high winds and heavy rain can cause problems for power transmission subsystems, snow and ice build-up on cables can lead to breakage problems, thunderstorms can lead to signalling failures, and so on. As for the in-road induction system, only the accumulation of snow and ice on the road surface can lead to less efficient energy transmission and make driving problematic. However, this is almost unlikely to happen as there is pavement maintenance in snowy conditions.
Secondly, both technologies have the risk of electricity leakage. Except, at the current stage neither technology has a direct negative impact on the driver's body. However, given future implementations, electromagnetism from embedded coils may be a consideration. Current electromagnetism meets the criteria, but there is no data available to demonstrate a continued level of safety in the future, especially as energy capacity increases.

The second issue is to consider the ease of operation of the two technologies in terms of traffic operation. The inductive system has higher speed requirements and lower lateral deflection requirements. However, according to the interview, drivers did not receive any additional requirements regarding maintaining the driving trajectory. So for the pilot project, this is not a problem.
Even in the future, an automatic lane-keeping system can help the driver follow a defined trajectory to achieve the highest energy transfer efficiency for wireless transmission. Conductive systems may face additional problems in real-world operations in the future, as the energy supply is more likely to be interrupted due to unforeseen circumstances. This could increase driving complexity and force drivers to change their plans.

Furthermore, it is worth mentioning after the second round of interviews that a new interest in driving comfort has arisen from the driver. The connection between the cables and the pantographs may generate additional aerodynamic noise and therefore the operation of the conductive system may be less comfortable for the driver. According to data from the railway system (Zvolenskỳ et al., 2021), a train travelling at 100 kilometres per hour generates a noise level of 51.3 dB due to the charging connection.

6.2. Key indicators selection

6.2.1. Selection rules

Having identified the different impacts of ERS technologies on various stakeholder groups in the previous section, this study also attempts to provide some ideas from the researcher's perspective as a whole as to which key indicators require extra attention in future research. Therefore, this section presents a selection of the 20 evaluation indicators involved in this study. There are four rules for the selection:
- This indicator is of common interest to multiple stakeholder groups, i.e. it was mentioned by many stakeholder groups in the first round of interviews.
- The performance of the two technologies on this indicator varies significantly.
- There is considerable uncertainty about the results of this indicator because of the lack of

data.
- This indicator will change significantly in the coming years.

6.2.2. Selection result

Based on the selection rules, the following indicators have been chosen for this section, which are key indicators that will require extra attention in future studies.

Safety issues for human health and traffic issues have the widest reach and will have direct or indirect impacts on five stakeholder groups, and the associated impacts can significantly affect stakeholder acceptance of the technology. Traffic issues manifest themselves differently depending on the stakeholder and they each face different problems such as road closures and high maintenance workloads. However, specific data such as the length of closures and frequency of maintenance are not currently available, making it difficult to give a simple definition of which technology is better. The same situation is faced with safety issues. In addition to this, the safety aspects may also face some major changes in the coming phase. For example, it is not yet clear what effect the increased electromagnetism during energy transfer will have on the human body in the future.

The impacts of **years to deployment** are also very wide-ranging, involving four stakeholder groups. Due to the immaturity of the current technology, the negative impacts of in-road inductive technology will be even greater in this regard. However, it is a new technology that is evolving at a very fast pace and therefore there is a lot of uncertainty regarding its deployment. Continued attention needs to be given, especially to the results of experiments and field tests conducted by the technology providers.

The two technologies differ significantly in terms of **infrastructure and vehicle maintenance cost** indicators. In-road inductive technology requires almost no additional maintenance of vehicles and infrastructure. It even lasts longer than the road surface. Therefore maintenance costs are low. However, overhead conductive systems put a lot of maintenance pressure on overhead conductors and pantographs. Especially as the size of the ERS increases, the maintenance costs increase accordingly with the number of users served.

International synergies possibility is an indicator that cannot be assessed now on the basis of existing experience but will be important in the coming period. If this indicator is to be assessed in the future, there are two unresolved issues at this stage that may need to be considered. One is which of the two technologies should be standardised first. Currently, standards for both technologies are in the process of being developed. The other focus is on the interoperability of the technologies. Interoperability between different types of vehicles and between different companies of the same technology needs to be considered.

Electricity supply pattern is currently not problematic, but there will be significant changes in the future for which solutions are not yet clear. For in-road induction technology, it has a discontinuous battery charging pattern and with the use of private cars in the future, the charging pattern becomes even more unpredictable. This will pose a significant threat to the stability of the energy system.

7

Conclusion and recommendation

In this chapter, the overall conclusion of this research will be given by first answering each sub-question based on the analyses presented in Chapters 3 to 6. Then, from the researcher's point of view, recommendations for implementing ERS in reality and suggestions for future research will be made.

7.1. Conclusion

This section will provide clear answers to the following key questions:

> *What are the current state of ERS and its two competing technologies?*

ERS represent a promising solution for mitigating GHG emissions within road system and is currently performing well in practical field tests. It is particularly suitable for electric HGVs, reducing their need for large batteries.

This study primarily focuses on two ERS technologies: overhead conductive and in-road inductive systems. The overhead conductive technology relies on established catenary and pantograph contact systems, similar to those employed in railway systems, for efficient electrical energy transmission. Key advantages encompass its proven technological maturity, safety, power transfer capability, etc. In-road inductive technology is realised through inductive wireless energy transmission, offering advantages across diverse vehicle types and minimal visual impact. Both technologies have different considerations during phases of construction, operation, and maintenance.

ERS technologies, especially overhead conductive systems, have been effectively implemented in pilot projects across multiple nations, proving their technical maturity and safety. Nevertheless, the multiple sub-systems, the coordination of diverse stakeholder interests, and the uncertainty that this creates for the transport system as a whole present many challenges.

> *Who are the relevant stakeholders involved in an ERS project and what value-based criteria are held by them?*

Nine related stakeholder groups are identified in this research.

1. Regulation authorities play an important role in the ERS programme and their influence is the greatest. They want to promote the rapid development of ERS projects to reduce GHG

emissions from heavy-duty vehicles with good social acceptance and to contribute to the achievement of climate goals in the long term.
2. The infrastructure provider is responsible for the actual implementation of ERS technologies and for ensuring their harmonisation with the existing road infrastructure. They expect the technology to maintain the safety of the road infrastructure and to create efficient road traffic for the transport system. There are also financial constraints, so they want to control the investment effectively.
3. The ERS operator is a new role that will emerge in the future, and at this stage, it is held by the infrastructure provider. Their main concern is that the technology performs well in terms of actual operation and maintenance.
4. ERS technology providers offer technical solutions in ERS projects, including power transmission and infrastructure development. They want to drive technological innovation, reduce greenhouse gas emissions, achieve commercial competitiveness and increase market share.
5. Service users want to realise logistical efficiencies at lower costs and effectively maintain their market leadership.
6. Citizens are concerned about road safety and want to ensure that ERS projects do not adversely affect their road use and living environment.
7. Energy providers have a low interest in ERS projects, focusing only on the stability of power consumption patterns and security of supply, as well as ensuring the effectiveness of their power distribution plans.
8. Vehicle manufacturers want to provide cost-effective e-mobility solutions as well as meet market demand and are more concerned with aspects such as vehicle investment costs, availability of electric infrastructure, and rapid return on investment.
9. Drivers focus on the driving experience, including the vehicle performance, and ease of operation of the electric truck.
These stakeholders represent different interests and concerns in the ERS project, and their cooperation and coordination are essential to the promotion of ERS.

> *What are the indicators that should be taken into account to calculate the value-based criteria?*

Conceptually, the indicators that should be taken into account to calculate the multi-criteria for evaluating the two different ERS technologies encompass a diverse range of factors. These indicators are grouped into several key categories:

1. Technical Indicators: These indicators assess the technological aspects of the ERS technologies, including technical feasibility, the latest progress, etc. These indicators help determine the readiness and practicality of implementing each technology.

2. Economic Indicators: These indicators focus on the financial aspect of ERS implementation. Key indicators include investment cost, market competitiveness, etc. Economic considerations play a crucial role in the decision-making process for ERS projects.

3. Environmental Indicators: Given the primary goal of reducing GHG emissions, environmental indicators are vital. They measure the extent to which each technology reduces CO_2 emissions and its potential contribution to overall environmental sustainability.

4. Social Indicators: These indicators help identify how well the technology integrates into society, including user experience, safety issues, etc.

Overall, all the indicators collectively form a comprehensive framework for evaluating and comparing the two ERS technologies. They allow for a thorough evaluation of technical feasibility, economic viability, environmental impact, and social implications while considering the values and priorities of the diverse stakeholders involved in ERS projects.

> *What are the impacts of overhead conductive and in-road inductive system on each stakeholder group?*

1. The overhead conductive system would not have any direct negative impacts on the **regulatory authority**. However, it can have a negative impact on service users and the public thereby affecting the regulation authority's point of view. Problems mainly include visual and safety risks associated with exposed overhead infrastructure and traffic problems due to high maintenance frequency. These risks will continue to exist in the future, regardless of how the technology develops.
The main negative impact of in-road inductive technology at the moment is the need to wait longer for large-scale deployment. In the future, it will perform better in terms of commercial development and will not present visual problems. However, new safety issues related to electromagnetism have emerged.

2. Both technologies pose significant challenges to current transport systems for **infrastructure providers** and **ERS operators**.
Overhead conductive systems do not work well in all weather conditions, are subject to frequent and costly maintenance, cannot support a wide range of vehicles, etc. It is difficult to guarantee an efficient transport system, both in the pilot phase and in the future.
In-road induction technology currently has a very limited energy transfer capacity and is accompanied by large investments that will face problems with the limited budget. In the future, the technology will also face additional problems in terms of electromagnetic safety issues and traffic issues, such as difficult and time-consuming maintenance.

3. **Technology providers** are relatively different, as they already have their own supported technologies. Currently, in-road inductive technology provider face more problems in selling their own solutions, in particular the need to push the technology to reach a rapid level of maturity, but also to pay more attention to the possibilities of international synergies.

4. For **service users**, the operational risks associated with the susceptibility of conduction technology to weather will impact logistical efficiency.
In-road induction technology has a more positive impact overall, as it does not pose any serious problems in the future that would compromise service users' values while having a high degree of economic viability and better achieving their goal of moving to e-mobility.

5. From the citizen's perspective, both technologies will present unacceptable problems in the future. In particular, clearer solutions are needed in terms of safety (electromagnetic) and traffic (frequency and duration of repairs, damage to road surfaces, etc.).

6. **Energy providers** have paid less attention to ERS projects. However, in-road induction technology will bring unavoidable problems of power system stability. This is because it cannot have a stable and predictable energy consumption pattern, as the charging process is discontinuous and the charging pattern of private cars is random.

7. **Vehicle manufacturers** need to perform more maintenance work on pantographs in overhead conductive technology. The main risk of inductive technology, on the other hand, lies in the current TRL, especially the interoperability of the software. If this problem can be solved, then the inductive technology will not have any negative impact on this stakeholder group.

8. **Drivers** face the same safety issues as the public who use the roads. In addition to this, they need to pay more attention to the transmission stability of the overhead conductive system when travelling in extreme weather. For induction technology, drivers need to put more effort into controlling speed and lateral deflection to maintain the most efficient energy transfer.

7.2. Recommendation

7.2.1. Recommendation for the implementation of ERS project

The roots of the major negative impacts of in-road inductive technology right now are all due to the immaturity of the technology. It is currently unable to provide enough energy to support the operation of many types of vehicles on the road. Therefore, at the current level of development, it is more realistic to suggest that in-road inductive technology is suitable for use in public transport. The analysis in this study found that the TRL of induction technology is higher in buses than in trucks. The potential of this possibility cannot be ignored. It may be a suitable solution to support dynamic charging in public transport and is somewhat less difficult to implement than trucks. It can be better used for urban and static fast charging as long as current maturity and performance metrics are met. In the future, as the technology evolves, uncertainty diminishes and guidelines become available, further decisions can be made on whether to deploy this technology at a large scale to support dynamic charging for all vehicle types.

The rapid deployment and maturity of overhead conductive systems can be an effective solution for reducing emissions on the road, particularly in light of the environmental targets. While the negative impacts are significant and unavoidable. One suggestion may be to create other benefits through better utilisation of infrastructure. For example, by sharing infrastructure with other road technologies such as 5G connection and automatic driving.

Regardless of which ERS technology is adopted, policy encouragement is essential. In both the transition period and the early stages of future development, governments will need to provide appropriate support, for example by guaranteeing a certain level of traffic flow on electric road sections or by subsidising the purchase or lease of vehicles suitable for electric roads by carriers. For other stakeholders, their participation in an ERS project depends to a large extent on the availability of ERS infrastructure and the standardisation of the technology. While it may be a chicken-and-egg question for governments, there is always a need for one party to act first. Considering the huge investment costs, if only a single route is deployed, such as the corridor in this study, then the economic viability is low and the payback period is extremely long. Therefore, large-scale deployment may be a better option, both to realise economies of scale and to attract more participation from other stakeholder groups.

Extra attention also needs to be paid to how key indicators will develop in the future, as summarised in section 6.2, such as safety issues, power supply patterns, international synergy possibilities, etc. Timely collection of new developments from technology providers or experiments in field test programmes can significantly reduce uncertainty as well as identify potential advantages and disadvantages.

7.2.2. Recommendation for future research

Considering the validity and limitations of the study, the following recommendations are made for further research.

Firstly, only the Rotterdam-Antwerp corridor is considered in this study. Given the location constraints of this study, it is recommended in the future to further analyse the potential feasibility of these two ERS technologies in a European context. Because of the close relationship of road transport networks across Europe, it would be valuable to investigate the entire European road network to take the economies of scale effect into account.

Secondly, given the time context constraints of this study, i.e. the focus is on pilot projects and the indicator calculations are based on assumptions of the current status quo, the analyses for the future are only based on projections from technology providers or literature. The reason for this is that it is difficult to predict the future direction as the technology is in a developmental stage. However, other new indicators may emerge in the future, stakeholder groups may change accordingly, and business models may change accordingly. Therefore future research should also focus on the potential of both technologies at future stages of technological maturity and what is the appropriate business model for each stakeholder group.

Third, it is worth noting that the current study has limitations in terms of information collection. The data related to overhead conductive technology are all obtained from the Siemens eMobility project. The data and information related to in-road inductive technology are mainly based on the demonstration projects by Electreon, as these are more readily available for this study. There are other companies that are also working on ERS technologies and have agreed to provide such solutions, but their perspectives have not been taken into account in this study. For example, in talking to another technology provider, IPT, it was found that their upcoming demonstration project in the US had better performance with different energy transfer capabilities and continuous charging modes than those demonstrated by Electreon in this study. It is, therefore, necessary to conduct a comprehensive data collection with most of the in-road inductive technology providers in order to obtain more convincing results. The main differences between their solutions are particularly important and will shed more light on the decision-making process for the ERS project roll-out.

What's more, it is also recommended that the weighting of the individual criteria, as well as the weighting of the stakeholder groups, be implemented in future studies. It is difficult for the interviewees in this study to give the weights of the criteria from their organisational perspective as they do not currently have extensive experience and knowledge of the two technologies being carried out in the field. However, this step is still very important for future research.

As the technology develops and people become more familiar with the project, it will become much more feasible to determine the weights of each criterion. In this way, quantitative assessments between technologies can give very clear comparisons. Similarly, the weighting of stakeholder groups would be very helpful in making final decisions from a systems perspective.

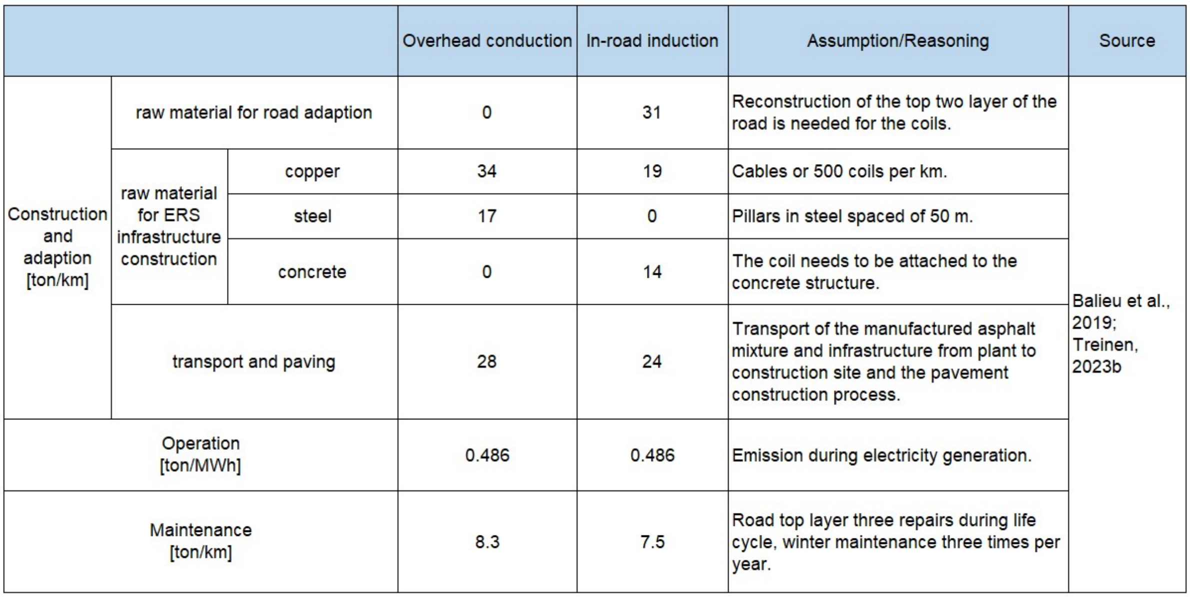
Finally, it is recommended that technological advances continue to be tracked, particularly in the case of in-road inductive technology. This is because the technology is currently in the dissemination phase. A lot of adjustments will be needed to reach the stabilisation stage. It is evolving at a very fast pace, for example, data such as energy capacity can also change several times during the time period of this study, and new concerns from stakeholder attitudes can arise. The results of the indicator calculations in this study are more of an intermediate result, contributing mainly to the pilot phase. In the future implementation, the indicators, especially the technical ones, will change considerably and require continuous attention at a high frequency.

A

Generic unit data on emission and cost

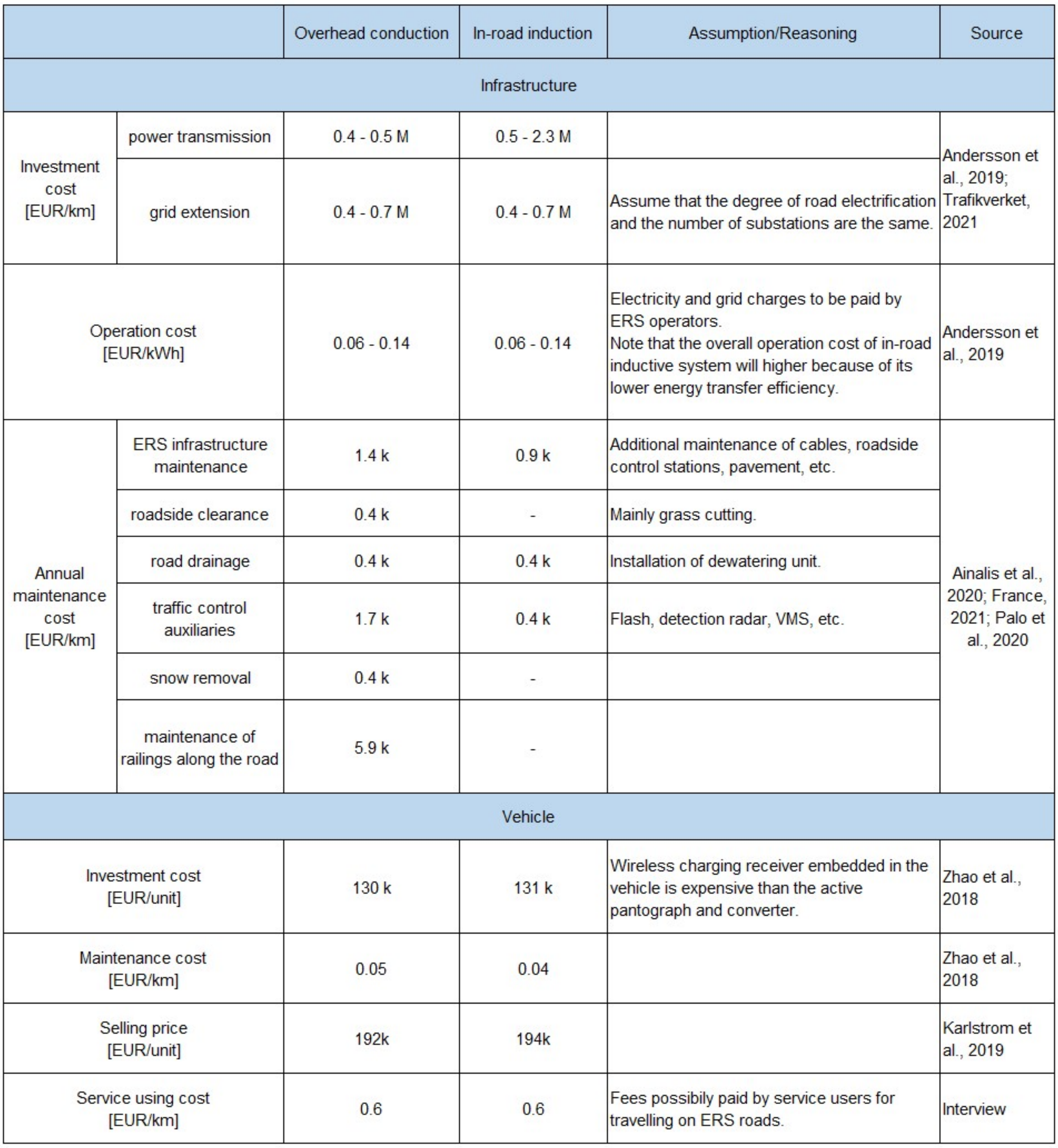
As one of the objectives of this study is to support future studies that may involve large-scale road networks, it is also important that the unit CO_2 emission and cost data is summarised. These more generic data can be directly applied to other studies.

Figure A.1 summarises the unit CO_2 emission parameters for both technologies. Figure A.2 summarises all the unit cost parameters used in this study in relation to investment, operation and maintenance of ERS infrastructure and vehicles.



			Overhead conduction	In-road induction	Assumption/Reasoning	Source
Construction and adaption [ton/km]	raw material for road adaption		0	31	Reconstruction of the top two layer of the road is needed for the coils.	Balieu et al., 2019; Treinen, 2023b
	raw material for ERS infrastructure construction	copper	34	19	Cables or 500 coils per km.	
		steel	17	0	Pillars in steel spaced of 50 m.	
		concrete	0	14	The coil needs to be attached to the concrete structure.	
	transport and paving		28	24	Transport of the manufactured asphalt mixture and infrastructure from plant to construction site and the pavement construction process.	
Operation [ton/MWh]			0.486	0.486	Emission during electricity generation.	
Maintenance [ton/km]			8.3	7.5	Road top layer three repairs during life cycle, winter maintenance three times per year.	

Figure A.1: Summary of unit CO_2 emission



		Overhead conduction	In-road induction	Assumption/Reasoning	Source
Infrastructure					
Investment cost [EUR/km]	power transmission	0.4 - 0.5 M	0.5 - 2.3 M		Andersson et al., 2019; Trafikverket, 2021
	grid extension	0.4 - 0.7 M	0.4 - 0.7 M	Assume that the degree of road electrification and the number of substations are the same.	
Operation cost [EUR/kWh]		0.06 - 0.14	0.06 - 0.14	Electricity and grid charges to be paid by ERS operators. Note that the overall operation cost of in-road inductive system will higher because of its lower energy transfer efficiency.	Andersson et al., 2019
Annual maintenance cost [EUR/km]	ERS infrastructure maintenance	1.4 k	0.9 k	Additional maintenance of cables, roadside control stations, pavement, etc.	Ainalis et al., 2020; France, 2021; Palo et al., 2020
	roadside clearance	0.4 k	-	Mainly grass cutting.	
	road drainage	0.4 k	0.4 k	Installation of dewatering unit.	
	traffic control auxiliaries	1.7 k	0.4 k	Flash, detection radar, VMS, etc.	
	snow removal	0.4 k	-		
	maintenance of railings along the road	5.9 k	-		
Vehicle					
Investment cost [EUR/unit]		130 k	131 k	Wireless charging receiver embedded in the vehicle is expensive than the active pantograph and converter.	Zhao et al., 2018
Maintenance cost [EUR/km]		0.05	0.04		Zhao et al., 2018
Selling price [EUR/unit]		192k	194k		Karlstrom et al., 2019
Service using cost [EUR/km]		0.6	0.6	Fees possibily paid by service users for travelling on ERS roads.	Interview

Figure A.2: Summary of unit cost

Bibliography

Ainalis, D., Thorne, C., & Cebon, D. (2020). Decarbonising the uk's long-haul road freight at minimum economic cost. *Centre for Sustainable Road Freight, White Paper CUED/C-SRF/TR17*.

Ajanovic, A., & Haas, R. (2019). On the environmental benignity of electric vehicles. *Journal of sustainable development of energy, water and environment systems*, *7*(3), 416–431.

Almestrand Linné, P. (2020). Standardisation of electric road systems: Report from workshop at firm19.

Andersson, L., Skallefell, P., Skjutar, K., & Arfwidsson, V. (2019). Business models and financing for the development of electric roads in sweden. https://api.semanticscholar.org/CorpusID:211733570

Aronietis, R., & Vanelslander, T. (2023). Economic impacts of the catenary electric road system implementation in flanders. *International Journal of Sustainable Transportation*, 1–16.

Ayodele, B. V., & Mustapa, S. I. (2020). Life cycle cost assessment of electric vehicles: A review and bibliometric analysis. *Sustainability*, *12*(6), 2387.

Balieu, R., Chen, F., & Kringos, N. (2019). Life cycle sustainability assessment of electrified road systems. *Road Materials and Pavement Design*, *20*(sup1), S19–S33.

Bateman, D., Leal, D., Reeves, S., Emre, M., Stark, L., Ognissanto, F., Myers, R., & Lamb, M. (2018). *Electric road systems: A solution for the future?*

Bernecker, T., Speiser, J., Engwall, M., Hasselgren, B., Helms, H., & Widegren, F. (2020). *Business models, ownership, and financing strategies: Implications of an introduction of electric road systems on markets and possible business models*.

Buysse, C., & Miller, J. (2021). Transport could burn up the eu's entire carbon budget.

Chi, S., & Bunker, J. (2021). An australian perspective on real-life cost-benefit analysis and assessment frameworks for transport infrastructure investments. *Research in transportation economics*, *88*, 100946.

Choi, S. Y., Gu, B. W., Jeong, S. Y., & Rim, C. T. (2014). Advances in wireless power transfer systems for roadway-powered electric vehicles. *IEEE Journal of emerging and selected topics in power electronics*, *3*(1), 18–36.

Cibean, T. (2022). First us road that charges electric vehicles while they drive will be ready next year.

CollERS. (2023). European electric road system symposium in berlin. https://electric-road-systems.eu/e-r-systems/news/news-items/European-Electric-Road-Systems-Symposium-in-Berlin.php

Commons, W. (2022). File:tecnology life cycle.png — wikimedia commons, the free media repository [[Online; accessed 9-June-2023]]. %5Curl%7Bhttps://commons.wikimedia.org/w/index.php?title=File:Tecnology_Life_Cycle.png&oldid=719223633%7D

David, R., Dube, A., & Ngulube, P. (2013). A cost-benefit analysis of document management strategies used at a financial institution in zimbabwe: A case study. *South African Journal of Information Management*, *15*(2), 1–10.

Davis, J., Nathan, L. P., et al. (2015). Value sensitive design: Applications, adaptations, and critiques. *Handbook of ethics, values, and technological design: Sources, theory, values and application domains*, 11–40.

de Treinen, R. (2023a). Train disruptions archive.

de Treinen, R. (2023b). Train disruptions archive.

Federal Ministry for the Environment, N. C., & Safety, N. (2018). Electric trucks are ready for practical testing. https://www.bmuv.de/pressemitteilung/florian-pronold-elektro-lkws-sind-reif-fuer-den-praxistest/

Fitri, N., Khamis, N., Koetniyom, S., Solah, M., Johari, M., Jawi, Z., Kassim, K. A., & Mansor, M. (2021). Cost-benefit analysis of autonomous emergency braking (aeb) system for pedestrian: A review. *Journal of the Society of Automotive Engineers Malaysia*, *5*(1), 57–63.

France. (2021). Electric road system (ers), working group n°2, technical solutions, potential and obstacles.

Göhlich, D., Nagel, K., Syré, A. M., Grahle, A., Martins-Turner, K., Ewert, R., Miranda Jahn, R., & Jefferies, D. (2021). Integrated approach for the assessment of strategies for the decarbonization of urban traffic. *Sustainability*, *13*(2). https://doi.org/10.3390/su13020839

Grunwald, A. (2009). Technology assessment: Concepts and methods. In *Philosophy of technology and engineering sciences* (pp. 1103–1146). Elsevier.

Gustavsson, M. G., Hacker, F., & Helms, H. (2019a). Overview of ers concepts and complementary technologies.

Gustavsson, M. G., Hacker, F., & Helms, H. (2019b). Overview of ers concepts and complementary technologies.

Hoogmartens, R., Van Passel, S., Van Acker, K., & Dubois, M. (2014). Bridging the gap between lca, lcc and cba as sustainability assessment tools. *Environmental Impact Assessment Review*, *48*, 27–33.

ICT, V. S. (2013). Slide-in electric road system. http://www.diva-portal.org/smash/get/diva2:1131846/FULLTEXT02.pdf

IEA. (2021). Prospects for electric vehicle deployment. https://www.iea.org/reports/global-ev-outlook-2021/prospects-for-electric-vehicle-deployment

Ilgin, M. A., & Gupta, S. M. (2010). Environmentally conscious manufacturing and product recovery (ecmpro): A review of the state of the art. *Journal of environmental management*, *91*(3), 563–591.

Jelica, D., Taljegard, M., Thorson, L., & Johnsson, F. (2018). Hourly electricity demand from an electric road system–a swedish case study. *Applied energy*, *228*, 141–148.

Jeswani, H. K., Azapagic, A., Schepelmann, P., & Ritthoff, M. (2010). Options for broadening and deepening the lca approaches. *Journal of Cleaner Production*, *18*(2), 120–127.

Johnsson, F., Taljegård, M., Olofsson, J., von Bonin, M., & Gerhardt, N. (2020a). Electricity supply to electric road systems: Impacts on the energy system and environment.

Johnsson, F., Taljegård, M., Olofsson, J., von Bonin, M., & Gerhardt, N. (2020b). Electricity supply to electric road systems: Impacts on the energy system and environment.

Jöhrens, J., Helms, H., Lambrecht, U., Spathelf, F., Mottschall, M., Hacker, F., Jelica, D., Alfredsson, H., Gustavsson, M. G., Nebauer, G., et al. (2021). Connecting countries by electric roads: Methodology for feasibility analysis of a transnational ers corridor.

Karlström, M., Pohl, H., Grauers, A., & Holmberg, E. (2019). Fuel cells for heavy duty trucks 2030+? https://doi.org/10.13140/RG.2.2.13814.37441

Lehmann, M. (2023). European electric road systems' symposium in berlin. %5Curl%7Bhttps://electric-road-systems.eu/e-r-systems/news/news-items/European-Electric-Road-Systems-Symposium-in-Berlin.php#:~:text=14%5C%20%5C%26%5C%2015%5C%20February%5C%2C%5C%202023%5C%20in%5C%20Berlin%5C%2C%5C%20Germany.,is%5C%20Fraunhofer%5C%20ENIQ%5C%2C%5C%20EUREF%5C%20Campus%5C%2023%5C%2F24%5C%2C%5C%2010829%5C%20Berlin.%7D

Macharis, C., De Witte, A., & Ampe, J. (2009). The multi-actor, multi-criteria analysis methodology (mamca) for the evaluation of transport projects: Theory and practice. *Journal of Advanced transportation*, *43*(2), 183–202.

Mankins, J. C., et al. (1995). Technology readiness levels. *White Paper, April*, *6*(1995), 1995.

Motuzienė, V., Čiuprinskas, K., Rogoža, A., & Lapinskienė, V. (2022). A review of the life cycle analysis results for different energy conversion technologies. *Energies*, *15*(22), 8488.

Muelaner, J. (2020). A solution for electric vehicle range and critical metal shortages.

Nordin, L., McGarvey, T., & Ghafoori, E. (2020). Electric road systems: Impact on road construction, maintenance and operations.

of Rotterdam, P. (2023). Road transport. https://www.portofrotterdam.com/en/logistics/connections/intermodal-transportation/road-transport#SnippetTab

Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on lca. *Construction and building materials*, *23*(1), 28–39.

Qiu, K., Ribberink, H., & Entchev, E. (2022). Economic feasibility of electrified highways for heavy-duty electric trucks. *Applied Energy*, *326*, 119935.

Rezaei, J. (2016). Best-worst multi-criteria decision-making method: Some properties and a linear model. *Omega*, *64*, 126–130.

Rijksoverheid. (2021). Verkenning electric road systems. https://open.overheid.nl/documenten/ronl-850ffb2c-44a7-4122-9173-0c04c4e64bf6/pdf

Rijkswaterstaat. (2022). Intensiteit wegvakken (inweva) 2022. %5Curl%7Bhttps://maps.rijkswaterstaat.nl/dataregister/srv/eng/catalog.search#/metadata/f58eacc9-ca69-487a-a53b-11efad0bbbd1?tab=relations%7D

Rip, A. (2001). Technology assessment. In N. J. Smelser & P. B. Baltes (Eds.), *International encyclopedia of the social behavioral sciences* (pp. 15512–15515). Pergamon. https://doi.org/https://doi.org/10.1016/B0-08-043076-7/03172-7

Schutte, N., Tavasszy, L., Bombelli, A., & Rezaei, J. (2022). A value-focused approach for the design of innovative logistics concepts: The case of off-peak pickup and delivery in the air cargo industry. *Advances in Best-Worst Method: Proceedings of the Second International Workshop on Best-Worst Method (BWM2021)*, 110–129.

Shoman, W., Karlsson, S., & Yeh, S. (2022). Benefits of an electric road system for battery electric vehicles. *World Electric Vehicle Journal*, *13*(11), 197.

Song, Y., Zhang, M., Øiseth, O., & Rønnquist, A. (2022). Wind deflection analysis of railway catenary under crosswind based on nonlinear finite element model and wind tunnel test. *Mechanism and Machine Theory*, *168*, 104608.

Talantsev, A. (2017). Who gains and who loses in the shift to electric vehicles: Impact assessment through multi-criteria multi-stakeholder analysis. *Procedia Environmental Sciences*, *37*, 257–268.

Taljegard, M., Thorson, L., Odenberger, M., & Johnsson, F. (2017). Electric road systems in norway and sweden-impact on co 2 emissions and infrastructure cost. *2017 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific)*, 1–6.

TNO. (2023). The potential of e-fuels for heavy duty road transport in the netherlands.

Troldborg, M., Heslop, S., & Hough, R. L. (2014). Assessing the sustainability of renewable energy technologies using multi-criteria analysis: Suitability of approach for national-scale assessments and associated uncertainties. *Renewable and sustainable energy reviews*, *39*, 1173–1184.

Van de Poel, I. (2013). Translating values into design requirements. *Philosophy and engineering: Reflections on practice, principles and process*, 253–266.

van Infrastructuur en Waterstaat, M. (2022a). Wet vrachtwagenheffing. https://www.eerstekamer.nl/wetsvoorstel/35910_wet_vrachtwagenheffing

Widegren, F., Helms, H., Hacker, F., Andersson, M., Gnann, T., Eriksson, M., & Plötz, P. (2022). Ready to go? technology readiness and life-cycle emissions of electric road systems.

Xia, Y., Van Ommeren, J. N., Rietveld, P., & Verhagen, W. (2013). Railway infrastructure disturbances and train operator performance: The role of weather. *Transportation research part D: transport and environment*, *18*, 97–102.

Zhao, H., Wang, Q., Fulton, L., Jaller, M., & Burke, A. (2018). A comparison of zero-emission highway trucking technologies.

Zvolenskỳ, P., Leštinskỳ, L., Ďungel, J., & Grenčík, J. (2021). Pantograph impact on overall external noise of a railway vehicle. *Transportation Research Procedia*, *55*, 661–666.