Carbon Neutral Road Transportation

An Assessment of the Potential of Electrified Road Systems

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Abstract

Sweden is striving towards a carbon neutral transportation sector by 2030 which includes reductions from CO\textsubscript{2} emissions by 70\%. This thesis focusses especially on the decarbonization of road freight transportation. Even though electrification of vehicles is seen as one of the available options to reach this goal, present battery technology does not meet requirements of energy density and cost.

The electrification of roads with electrified road systems (ERS) enables vehicles to charge electrical energy while in motion and has the potential to reduce weight and costs of on-board batteries for electric vehicles and avoids range anxiety of vehicle operators.

Within this Master’s thesis, available ERSs are assessed and it is shown which of the available systems performs best in selected categories. Furthermore, alternative options for large CO\textsubscript{2} emission reductions in the road transportation sector are evaluated and it is shown that ERSs constitute the most promising alternative.

Results of this dissertation are based on a qualitative research approach and limited to data availability.
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Chapter 1

Introduction

1.1 Background and problem description

Sweden is striving towards a carbon neutral transportation sector by 2030 which includes a reduction of CO$_2$ emissions of the vehicle fleet by 70% [Regeringskansliet, 2015] [Interviewpartner D, 2017]. Since the transportation sector depends on fossil fuels by 87% [Nykvist et al., 2016] and should remain reliable, time and cost efficient, this goal constitutes a challenge.

Especially the decarbonization of heavy-duty vehicles is on focus as this sector increased its greenhouse gas (GHG) emissions between 1990 and 2011 by 44%, while the passenger vehicle sector could reduce its GHG emissions in the same time despite growing traffic [Regeringskansliet, 2014]. Considering the goal of a CO$_2$ reduction by 70%, means of road transportation have to become more or less independent from fossil fuels.

Consequently, vehicle manufacturers are developing alternative propulsion systems and refine internal combustion engines (ICE) to enable them using alternative fuels which emit lower amounts of CO$_2$. Though, most of these alternative propulsion methods decrease emissions, not all of them have the potential to contribute to the required CO$_2$ savings by 2030. An increased share of biofuel for example may reduce the CO$_2$ emission during production of the fuel but not necessarily during combustion in the vehicle engines [Wallington et al., 2016]. Hybrid battery electric vehicles (HBEV) and plug-in hybrids (PHEV) which are using classic ICEs and an electric propulsion system do not decrease the GHG-emissions sufficiently enough. Solely, electric vehicles (EV) have a zero emission potential and would be
able to decarbonize road transportation. Unfortunately, present energy density of EV batteries is not sufficient to run heavy trucks in an economic feasible manner over long distances [den Boer et al., 2013].

Despite this, the electrification of road freight transportation vehicles seems to have the potential of large GHG reduction [den Boer et al., 2013]. Hence, electrified road systems (ERS) which enable a dynamic power transfer between road and electric or hybrid vehicle move into focus. With the implementation of ERSs on strategically chosen roads in Sweden, the on-board battery’s size can be decreased while the range of the vehicle is increased. While driving on the electrified road, the vehicle receives energy from the ERS and uses a secondary propulsion system when driving outside the system.

Even though, ERSs are seen as a promising solution to reach a 70% reduction of CO$_2$ emissions, one can see in figure 1.1, how strong the use of fossil fuels in the Swedish road transportation sector has to decline, in order to meet this goal, which can also be seen as a milestone to reach a 100% reduction of CO$_2$ emission by 2050. The historic development of fossil energy is represented by the black line, while the gray line shows the development, if fossil fuels are used as in 2014 but road traffic develops, as forecasted by the Swedish Road Administration (Trafikverket). Decisions, made by the government until 2014 on instruments and measures to reduce fossil fuel use are represented by the yellow line whereas the green line shows, how the fossil fuel actually has to develop to meet the agreed targets [Johansson and Eklöf, 2014].
1.2 Research Question

In this thesis, ERSs are considered as an option to decarbonize the transportation sector accordingly. Several suppliers are developing systems with specific characteristics. Through this, the overarching research question of this thesis is derived: Which of the available ERSs has the strongest potential on decarbonizing the road transportation sector through a large scale implementation in an economic and environmental feasible manner in Sweden by 2030 and are ERSs indeed the best possible solution to reach this aim?

1.3 Aims and Objectives

The aim of this thesis is to identify the ERS with the strongest potential to meet the goal of carbon neutral road transportation in Sweden by 2030.
Furthermore, this report aims to investigate the potential of other CO₂ reduction options. The objectives are:

- To explore available CO₂ emission reduction options in the road transportation sector.
- To make a sound recommendation on which solution has the biggest potential to decarbonize the road freight transportation sector accordingly.
- To assess key ERSs regarding relevant characteristics.
- To determine the ERS that performs best within the assessment of the relevant characteristics.
- To examine the technological maturity of the assessed ERS systems.
Chapter 2

Background

2.1 The Case of Electric Propulsion

2.1.1 Battery Dilemma

Hybrid passenger vehicles with a small on-board battery, electric plug-in option, or rather a full electric propulsion system can be found in the portfolio of most established car manufacturers. Light commercial vehicles as the Nissan e-NV 200 on the other hand are not often represented and light distribution trucks as the Fuso Canter E-Cell with a potential gross vehicle weight (GVW) of 12.5t are even less available and often only in small series. Heavy trucks with a GVW of more than 18t are currently in planning, as for example Mercedes-Benz Urban eTruck and MAN’s electric TGM series but will not be produced in large series in near future either. This may be due to the weight and cost of the required battery pack as the following paragraph shows.

Battery weight

Den Boer et al. [2013] indicate that a long haulage truck with a GVW of 40t has an energy consumption of 2 kWh/km. If the used Lithium-ion (Li-ion) battery has an energy density of 0.1kWh/kg, which refers to the historical energy density of a Li-ion battery, the total battery weight of the truck would be 25t to enable a driving range of 1,000 km. Table 2.1 shows the energy carrier weight for different range applications of den Boer’s et al. (2013) model, adapted to present, available battery technology with an energy density of 160Wh/kg [Thielmann et al., 2015]. The weight of the energy carrier is calculated as follows in equation 2.1:
Energy Carrier Weight = $\frac{\text{Energy Consumption} \times \text{Range}}{\text{Energy Density}}$ (2.1)

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<tr>
<td>Energy Density [kWh/kg]</td>
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<tr>
<td>Energy carrier weight [kg]</td>
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Though, the energy density of batteries has been increased since 2010 and a driving range of 1,000km might neither be necessary nor possible, considering speed limits and mandatory breaks for the driver, it is clear that EV for the transport of heavy freights over long distances are not a viable option with present battery technology.

**Battery cost**

The New Energy and Industrial Technology Organizaiton (NEDO) in Japan estimated costs of 300EUR/kWh in 2015 for Li-ion batteries that are used in EVs and PHEVs [Thielmann et al., 2015]. Table 2.2 shows the estimated costs of the energy carrier for den Boer’s et al. (2013) model. The calculation of the energy carrier’s cost is shown in equation 2.2.

\[
\text{Energy Carrier Cost} = \text{Energy Consumption} \times \text{Range} \times \frac{EUR}{kWh} \quad (2.2)
\]

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<td>Energy Storage [kWh]</td>
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<td>800</td>
<td>1,200</td>
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<tr>
<td>Cost of energy carrier [EUR]</td>
<td>120,000</td>
<td>240,000</td>
<td>360,000</td>
<td>480,000</td>
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2.2 Introduction of ERS

2.2.1 Definition

Electrified road systems (ERS) enable adapted EVs to be charged with electrical energy while in motion [ICT, 2013a]. Thus, their range could be tremendously extended and battery sizes decreased [Singh, 2016]. If the energy for such a system is obtained by fossil free electrical energy sources, transportation with ERS can be carried out nearly GHG-emission free [Wang and Mompo, 2014]. Therefore, ERSs have to be considered as a viable option to achieve Sweden’s goal of a carbon neutral transportation system by 2030.

Siemens [2012] formulated in one of their press releases the necessity of three elements in their ERS: the energy supply which is provided by the ERS, the car’s current collector and hybrid drive technology to drive outside the system. As all ERSs function according to the same principle, all road vehicles can drive on electrified roads, if above mentioned three elements are available. With the implementation of this technology on strategic chosen roads in Sweden, the country could become accessible for electric vehicles without the necessity for them to stop for charging [Singh, 2016].

2.2.2 Available ERS

In an ERS, electrical power is either transmitted by conductive or inductive energy transfer. In the case of conductive energy transfer, the power transmission is either based on rails which are implemented in the road or on overhead catenary lines. The transfer of energy through induction happens through charging devices which are implemented in the road. Consequently, energy transmission to a vehicle comes from under or above the vehicle.

Transmitting electrical energy in an ERS via conduction requires a physical connection between the vehicle and the conductor in the overhead catenary line or in the rail in the road. This current collector is also called pick-up. Due to changing road and traffic conditions, the pick-up has to be active. Not only to enable a flexible and automatic connection and disconnection but also to minimize wear and tear of the system [Siemens, 2012a].

Inductive charging systems transfer electrical energy wireless. A conductor in the road generates a magnetic field as in the primary coil of a trans-
former. The secondary coil is implemented in the bottom of the vehicle and converts the magnetic field into current that fuels the vehicle’s propulsion system. Thus, it serves as the pick-up of the vehicle. [ICT, 2013a]

2.3 Research and Development Projects on ERS

2.3.1 Conductive ERS Projects and Test Tracks

Elways, Sweden

The swedish based ERS supplier Elways AB developed an in-road conductive charging system. A rail which holds the electricity line on its bottom is installed in the road. An EV can connect to the ERS through a moveable arm that is adjusted underneath the car and slides through the rail [Elways, 2011b]. Elways AB which is also part of a project from the Swedish Road Administration, Trafikverket, receives financial funding through Energimyndigheten, the Swedish Energy Agency. Furthermore, a research cooperation with the Royal Institute of Technology (KTH) exists and NCC, a road-building contractor, develops methods for an efficiently installation of the rails in the road. The real state investment company Arlanda Stad Holding agreed with Elways on a cooperation regarding a road test track with vehicles [Elways, 2011a]. On a 2 km section of a road between the Arlanda Cargo Terminal and Roserberg’s logistics area will be electrified. The overall goal of this track is to develop and evaluate the technology and create more knowledge on the implementation of ERS in Sweden. Constructions will begin in autumn 2017 [eRoadArlanda, 2017].

Elonroad, Sweden

Another swedish based company, Elonroad works on the development of ERS. The difference between Elonroad and Elways is that Elonroad installs the electric contact on the surface of the road and the current collector of the car slides on it. The system protrudes over the road [Sundelin et al., 2016]. With fundings from the Swedish Energy Department, additional support from the energy company Kraftringen AB, the vehicle manufacturer Coach Manufacturing Sweden AB and the innovation platform Future by Lund, Elonroad is planning on the construction of a 200m long test track outside Lund by the summer of 2017 [Elonroad, nd].
Alstom/ Volvo, International

Due to a collaborative project with the truck manufacturer Volvo, the French rail transport company Alstom has extended the usability of its conductive APS-Ground-level Power Supply technology for road vehicles. Previously, this system has only been in use to electrify trams. APS-Ground Level Power Supply electrifies vehicles through rails that are implemented in the road. In comparison to the Elways system, the Alstom rails don’t require a slot in the rail where the current collector connects to the power supply. Much more, the current collector slides on the rail. [Alstom, 2015]

Since 2012, the system is tested on a facility in Hällered, Sweden which is operated by AB Volvo. A 435m long track, with a 275m electrified section, is used for the development of the electric road technology [Fabric, ndc].

Siemens, International

A conductive ERS that supports electrical power transfer through overhead catenary lines is provided by the German conglomerate company Siemens. The so called eHighway is already in operation on a test track outside Berlin in Germany since 2010 [Siemens, 2012a]. Furthermore, Siemens operates a demonstration project in Gävle, Sweden since 2016 [Sundelin et al., 2016], where a 2km stretch of a highway is electrified. The Swedish Transport Administration awarded the contract for this project [Siemens, 2016a]. A second demonstration project is planned in California, USA where a 2 mile stretch of a road that connects the ports of Los Angeles and Long Beach will be installed. The contract was awarded to Siemens by the Southern California’s South Coast Air Quality Management District (SCAQMD) [Siemens, 2016a]. Due to unplanned delays, the demonstration track in the United States will start operation within 2017 [Interviewpartner A, 2017]. Siemens is working on its ERS in cooperation with the truck manufacturers Scania and AB Volvo’s subsidiary brand Mack Trucks [Siemens, 2016a].

2.3.2 Inductive ERS Projects and Test Tracks

Bombardier, International

The Canadian transportation company refined their Primove technology to enable inductive power transfer to road vehicles. Previously, it has been mainly in use to charge electric trams [Bombardier, 2012]. With support by governmental institutions and cooperations within the electric vehicle and energy industry, Bombardier uses its Primove technology for static en-route
charging of electric busses on certain routes in Berlin and Braunschweig, Germany, in Bruges, Belgium and in Södertälje, Sweden [Bombardier 2014, 2015, 2016 and nd].

Even though this may refer to all ERSs, Interviewpartner E [2017] states that the passenger car industry is primarily looking for ways to stationary charge cars without using a plug which could be the reason, why Bombardier closed a deal with a yet not published automobile manufacturer which enables them to implement their technology in private cars [Bombardier, 2015a].

**CIRCE, International**

The Research Centre for Energy Resources and Consumption (CIRCE) in Zaragoza, Spain developed an inductive power transfer system to charge vehicles while in motion or at rest. Within the European Union (EU) project, Unplugged, a demonstration system has been implemented on a 27km long bus route in Florence, Italy. A second system has been implemented on a 100m long bus track in Malaga, Spain under the umbrella of the project Viktoria. [CIRCE, 2015]

**FABRIC, International**

The project FABRIC (Feasibility analysis and development of on-road charging solutions for future electric vehicles) which is supported and co-funded by the EU, works on the large-scale deployment of EVs. Therefore, FABRIC is investigating within a feasibility analysis and technology development the potential of on-road charging solutions [Fabric, ndd] on test tracks in Hällered, Sweden, Satory, France and Torino, Italy [Fabric, ndc] [Fabric, nda] [Fabric, ndb]. Partners of the project can be seen in Annex 1.

**Korea Advanced Institute of Science and Technology (KAIST), South Korea**

The institute introduced their own development, Shaped Magnetic Field in Resonance (SMFIR), a technology that enables the wireless transfer of electrical energy. It is used in combination with another of KAIST’s developments, the online electric vehicle (OLEV) to transport passengers in shuttle buses at KAIST campus since 2012 [KAIST, 2013] and in the city of Gumi, on a 24km inner-city route, since 2013 in South Korea [Kelion, 2013]. As the shuttle busses are carrying a small on-board battery, it has been proved to be sufficient that the roads contain only a few sections with the SMFIR.
technology to run the busses without the need to stop them for charging. [KAIST, 2013]

2.3.3 Other Projects on ERS

Field Test on Highway, Germany

The Federal Environment Ministry of Germany announced that it funds the construction of an overhead catenary line system in the state of Schleswig-Holstein which borders with Denmark. Within this field test, a section of 6km on the highway A1 will be electrified on lanes in both directions. With a financial support of EUR 14 million the engaged ERS supplier is supposed to start operation of the system until the end of 2018 [BMUB, 2017]. This project will be commercially used by regional transport service providers and is intended to prove the reduced environmental impact of such a system in comparison to conventional transportation as well as the compatibility of the system with regard to everyday usage [Interviewpartner A, 2017].

First Electric Road System Conference, Sweden

In June 2017, the first ERS conference has been held in Sandviken, Sweden, organised by the Swedish research and innovation platform for electric roads. The aim of the conference was to attract international representatives and stakeholder from the ERS industrie to discuss new findings and form new collaborations amongst the members [Conference, 2017].

International Cooperation, Germany and Sweden

During their meeting, in January 2017, the german chancellor Angela Merkel and the swedish prime minister Stefan Löfven initiated a new innovation partnership between the two countries. Amongst others, a joint study on the electrification of roads that includes financing, business and operation aspects has been planned [Hjalmarson, 2017].

SINTEF, Norway

Statens vegvesen, the norwegian public road administration expects an increase by 65 percent of freight transport in Norway parallel to the governments goal of becoming climate neutral by 2050. Thus, in 2016, the R&D project ELinGo has been started with the objective of analysing the electrification of heavy freight transport. The research company SINTEF is manag-
ing the project and investigates the three core technologies [SINTEF, 2016]. Project partners can be seen in Annex 1.

**Transport Research Laboratory, United Kingdom**

The Transport Research Laboratory has executed a project in 2015 to prepare the United Kingdom’s strategic road network for electric vehicles. Within this project, vehicles and test tracks have been fitted with technology and testing equipment to investigate the potential of wireless charging of electric vehicles. Furthermore, Highways England has announced to expand their system of plug-in charging points as part of their road investment strategy [England, 2013].

**Utah State University, USA**

The Sustainable Electrified Transportation Center (SELECT), has been opened at Utah State University in 2016. This multi-university research center, which is partnered by further universities (see Annex) brings members of the electrified transportation industry and researchers together. Industry representatives get a first look at new technologies and the opportunity to transition them to the marketplace. Furthermore, the facility operates a test track for dynamic charging through induction. [SELECT, 2016]

### 2.4 Similar Thesis Work

#### 2.4.1 Electric Road Systems for Trucks

Within their Master’s thesis, Andersson and Edfeldt [2013] examined the potential of ERSs to electrify trucks in Sweden. A comparison of an ERS-hybrid, hybrid and conventional vehicle in regard to their kilometer-based energy usage, CO$_2$ emission and cost has been carried out. These characteristics have been investigated through different cases, a distribution case, a long-haulage case and a mining case. Furthermore, different scenarios regarding energy and infrastructure costs have been considered. An overhead catenary system with expected costs of 10,000,000SEK/km and additional 5,000,000SEK/km for the adjustment of the power grid is assumed [Andersson and Edfeldt, 2013].

It is concluded that the energy usage is decreased in all three cases which leads to a reduction of CO$_2$ emission up to 77.7% in the long haulage case
due to the rather clean electricity production in Sweden. In addition, the system is profitable in four out of five scenarios in the long haulage case and therefore shows a great potential regarding a feasible way of large CO₂ emission reduction [Andersson and Edfeldt, 2013].

2.4.2 Electric Road Systems - A feasibility study investigating a possible future of road transportation

Singh [2016] compared three proven ERS technologies, the inductive Prime move system from Bombardier, the conductive overhead system eHighway from Siemens and the conductive roadbound ERS Elways from an environmental and economic perspective. Basis of the economic comparison are costs of 15MSEK/km, 6MSEK/km and 4MSEK/km respectively.

If considering future battery pricing, all three ERSs are expected to result in savings. Though, the Elways system will offer the largest savings followed by Siemens’ eHighway. In addition, Singh [Singh, 2016] shows that the likelihood of an ERS implementation correlates with a decreasing share of EVs.
Chapter 3

Methodology and Thesis Approach

3.1 Methodology

General

As this thesis project has been tendered by the Stockholm Environment Institute (SEI), the first step has been a discussion between the supervisor from SEI and the author of this thesis. Thus, a suitable framework has been created which covers on the one hand objectives that will contribute to SEI’s research and on the other hand covers the authors interests. Following, a suitable supervisor from the author’s university, the Royal Institute of Technology in Stockholm (KTH) has been found to ensure the academic purpose of this thesis. As a research cooperation has been aimed between SEI and the supervisor’s department from KTH, the Integrated Transport Research Lab (ITRL), their interests have been included in the thesis’ framework as well.

The first part was to assess available literature in order to gain an overview of the field of ERSs. Through this, it became clear that next to a more comprehensive literature review, also interviews with experts have to be conducted to find the necessary data to reach the aim of the thesis.

Order of the Results

Presenting the results in a useful chronological order, a step by step plan from the Swedish Transport Administration has been adopted. This plan
consists of four principles to evaluate requests from external stakeholders. In consultation with Interviewpartner D [Appendix B.5], this approach can be applied to the goal of decarbonization and mirrors the order of the presented results. The principles are:

1. Rethink
2. Optimize
3. Rebuild
4. Build new

Assuming the request of a decarbonized road transportation sector, the principle *Rethink* can be interpreted as a change of transportation strategy. As it is not expected that alternative means of transportation will be able to substitute road freight transportation, this part solely consists of general information and state of the art knowledge about the Swedish road transportation, its development and characteristics. Following, the principle *Optimize* is referred to the implementation of new propulsion methods to reduce carbon emissions. Finally, the assessment of ERSs is introduced and accordingly refers to the principle *Rebuild*. In the context of this thesis, to rebuild a system relates to the addition of new functions of a consisting infrastructure, as for example dynamical charging options for road vehicles. The fourth principle, *Build new* may refer to a completely new mean of transportation that requires major investments in infrastructure and construction measures as for example a hyper loop as presented by Elon Musk. Nonetheless, such a system offers new opportunities, the fourth principle is not considerd in this thesis work.

**Literature Review**

A literature review was conducted to gain an overview of the topic and to collect data to be able meeting the objectives. Relevant literature has been found through KTH’s library online searching tool. This tool is based on keyword search and shows matching reports, articles, thesis etc either from KTH’s own database or other scientific and academic databases. Literature found through this searching tool has been peer reviewed and complies with academic standards.

Not all of the required and gathered data could be found through this tool. Especially, data about certain characteristics of ERS, current ERS and vehicle projects could only be found at the respective institutional or
company’s website. Therefore, these sources of literature have been critically evaluated before usage within this thesis.

**Expert Interviews**

Following the literature review, the author realized that not all of the required data for this thesis’ purpose is published and has to be completed through interviews with experts. This applied especially for test results of ERSs which have been written directly by the ERS supplier. Those reports were often lacking references and required background information. Thus, informants have been found either through academic or business connections of the author’s supervisor or through correspondence via email with respective institutions and companies.

Interview partners are company representatives or work in prominent positions in the development of ERSs. Furthermore, interviews were conducted with researchers at universities and research institutions but also with representatives at transportation institutions of the Swedish government.

Whenever it has been possible, the interviews were conducted in person. Due to large spatial separation, three interviews have been carried out on the phone. Interview partners were informed that their names will be anonymized within this thesis to gather unbiased information. Nonetheless, it has to be considered that company representatives still might have certain motivations with their replies to the interviewer’s question. Therefore, gathered information has been evaluated carefully before implementation in this thesis.

Furthermore, the interviewer made notes of the interviewed person’s statements and presented the notes afterwards for cross-checking to the interview partner. If the interview partner confirmed the interviewer’s notes regarding its correctness, the acquired data has been used in according sections of this thesis and the interview notes were attached to the thesis’ appendix.

**Characteristics of ERS**

The individual performance of key ERSs in chapter 4.4 is investigated with the help of several criteria. Those characteristics have been developed by the author after evaluation of the collected data during the literature review and conducted interviews to match the research question in this thesis and
are presented in table 3.1. The characteristics were also updated after initial literature review and interviews and related to evaluation criteria.

Table 3.1: Characteristics of ERSs and their Evaluation Criteria

<table>
<thead>
<tr>
<th>Introduction</th>
<th>Functional principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Measures</td>
<td>Road structure, required infrastructure</td>
</tr>
<tr>
<td>Efficiency</td>
<td>ERS to vehicle, efficiency of components, global efficiency</td>
</tr>
<tr>
<td>Cost</td>
<td>Cost per kilometer of ERS, cost for energy supply</td>
</tr>
<tr>
<td>Safety</td>
<td>Safety hazards</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Maintenance cost, maintenance issues, wear and tear</td>
</tr>
<tr>
<td>Vehicle</td>
<td>Cost of ERS components, weight of ERS components</td>
</tr>
</tbody>
</table>

This thesis is based on qualitative research. Due to many uncertainties, a sound quantification of the gathered qualitative data turned out to be not defensible. Nonetheless, a valuation within the examined characteristics has been carried out, if collected data allowed a reasonable and sound comparison. Therefore, an evaluation system has been developed to classify the different ERSs within the assessed characteristics which can be seen in table 3.2. Here presented classification values serve the purpose to be able comparing each ERS regarding its characteristics relatively to other ERSs. Collected information on the characteristics of an ERS is either rated as better (+), equal (o) or worse (-) compared to another ERS.

Table 3.2: Means of Comparison

<table>
<thead>
<tr>
<th>Better</th>
<th>Equal</th>
<th>Worse</th>
<th>No comparison possible</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>o</td>
<td>-</td>
<td>/</td>
</tr>
</tbody>
</table>
Also the technological maturity of single ERSs plays a role. The tool Technological Readiness Level (TRL), adapted to the purpose of ERSs by Tongur and Sundelin [2016], has been updated by the author with latest data and information, gathered by the time of the drafting of this thesis. It has to be considered that the classification of ERS characteristics serves the purpose to compare single qualities but not the ERS as a whole, while TRL does evaluate the ERS as a whole. Hence, TRL gives an excellent overview about the maturity of an ERS. Nonetheless it is not part of the classification process due to the fact that this thesis focusses on properties and potential of different systems, while further development is expected and should be given more time, before decision maker will choose a system for large scale implementation.

3.2 Limitations, Boundaries and Assumptions

Assumptions

- In this thesis presented ERSs are the ones that are most likely to be implemented on large scale.

- It is assumed that only one of the evaluated ERSs will be chosen for implementation.

- Electrical energy will be produced from renewable sources.

- Sweden is able to fund the large scale implementation of an ERS and required additional power plants.

- Biofuels that have been evaluated for tailpipe emission have the same characteristics as biofuels used in the lifecycle assessments.

- Liquid biofuels are expected to have the biggest share in the biofuel consumption and production. Biogas is therefore not considered in this thesis.

- Operators will buy more environmental friendlier vehicle, if operating costs are lower.

- Battery swapping stations are assumed to be neither financial feasible nor time efficient and therefore not included in this thesis’ extent.
Limitations and Boundaries

Results of this thesis only refer to Sweden and should not be transferred to other countries. In addition, considered CO₂ emission saving options are chosen with regard to the goal of a 70% reduction by 2030. Thus, whenever possible, data and information has been considered that refers to Sweden or comparable countries of the European Union. Even though, the most environmental friendliest transportation option should be chosen, this report focusses on road freight transportation. A shift to railway transportation is not considered. The results are limited to data availability and uncertainties on respective ERs.
Chapter 4

Results

4.1 Road Transportation in Sweden

Despite growth in traffic, emissions by passenger vehicles in Sweden have decreased by 9% in 2011 compared to 1990. Emissions of heavy vehicles on the other hand have risen by 44% over the same period, which led to an increase in total road transport emissions by 4%. This is due to an increase in transported goods over longer distances. Compared with CO$_2$ equiv. emissions in 1990, it is assumed that the transport sector’s emission will decline by 3% until 2030 because of more efficient means of transportation and optimized transportation strategies. Nonetheless, the assumed decline is not enough to meet the Swedish Government’s goal of an fossil fuel independent vehicle fleet by 2030. Therefore, ways to realise this goal have to be identified. [Regeringskansliet, 2014]

To further emphasize the major environmental impact of road transportation, figure 4.1 shows the development of CO$_2$ equiv. emissions in thousand tons from transportation sector. Though, this graph includes emissions from rail, water, air and military transportation, those impacts are rather minor and don’t influence the total emission as much as the road transportation sector. One can clearly see the correlation between emissions by road transportation and total emissions of means of transportation in Sweden. CO$_2$ equiv. emissions from road transportation decreased from 17,676 thousand tons in 1990 to 16,955 thousand tons in 2015. Emissions by road transportation decreased by 8.6% between 2011 and 2015.
4.1.1 Road Freight Transportation

In figure 4.2 one can see the development of road freight transportation from 2005 until 2015. It has to be considered that Trafikanalys introduced a new method for data acquisition. The new method does not debunk the earlier collected data but ensures a more precise acquisition of transportation data. The development of road freight transportation in tonkm in Sweden rose between 2005 and 2015 only slightly with a large drop in 2009 due to the world’s economic crisis. This also proves that the road freight transportation sector correlates with the economic situation as it is stated by Regeringskansliet in 2014.
Figure 4.2: Road freight transportation in tonkm [Trafikanalys, 2016b]

The average distance of single hauls by means of road freight transportation is shown in figure 4.3. Dark green columns represent the share of single hauls by distance in the years 2013 and 2014 while the light green columns represent the distance share in 2015. Though, a small shift towards shorter distances can be observed, the average distances of single hauls is quite balanced with two maxima in 2015 at 200-299km and 500-699km.
Figure 4.3: Development of road freight transportation in tonkm [Trafikanalys, 2016b]

Figure 4.4 shows the share of the vehicle combination that are used for road freight transport both the average from 2013 until 2014 and 2015. It is clear that the largest share of vehicle combinations have a GVW between 40 and 49.9 tons.
4.1.2 Passenger Vehicles

Though it can be seen that the total distance, driven by passenger vehicles in Sweden increased since 1999, the annual average driven distance per vehicle decreased which can be led back to an increased amount of passenger vehicles [Trafikanalys, 2017]. In 2016, the average distance driven by a passenger vehicle in Sweden accounts for 12,240km [Trafikanalys, 2017] which equals approximately 34km per day. Electrification is just one of many measures that have to be fulfilled to cope with climate ambitions within transportation sector. In order to reduce the daily driven distance of passenger vehicles, shifting from cars to bicycles and improving the public transport offer is also a considered option for decarbonisation [Interviewpartner E, 2017].
4.2 Possible CO$_2$ Reduction of Road Freight Transport

Out of 2.8 billion km on national and approximately 0.2 billion km on international roads that were driven by Swedish registered lorries in 2015, 17% were empty runs [Trafikanalys, 2016b]. Transportation of goods would become more efficient, if the amount of empty runs can be decreased.

If road freight transport vehicles are decreasing the distance between themself and the vehicle in front, they can make use of their slipstream and reduce air resistance which leads to a lower consumption of fuel. Such an effect can be attained with an approximate distance of 4.5m between vehicles at a speed of 80km/h and is referred to as platooning. Driving assistance systems are ensuring the safety of this method. Additionally, it has been observed that platooning will lead to an improved traffic flow as drivers are more likely to maintain a consistent speed [Trafikanalys, 2016a].

Automatization of vehicles has the potential to reduce the number of drivers or it will improve their capability as they will be enabled to dedicate their driving time to administrative tasks but on the other hand, it may increase the number of vehicles.

With an increase of the share of vehicles with the maximum allowed GVW of 60t, the cost per transported ton could be lowered. Increasing this share will not only lead to less vehicles on the road but also decrease road maintenance costs. Though, the vehicles are heavier, they also have more axles and optimize the weight distribution so that every axle carries less weight [Trafikanalys, 2016a].

The combination of platooning, longer vehicles and automatization could reduce external costs as emissions and wear and tear by 30%. Furthermore, operation costs of this combination will lead to a reduction of operating costs by 30% due to fewer drivers and fuel savings. Taking all costs into account, future platooning will save costs of about 25% compared with the current traditional road transport system [Trafikanalys, 2016a].

On the vehicle side, Siemens [2016b] expects an increase of energy efficiency of diesel trucks by, amongst others, hybridization, decrease of air resistance of the vehicle, decrease of rolling friction due to improved tyres
and their pressure surveillance, improvements of the combustion engines and reduction of the vehicle weight.

4.3 Alternative Propulsion

4.3.1 Biofuels

Regulations and concerns regarding, amongst others, energy scarcity and global warming [Wallington et al., 2016] and the ability of replacing fossil fuels in the road transportation sector [Zilberman and Timilsina, 2014] led to an increased use of biofuels on a global level. In 2009, the European union adopted a directive that requested its member states to use a minimum of 10% of biofuels in transportation fuel by 2020 which led to an increased consumption of especially biodiesel in the following years as can be seen in figure 4.5. However, Sweden already surpassed the goal of a 10% share of biofuels in transportation fuel [Nykvist et al., 2016] and the production of biofuels in Sweden increased between 2006 and 2012. Furthermore, figure 4.5 reveals that the demand for biofuels and especially biodiesel, which is represented by the green dotted line, can not be satisfied by local production, which is represented by the green line. Consequently, Sweden depends on imported biofuels [Sanches-Pereira and Gomez, 2015].

Figure 4.5: Swedish biofuel production and consumption [Sanches-Pereira and Gomez, 2015]
Hence, as Sweden and other countries with similar ambitious goals rely on imported biofuels, the global production of biofuels increased from 16 to 71 Mton oil equivalent between 2004 and 2014 [Wallington et al., 2016]. At the same time, it has to be considered that biofuels rely on certain crops that compete with other resources as for example food production [Zilberman and Timilsina, 2014] and still have to prove that they actually contribute to GHG-emission goals.

**Life Cycle Approach on Biofuels**

Nanaki and Koroneos [2011] carried out a comparative life cycle assessment (LCA) on biodiesel from rapeseed and conventional petrodiesel in a passenger vehicle. At the time of the assessment rapeseed has been used as primary feedstock for the production of biodiesel. The assessment included the extraction of raw materials as well as the combustion of the respective fuel in the vehicle’s engine.

Assumed that efficiencies of the engines are the same for both fuels and emitted the same GHGs, biodiesel has proved itself as being beneficial with respect to saving fossil energy and reducing the greenhouse effect but detrimental regarding acidification, inorganic respiratory effects and ecotoxicity [Nanaki and Koroneos, 2011].

Another comparative LCA has been conducted by Hong [Hong, 2011]. In this study, the author included feedstock production as well as the bus production and disposal, as well as an uncertainty propagation. The LCA resulted in a reduced global warming impact from 0.137 kg CO$_2$ equiv. to 0.085 kg CO$_2$ equiv., if biodiesel is used, indicating a reduction of CO$_2$ equiv. by 38%. Hong [Hong, 2011], notes that similar results have been observed by other researchers who conducted comparative LCAs on petro- and biodiesel.

Though, biofuels have proven themselves to be able having a beneficial impact on the reduction of global warming, the American Environmental Protection Agency (EPA) claimed that an increased share of biofuel blend in fossil fuels will lead to larger NO$_x$ tailpipe emissions [Nanaki and Koroneos, 2011]. As it has to be shown that increased use of biofuels does lead to worse local air quality, Wallington et al. [Wallington et al., 2016] examined tailpipe emissions from both, petro- and biodiesel.
Tailpipe Emissions of Biodiesel

This assessment has been carried out with consideration of different drive scenarios: city driving, highway driving and aggressive driving. First in production engine calibration and afterwards with adjusted engine calibration of the same car. While tailpipe emissions of CO$_2$ do not differ strongly between petro- and biodiesel, emissions of other GHGs as NO$_x$, hydrocarbons (THC), CO and particulate matter can differ and influence especially urban air quality. Butyl nonanoate that has been studied as a potential biodiesel fuel, has been used as the compared biofuel [Wallington et al., 2016].

In production engine calibration all three scenarios showed lower emissions of THC, CO and PM from biodiesel but larger NO$_x$ emissions in comparison with petrodiesel. Adjusting the engine to the biofuel led to lower NO$_x$ emissions in the scenarios city and highway driving but also to larger emissions of CO in the scenario city driving.

Wallington et al. [Wallington et al., 2016] showed that an increased share of biofuels does not result in worsened air quality, if the vehicle and fuel are adjusted to each other. In this case, the increased use of biodiesel may even lead to an improved air quality.

Impacts of Biofuels on the Economy, Environment, and Poverty

As mentioned above, the biofuel sector grew tremendously within the last decades. With an increased demand on certain crops and plants, prices rise which makes it more profitable to plant crops and plants with the largest profit maximisation. For example, the price for rapeseed experienced a price development from 223$ per ton in 1991 to 580 $ per ton in 2009 (in 2005 USD). Next to a peak price for rapeseed and fuel commodity prices also food prices peaked and led to a food crisis. Even though, not only the production of biofuels but also global economic and population growth and other factors influence food prices, a variety of researchers attributed the food crisis to some extent to increased biofuel production [Zilberman and Timilsina, 2014].

The agricultural industry gains by the biofuel industry with increasing prices for crops and plants. Thus, also workers in developing countries will profit due to higher returns. On the other hand, those areas will experience
increased inequality and even poverty. It is estimated that, if all countries will meet their biofuel goals by 2020, as for example countries of the European Union, not only deforestation and other land use change will be a consequence but also the drop of 42 million people to incomes below USD 2.50/ day and approximately 5.8 million people to incomes below the USD 1.25/ day poverty line [Zilberman and Timilsina, 2014].

4.3.2 Fuel Cells

Currently, two options are available to use hydrogen as a fuel. The first option is to substitute diesel with hydrogen in a common internal combustion engine. Since the efficiency of such a system is limited due to the thermodynamic process, it is more popular to use hydrogen in a fuel cell. Efficiencies of 50 to 60% can be attained through the electro-chemical process in a fuel cell. However, an additional battery is needed to meet requirements of acceleration and to store energy, both from brake recuperation and the electro-chemical energy transmission in the fuel cell [den Boer et al., 2013].

Fuel cell technology described by den Boer et al. [den Boer et al., 2013] is able to make the required, rather high, power output available. Though the durability of fuel cells has to be increased tremendously. A durability of 10,000 operating hours has been achieved which means that the required minimum durability for light distribution trucks of 10,400 hours is in reach but further development is required to reach the suggested durability of 14,560 hours for long haul trucks.

Storage of hydrogen in the vehicle constitutes another bottleneck. Currently, hydrogen can be stored either as a liquid or under pressure with 350 or 700 bar. Though, the liquefaction of hydrogen requires a rather small and light tank in comparison to the pressurized system, the liquefaction process itself is rather energy demanding and consumes energy that equals 30 to 40% of the hydrogen’s energy content while the pressurized 350 bar procedure consumes only around 15%. In addition, liquid hydrogen will boil-off which leads to an increased pressure in the storage tank. Due to security reasons, hydrogen has to be blown off to decrease the pressure. Additional and promising procedures to store hydrogen efficiently are chemical and physical adsorption. Though, these systems require further development and evaluation [den Boer et al., 2013].
Den Boer et al. (2013) concludes that, depending on the required fuel infrastructure and competitive costs, it will be possible to use fuel cells in light distribution trucks but an implementation in long haul trucks requires further research, especially in the fields of storage, durability and the improvement of efficiency. Furthermore, it has to be considered that hydrogen is often produced as a by-product from fossil fuel production. In 2013, the global hydrogen production derived from 49% natural gas, 29% crude oil, 18% coal and 4% electrolysis [Hwang, 2013]. Hence, environmental issues in the production of hydrogen occur and have to be reviewed, before hydrogen can be used as a renewable energy source.

4.3.3 PHEV and Hybrid Vehicles

Usually, a hybrid vehicle consists of two energy converters. A fuel tank that is connected to an ICE and a battery that is connected to an electric engine. The battery is solely charged through brake recuperation and therefore has a rather short range. However, the battery contributes to propulsion which led to energy and therefore CO$_2$ savings by 11.8%/km in Anderssons and Edfeldt’s [2013] comparison to conventional diesel propulsion.

Similar to a hybrid vehicle, a PHEV has an electric engine as well as an ICE. An on-board battery that can be charged through a plug and brake recuperation fuels the electrical engine. Hereby, it is possible to overcome a larger range in pure electric mode than with the smaller battery that’s in the hybrid vehicle [Anderss son and Edfeldt, 2013]. However, in comparison to pure EVs, PHEVs have rather small batteries on board which enable them to drive only shorter distances in full electric mode. Nonetheless, the range anxiety can be further dampened [Thomas, 2015]. It has to be considered that due to the two propulsion systems, PHEVs are neither the most efficient electric nor ICE driven vehicles but the combination of both propulsion systems results in a more efficient energy usage [Andersson and Edfeldt, 2013]. PHEV applications for long haulage vehicle application are due to the high investment costs rather rare. Even though, operating costs are lower than diesel driven counterparts. Increasing the share of PHEVs in long haulage applications depends on decreased battery costs and high volumes of PHEVs in the passenger vehicle sector [den Boer et al., 2013].

Hybrid vehicles and PHEVs are seen by Siemens as the currently most efficient propulsion systems for ERS applications [Interviewpartner A, 2017].
4.4 Performance of Key ERSs

4.4.1 Potential of CO₂ Reduction

Andersson and Edfeldt [Andersson and Edfeldt, 2013] assessed conventional, hybrid and ERS-hybrid long haulage vehicles with regard to their CO₂ emissions on a typical transport route between Stockholm and Gothenburg. The distance between these two cities is 447km and it is assumed that 1430 trucks per day are driving this route. A GVW of 40t has been chosen as this weight constitutes the largest share in Swedish registered long haulage trucks [Trafikanalys, 2016b]. The trucks are able to run between 50 and 80kmph. Table 4.1 shows the results of the assessment. Though, this constitutes a best case scenario, it can be seen that the CO₂ reduction potential of 77.7% in comparison to conventional diesel vehicle in the scenario of an ERS that is implemented on the whole distance and only ERS-hybrid trucks are used would enable the Swedish road freight transportation sector to meet the government’s goal of a 70% reduction.

Table 4.1: Annual CO₂ emission from long haulage trucks [Andersson and Edfeldt, 2013]

<table>
<thead>
<tr>
<th></th>
<th>100% Diesel vehicles</th>
<th>100 % ERS, 50% ERS-hybrid vehicles</th>
<th>100% ERS, 100% ERS-hybrid vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual CO₂ emission [t]</td>
<td>179,000</td>
<td>115,000</td>
<td>39,900</td>
</tr>
<tr>
<td>Annual CO₂ savings compared to diesel [%]</td>
<td>0</td>
<td>-35,4</td>
<td>-77,7</td>
</tr>
</tbody>
</table>

As earlier stated, electric vehicles and therefore vehicles connected to the ERS have zero tailpipe emissions [den Boer et al., 2013]. Assumed that electricity is produced from renewable energies, hybrid vehicles should drive as much as possible in electric mode, which also depends on the ability of the ERS to supply the vehicle with the required energy. Equation 4.1, which is derived from Henriksson et al. [2015] show a simplified form of calculating the energy demand $P$ of a long haulage vehicle with a mass of $m = 40t$ to maintain a speed of $V = 25ms^{-1}$ which equals 90kmph on a road with a pitch angle of $\alpha = 7.97$ or 14%. Additional values that have been considered
are the air density $\rho = 1.2 kg * m^{-3}$, drag coefficient $C_d = 0.6$, the gravitational force $g = 9.81 ms^{-2}$ and a rolling resistance coefficient of $C_r = 0.006$. Adding those values in the equation results in an energy demand of approximately 188kW.

$$P = \frac{1}{2} \rho_a \cdot C_d \cdot A \cdot V^3 + m \cdot g \cdot C_r \cdot V \cdot \cos(\alpha) + m \cdot g \cdot \sin(\alpha)$$

(4.1)

If the vehicle would drive on a flat road $\alpha = 0$, the energy demand would equal 110kW. Assuming those values, an ERS should be able to transfer a minimum of 110kW but rather up to 190kW to every connected vehicle. However, Interviewpartner A and B [2017] stated that the on-board fuel tank has to support the vehicle, in times of high energy demand. Even though, this depends on different factors as for example cost, energy supply from the grid and the kind of ERS, Interviewpartner E [2017] pointed out that support of the extra propulsion system may even constitutes a better solution than investing in a system with higher peak power.

### 4.4.2 Conductive Roadbound ERSs

Alstom’s APS solution and the Elways system are evaluated as roadbound conductive charging systems.

**Introduction**

Both systems are visible on the road and enable both, passenger vehicles and long haulage trucks to connect to the system [ICT, 2013a; Andersson and Edfeldt, 2013]. Furthermore, switching devices are required to power single segments, if a vehicle drives on the electrified road [Interviewpartner D, 2017].

**Alstom APS** Alstom’s APS system is used in tramway applications for several years. The power supply rail is integrated on the surface of the track and segmented in sections of maximum 11m. Segments are only electrified if they are covered by the tram [ICT, 2013a]. Naturally, minor adjustments had to be done for ERS applications. The length of segments has been reduced to meet requirements for road traffic and road vehicle applications. Furthermore, the current collector has been refined to be more adaptable to different road conditions, automatically finding the power line and remain
connected, even if the vehicle is not perfectly aligned to the power line [Aldamad et al., 2016].

**Elways** The Elways system requires a rail in the road that contains the electricity line near its bottom. To transfer energy from the road to the vehicle, the current collector slides through the rail [Andersson and Edfeldt, 2013]. Single segments have a length of about 50m. Due to safety and efficiency reasons they are only electrified, if a vehicle with the required technology drives on it [Interviewpartner B, 2017]. The current collector is able to detect, connect and disconnect automatically to the power line and due to its flexibility follows it even if the vehicle is not perfectly aligned [Andersson and Edfeldt, 2013]

**Construction Measures**

As both systems are implemented in the road, the road structure will be changed [Elways, 2011b] [ICT, 2013a]. Besides that, infrastructure for the steady and safe supply of energy and operation, as for example transformers and rectifiers, are required. Those components can be built next to the road [Interviewpartner D, 2017] but the Elways solution enables the rectifier to be in the vehicle.

**Efficiency**

If the losses of the system justify costlier usage of material, both systems, can be further improved in terms of efficiency [ICT, 2013a] [Interviewpartner B, 2017].

**Alstom APS** Due to the mechanical friction between the current collector and the power line on the road, the pick-up results in losses of electrical energy by approximately 1.5%, depending on road condition, contact pressure, speed of the vehicle and the material of the pick-up. It has to be noted, that the current collector is adapted from tramway application and can be further optimized which will lead to lower friction losses. Considering electrical losses due to the cables of 1.8%, the efficiency of the system is about 96.7%, before the transmission of electrical energy from the road to the vehicle is executed [ICT, 2013a].

Table 4.2 lists the degree of efficiency of crucial parts of the ERS and is based on the assessment of Alstom’s APS technology by Victoria Swedish
ICT [ICT, 2013a]. Losses due to energy transmission through the ERS are estimated to 3.3%, 5% by the electric engine, 5% by the inverter that’s supplying the engine, 2% by other losses on board and 1% by the substation’s traction which leads to a total efficiency of 84.6% of Alstom’s APS [ICT, 2013a].

<table>
<thead>
<tr>
<th>Table 4.2: Efficiency Alstom APS</th>
</tr>
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<tbody>
<tr>
<td>Electric motor</td>
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<tr>
<td>Degree of Efficiency [%]</td>
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<tr>
<td>Global Efficiency [%]</td>
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</tbody>
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Elways  The CEO of Elways estimated an efficiency of their ERS of 96%. Hereby, losses in transformers, alteration switches, rails and vehicle contacts are included [Andersson and Edfeldt, 2013]. Singh [2016] expects a well-to-wheel efficiency of the system between 85-96%. Both, Interviewpartner B and Singh add that the efficiency depends on the quality of electrical components, which means that costlier components will lead to a higher degree of efficiency. A power transfer of 200kW per track has been proven [Singh, 2016]. Even though, energy losses in crucial parts are not known, table 4.3 lists the available information regarding the Elways ERS for further comparison to other ERS.

<table>
<thead>
<tr>
<th>Table 4.3: Efficiency Elways</th>
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<tr>
<td>Electric motor</td>
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<tr>
<td>Degree of Efficiency [%]</td>
</tr>
<tr>
<td>Global Efficiency [%]</td>
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</tbody>
</table>
Cost

Cost estimations for both ERS do not include payment systems for vehicles that use the ERS and control systems to ensure the safe and continuous operation of the system [ICT, 2013a] [Interviewpartner B, 2017].

**Alstom APS** Cost estimations of Alstom’s APS system are based on Victoria Swedish ICT’s extension models, that includes the electrification of the road connection between Stockholm and Gothenburg in Sweden. Two scenarios have been considered. In one scenario, the system is able to provide between 0.96 and 1.4 MW/km while the other scenario enables the system to transfer 6.7MW/km, though in this case, only 35% of the whole distance are electrified [ICT, 2013a].

Table 4.4 lists costs regarding ERS and required infrastructure in relation to the potential energy supply of the system. The ERS itself, including APS beams, APS power boxes, APS cabinets, MFC cables and antenna cables, double track based, will cost 8.6 MSEK/km. As the ERS has to be supplied with energy from the grid system, infrastructure costs of 7.7MSEK/km are assumed for the scenario with a lower energy transfer. If the scenario with the larger power supply will be implemented, the infrastructure cost will be around 23.1MSEK/km which leads to total investment costs of 16.3MSEK/km and 31.7MSEK/km respectively [ICT, 2013a].

<table>
<thead>
<tr>
<th>Table 4.4: Cost Alstom APS</th>
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<tbody>
<tr>
<td><strong>Power supply [MW/km]</strong></td>
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<tr>
<td><strong>ERS [MSEK/km]</strong></td>
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<tr>
<td><strong>Infrastructure [MSEK/km]</strong></td>
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<tr>
<td><strong>Total Cost [MSEK/km]</strong></td>
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</tbody>
</table>

**Elways** If the system is implemented on more than 1000km, the costs are estimated to be around 4-5MSEK/km while the first 100km will be slightly more expensive with 7-19MSEK/km [Singh, 2016]. Interviewpartner B [2017] estimated costs for two lanes in both directions to be around 5MSEK/km, if the ERS is implemented on large scale. Hereby, the required infrastructure of the ERS is included but not the infrastructure cost to adapt the grid to the ERS [Interviewpartner B, 2017]. Nonetheless, costs for infrastructure are not known, table 4.5 lists the available information
regarding costs of Elways’ ERS. With an assumed energy supply of 120kW per segment, an energy supply of 2.4MW/km has been extrapolated.

<table>
<thead>
<tr>
<th>Table 4.5: Cost Elways</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumed Power supply [MW/km]</td>
</tr>
<tr>
<td>ERS [MSEK/km]</td>
</tr>
<tr>
<td>Infrastructure [MSEK/km]</td>
</tr>
<tr>
<td>Total Cost [MSEK/km]</td>
</tr>
</tbody>
</table>

**Safety**

If the infrastructure of the ERS is installed with certain safety distance from the roadside, a road restraint system is not required. As every other electrical installation, the ERS has to comply with existing rules and guidelines by relevant authorities [ICT, 2013a].

**Alstom APS** Vehicles having a speed between 60 and 100km/h can activate the single segments. In the unlikely case that a pedestrian is walking in the ERS supplied road, the electrification of a segment does not constitute a danger for the pedestrian but the moving vehicle does. Hereby it is ensured, that that a roadway does not become more dangerous, if electrified. Nonetheless, motor bikers may follow cars with a much closer distance and access an activated segment [ICT, 2013a].

The influence of the power line on road friction has not been investigated yet.

**Elways** Single electric segments are only powered, if a vehicle is driving on the road. Additionally, the electric conductor line is at the bottom of the rail in the road which means that standing on an activated segment does not constitute a safety hazard to pedestrians [Andersson and Edfeldt, 2013]. In comparison to Alstom’s system, Elways is covering the power rail with asphalt in order to have the same friction on the whole road [Interviewpartner B, 2017].
Maintenance

In-road charging systems involve major interventions of the road structure which leads to the need of new routines and construction equipment for maintenance, repair and winter road clearance [ICT, 2013a]. Due to switching devices that turn single ERS segments on and off, Interviewpartner A [2017] expects increasing need for maintenance of the components. Interviewpartner B and D [2017] claim that switching components do not constitute problems, if the switching cycles are electronically induced and not mechanically. Victoria Swedish ICT [ICT, 2013a] expects that the rutting effect will be greater as vehicle operators will tend to drive in a constant straight line to ensure being powered by the ERS. Interviewpartner E [2017] assumes that if the asphalt is adapted to the vehicle density and to the ERS and vice versa, its lifetime will not be altered. Similar estimations are made by Interviewpartner B [2017].

Alstom APS Though, most of the equipment will be designed maintenance free, periodic checkups and needed reinvestments will be required. Equipment and components are monitored by a computerized system that detects faulty parts. Based on the expansion model and a rough estimation, the maintenance costs per year over the calculated lifespan of equipment refers to 1-2% of the total investment costs. In tramway applications, the collector shoe has to be replaced every 20,000km. It has to be considered that the transmitted power is much higher in tramway applications than in ERS application. Hence, the collector shoe in ERS applications has to be replaced seldomly [ICT, 2013a].

Elways Water, snow and debris may accumulate in Elways’ rail. Therefore, the system has been designed that passing by pick-ups rinse the rail [Andersson and Edfeldt, 2013] and drainage systems avoid water accumulation. It is also possible to include heating components to the rail to avoid icing and snow-covering during Winter [Andersson and Edfeldt, 2013]. According to Interviewpartner B [2017], faulty current collectors will not endanger the system’s operatability because of its included mechanical resistance. It is estimated that daily costs of 60SEK/km occur due to required cleaning of the rails [Singh, 2016].
Vehicle

**Alstom APS** The current collector of a truck, with a GVW of 40t, will add 80kg and cost around 30,000SEK. In addition, a power converter is required, to stabilize and control power and voltage which will add another 40kg and cost around 20,000SEK [ICT, 2013a].

**Elways** Additional weight of equipment in a heavy vehicle will be around 30kg [Interviewpartner B, 2017] and will be constructed to have a similar lifespan as the vehicle itself [Singh, 2016]. The costs are predicted to lay between 5,000 and 10,000SEK [Singh, 2016]. It is not known, if the rectifier is included in the cost and weight predictions.

### 4.4.3 Conductive Overhead

**Introduction**

Transfer of electrical energy with catenary lines requires a vehicle equipped with an pantograf. The two pantografs on the vehicle press against the power line and have to ensure a steady connection to the power line regardless the road condition to enable a continuous electrical propulsion and minimize wear and tear at the same time to minimize costs for maintenance and repair. Though, the technology is similar to trolleybusses trucks for road freight transportation have to be much more flexible. Consequently, the pantografs have to be able to disconnect from the power line to enable overtaking slower driving vehicles or to leave the electrified road to reach their transport destination [Siemens, 2012b]. Due to safety regulations and even though this law may be adapted, the overhead wires have to be installed in a height of at least 5.1m which enables only vehicles with a corresponding size to connect to them. Special arrangements may be expected for implementations of the system under bridges and in tunnels which may lead to lower hanging wires [Andersson and Edfeldt, 2013].

With the development goal of road vehicle electrification, Siemens evaluated available options and favoured the OH catenary solution. Accordingly, Siemens developed their eHighway system. This is due to the expectation that passenger vehicle are more often used for short haul commutes and spend more time in parking lots. Heavy trucks for freight transportation are much more often used for long-distance hauls and spend more time on the road. In addition, more options for the decarbonisation of passenger vehicles are available than for heavy freight trucks [Interviewpartner A, 2017].
With over 2,000,000 passengers per year in Sweden [Swebus, nd], also long distance bus operators could equip their vehicles with the required technology to connect to the catenary line and benefit from the system.

Construction Measures

Overhead catenary lines do not require changes in a road’s structure but rather extended with OH lines. Though, due to the power poles next to the road that carry the electricity lines, a continuous road restraint system is necessary to protect road users from collisions. With a minimum contact wire height of 5.1m, safety systems have to be built on public accessible bridges, to protect pedestrians [Siemens, 2012b]. Hence, the system is also clearly visible on and next to the road.

Efficiency

The current collector has a middle degree of efficiency of 99% and the power line of 95%. With degrees of efficiency in the substation by 97%, in the rectifier and inverter by 98/97%, powertrain by 95% and gearbox by 95%, the degree of efficiency of the whole system is about 80% [Siemens, 2016b] and listed accordingly in table 4.6 to enable a comparison to other ERS. Singh [Singh, 2016] lists a well-to-wheel efficiency of 80-85%. In addition, due to the pantograf, the air resistance of the truck changes. Tests with an 18t-truck disclosed that the truck has an air resistance of $cw_{up} = 0.83$ if the pantograf is connected to the catenary line and $cw_{down} = 0.66$ if it’s disconnected and retracted. Brake recuperation from the vehicle to the ERS grid is already enabled [Siemens, 2016b].

<table>
<thead>
<tr>
<th>Degree of Efficiency [%]</th>
<th>Electric motor</th>
<th>Gearbox</th>
<th>Current line</th>
<th>Transmission ERS to vehicle</th>
<th>Substation</th>
<th>Inverter and rectifier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95</td>
<td>95</td>
<td>95</td>
<td>99</td>
<td>97</td>
<td>97-98</td>
</tr>
<tr>
<td>Global Efficiency [%]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80</td>
</tr>
</tbody>
</table>

Table 4.6: Efficiency Siemens eHighway
Cost

Though, costs correlate strongly with energy supply and the road environment, Interviewpartner A [2017] mentioned that different sources presumed costs of about 2.5MEUR/km for the electrification of one lane in both directions, which estimates to approximately 24MSEK (02.05.2017). It has to be noted that this cost includes external energy supply and distribution, substations etc. Under reference of other sources, Victoria Swedish ICT [ICT, 2013a] expects cost between 7 and 35MSEK/km, while Trafikverket estimated the costs to lay between 6 and 18MSEK/km [AB, 2014]. In Projektengagemang’s and Svenska Elvägar’s report from 2011 cost for overhead lines are approximately 10 million SEK per km [Andersson and Edfeldt, 2013] while den Boer et al. [den Boer et al., 2013] expects cost to be around 2 and 3MEUR which corresponds to 19 to 29MSEK for the whole system. The sources did not clearly communicate which components are included in the cost estimations and if the assumed costs also include the road restraint system. Nonetheless, known costs are listed in table 4.7 for comparison in future.

<table>
<thead>
<tr>
<th>Table 4.7: Cost Siemens eHighway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumed Power supply [MW/km]</td>
</tr>
<tr>
<td>ERS [MSEK/km]</td>
</tr>
<tr>
<td>Infrastructure [MSEK/km]</td>
</tr>
<tr>
<td>Total Cost [MSEK]</td>
</tr>
</tbody>
</table>

Safety

As earlier mentioned, restraint systems have to be installed to protect road users from collisions with the power poles and to protect pedestrians on public accessible bridges. Nonetheless, the disaster management of fire departments, ambulances and rescue helicopters have to adapt to the overhead catenary system [Siemens, 2012b]. Within the development of their ERS, Siemens tested and evaluated several hazardous situations as for example the tearing of a catenary line, the drive into grounded and short-circuited section and quick-lowering of pantograf after evasive swerves. Measures have been taken to ensure the harmlessness of the eHighway, if it comes to those situations [Siemens, 2016b].
Due to the rather high insulation resistance of air, the hazard of an electric arc is rather limited. Though, through reckless behaviour of people, it came to accidents due to electric arcs from overhead catenary lines in train applications. In the unlikely case of a line break, the line rolls to the nearest pole because the manufacturers arranged internal tension in the material of the OH catenary line [Interviewpartner D, 2017].

Maintenance

Maintenance work and repairs of such a system have to be minimized and carried out as time efficient as possible due to dependency of the system’s users and it’s payment model. The system does not change the road structure which means that maintenance cost for the road are likely to remain on the same level as if no ERS is implemented. Den Boer et al. [2013] expect annual maintenance costs of 1-2.5% of the initial investment costs which is similar to the estimated operational costs which include maintenance and repair and correspond to 2% after Siemens [2016b].

Vehicle

The pick-up system developed by Scania to connect to the catenary line doesn’t decrease the volume capacity of the truck [Siemens, 2016b]. Though, hybrid vehicles, e.g. diesel-hybrid are not easy to retrofit due to necessary adaptions of the engine callibration, gearbox, auxiliary system and the shift of emphasis (current collector) etc. [Siemens, 2012b].

It is estimated that pantografs for trains cost between 60,000 and 80,000SEK. Based on that, for ERS applications on trucks, the pantograf will be more complex and therefore cost between 120,000 and 240,000. It has to be noted, that active pantografs for trucks will be produced in huge amounts which will decrease the costs [på uppdrag av Svenska Elvägar AB, 2011].

4.4.4 Inductive In-road - Bombardier Primove

Introduction  Bombardier is using 20m long segments for their Primove system which are implemented under the road’s surface. Each of those segments includes primary coils which are only powered, if a single authorized vehicle that is equipped with the required technology and a secondary coil as a current collector drives with more than 50km/h on the segment. Thus, in times of high road congestion it can happen that the segments are not powered due to a lack of distance between the vehicles. The system is
not visible on the road [ICT, 2013b]. Next to an application in dynamic roadbound charging systems, inductive charging also gains popularity with vehicle manufacturers who are interested in driver independent, wireless, stationary charging systems [Interviewpartner E, 2017].

Necessary infrastructure components are: wayside box (pre-cast concrete housing with lid), wayside power converter (two per wayside box), wayside cooling tower (one per wayside box), wayside winding material (all materials including shielding, excluding concrete), installation and commissioning is included [ICT, 2013b].

Construction Measures

If the required infrastructure next to the road is installed with regard to a safety distance to the road, no additional construction measures, as for example road restraint systems, have to be taken. Within normal circumstances, 200mm of the top of the road in a 800mm wide strip have to be grounded away to install the windings and other required in-road infrastructure. The installation of the windings is similar to the installation of heating coils in the road and will be located 40mm under the road’s surface [ICT, 2013b]. Hence, the system changes the road structure.

Efficiency

The degree of efficiency of contactless dynamic energy transfer depends amongst other strongly on the distance between primary and secondary coil as well as on the alignment of the coils towards each other. Misalignments until 100 to 150mm have only a marginal impact on the quality of the energy transfer but misalignments between 200 and 250mm already show a lower degree of the energy transfer’s efficiency. Though, the degree of efficiency for such power transfers is unknown, a transfer above 150kW per segment is stated as possible which means that also heavy trucks may be powered by inductive energy transfer [ICT, 2013b][Singh, 2016].

As according data is derived from Viktoria Swedish ICT [ICT, 2013b], the degree of efficiency of the electric engine, inverter, other vehicle losses and substation are the same as in the Alstom case but the efficiency of the energy transfer from the ERS to the vehicle is only about 78.6-88.4%. Nonetheless, for reasons of clarification, table 4.8 presents the single component’s degrees of efficiency which lead to the total efficiency of 68.8 to 77.4% [ICT, 2013b].
Table 4.8: Efficiency Bombardier Primove

<table>
<thead>
<tr>
<th>Electric motor</th>
<th>Inverter</th>
<th>Other vehicle losses</th>
<th>Transmission ERS to vehicle</th>
<th>Substation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree of Efficiency</td>
<td>95</td>
<td>95</td>
<td>98</td>
<td>78.6 - 88.4</td>
</tr>
<tr>
<td>Global Efficiency</td>
<td></td>
<td></td>
<td>68.8 - 77.4</td>
<td></td>
</tr>
</tbody>
</table>

It has to be noted that the tests were limited to a maximum velocity of the vehicle of 70km/h due to limitations of the test tracks length and the degree of efficiency refers to the 30kV grid [ICT, 2013b]. Nonetheless, also Interviewpartner D [207] states that an energy transfer with an efficiency of 90% is possible but does not specify to which amount of transferred energy this value refers to.

Cost

Viktoria Swedish ICT [ICT, 2013b] uses the same extension model, as seen in the conductive ERS case, regarding a potential implementation between Stockholm and Gothenburg. For this purpose, two scenarios are investigated, scenario 1 where the system is implemented throughout the whole distance but the transfer will be limited to 120kW and scenario 2 that intends to electrify only sections of the distance but segments are able to transfer up to 200kW. Based on that, the possible energy transfer per kilometer equals 6MW in scenario 1 and 10MW in scenario 2.

In table 4.9, the cost incurrence of the ERS in both scenarios can be seen. Costs for adoption of the regional grid, substations and traction substations for the inductive ERS are estimated to be 7.2MSEK/km. In case of the first scenario, the costs of the ERS for one lane in both directions per kilometer are expected to be 56MSEK/km. Considering, that the complete distance will be covered with the system, the costs are expected to be reduced to 30MSEK/km. With regards to the second scenario, which requires costlier equipment due to the larger energy transfer, the costs are slightly higher and correspond to 36MSEK/km, as only 35% of the distance have to be covered with the ERS. However, Viktoria Swedish ICT uses the cost estimation of 56MSEK/km for the ERS which adds up to 63.2MSEK/km
including costs for energy supply. In both cases, an additional cost reduction can be achieved, if the segment length is increased to 25m instead of 20m [ICT, 2013b].

Based on costs of 56MSEK/km, an assumption of the traffic flow intensity from 2012, which has been developed by the Swedish Road Administration on certain sections of the road between Stockholm and Gothenburg, the required equipment of the ERS has been adapted in terms of power supply. Furthermore, the adoption of the regional grid substations and transformers as well as the distribution from the substations to the roadside traction substations, including installation, has been taken into account, which leads to total investment costs of 63MSEK/km to completely cover the distance between Stockholm and Gothenburg [ICT, 2013b].

<table>
<thead>
<tr>
<th>Table 4.9: Cost Bombardier Primove</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumed Power supply [MW/km]</td>
</tr>
<tr>
<td>ERS [MSEK/km]</td>
</tr>
<tr>
<td>Infrastructure [MSEK/km]</td>
</tr>
<tr>
<td>Total Cost</td>
</tr>
</tbody>
</table>

**Safety**

Vehicles that connect to the ERS are equipped with shielding devices to protect passengers from the strong magnetic field. As the magnetic field strength is decreasing rather quick, pedestrians next to the road are not exposed to any threats of the magnetic field either. As earlier mentioned, segments are only activated, if a vehicle drives faster than 50kmph. Hence, the bigger threat for a pedestrian who’s walking on the road is the moving vehicle but not the activated segment. Due to proximity sensors which belong to a vehicle required Primove equipment, the distance between the ERS-ready vehicle and a following vehicles is constantly measured and communicated to the primary segments in the road which will refuse to power, if another vehicle is too close [ICT, 2013b]. According to Interviewpartner D [2017], inductive dynamic power transfer is the safest ERS option.
Maintenance

Due to the installed windings, the road structure is changed. The rather large efficiency of the energy transfer, if the vehicle has none or only a small misalignment to the primary segment in the road encourages driving centered on the road which may increase the rutting effect. To which extend this will increase road maintenance has to be investigated. Damages in the road structure, which can occure more frequent due to the rutting effect have to be repaired contemporary to avoid damaging of the windings [ICT, 2013b]. Interviewpartner C [2017] agrees that road maintenance cost are possible to increase due to the inductive ERS. Hence, research is carried out on different casing materials to decrease costs. It is also possible to add components for heating which will decrease wear and tear of the road during winter. The system itself is expected to have a large availability and is designed for operation within a temperature range of -40 until 40°C and 0 to 100% humidity. Nonetheless, external monitoring oversees the functionality of the segments and measures can be taken quickly, if a segment appears faulty. Overall, annual costs for maintenance are expected to be around 1-2% of the total investment costs. Vikoria Swedish ICT admits that the maintenance cost estimations might differ [ICT, 2013b].

Vehicle

Equipment that is fundamental to enable a connection between ERS and consists of the current collector and the connected lifting device which will add 330kg to the vehicle. Furthermore, a control device combined with a rectifier and magnetic shielding is required and adds 60 and 201kg respectively [ICT, 2013b]. It has to be considered that the estimated weights are derived from prototype components for a heavy vehicle and are focusing on functionality but not on lightweight design. In the future and in series applications, weight can be reduced due to alternative materials and a better managing of space [Interviewpartner C, 2017]. Smaller vehicles require smaller pick-ups, which will lead to a reduction of weight for the components but also to a smaller instantaneous power transfer [ICT, 2013b].

4.5 Technological Readiness Level of ERS

Based on the tool Technological Readiness Level (TRL), researchers from the Royal Institute of Technology (KTH) and Victoria Swedish ICT assessed the maturity of the available ERS and assigned different ERSs to defined
levels of maturity [Sundelin et al., 2016]. The levels are:

- TRL 1. Basic principles observed and reported.
- TRL 2. Technology concept and/or application formulated.
- TRL 3. Analytical and experimental critical function.
- TRL 4. Component and/or breadboard validation in laboratory environment.
- TRL 5. Component and/or breadboard validation in relevant environment.
- TRL 6. System/subsystem model or prototype demonstration in a relevant environment.
- TRL 7. System prototype demonstration in an operational environment.
- TRL 8. Actual system completed and qualified through test and demonstration.
- TRL 9. Actual system proven through successful mission operations.

For a more precise evaluation, the ERSs have been divided by Sundelin et al. [Sundelin et al., 2016] into the subsystems road operation, power transfer, road, energy and vehicle. With regards to this evaluation model, Siemens eHighway has been assigned to TRL 6, while the Elways, Alstom and Bombardier were assigned to TRL 4 [Sundelin et al., 2016].

Considering the recent development, Elways can be assigned to TRL 5 and with start of operation of eRoadArlanda within 2017 it may reach TRL 6, as a complete system will be tested in a relevant operation. In addition, and as mentioned in chapter 2, a 6km long section of the highway A1 will be equipped with an OH system [BMUB, 2017]. If Siemens will become the supplier for this project, it is most likely that their ERS will reach TRL 7, as the ERS will be integrated in the local logistic chain [Interviewpartner E, 2017]. Unfortunately, no information regarding test tracks and projects in a relevant environment could be found for Alstom’s APS and Bombardier’s Primove. Therefore, those ERS will remain on TRL 4 for the time being.

Interviewpartner E [2017] concluded that Siemens’ product is the most mature ERS. Beneficial for Siemens is the gathered know-how from already existing systems as for example tramways, railroads and trolleybuses and the potential transmission of safety regulations from those proven systems to its ERS. It can be said that if, for example, safety standards are already in place, as it is the case for Siemens’ but also for Alstom’s and Bombardier’s
ERS, it is easier to adapt the ERS to new applications and demands. In contrast to that, new standards for a new system as for example Elways have to be developed. Even though, Alstom has no test track of its ERS in a relevant environment, they have a head start in comparison to a completely new system as the APS is already commercialized and proven in tramway applications without reported accidents due to electricity [Interviewpartner E, 2017].

4.6 Prerequisites for an Implementation of ERSs

**General**

Interviewpartner A, B and C [2017], agreed that an ERS has to prove itself first in real road environment with other road participants, before a large scale implementation can be considered. Viktoria Swedish ICT [2013a] concluded that none of the available ERS has been qualified for a large scale implementation. Apart from this, additional and promising ERS are still in early development stages and should be given time, before major decisions are made [ICT, 2013a]. Here listed prerequisites assume that the energy supply and potential grid enhancement is already enabled.

**Electric Vehicle**

Relevant ERS infrastructure has to be implemented first, to encourage the purchase of EVs that are able to make use of electrified roads [England, 2015]. A similar view is shared by Interviewpartner C [2017] who suggests first to implement the ERS to let vehicle manufacturers adapt. Interviewpartner A [2017] advised that decision makers should agree on a single ERS in order to send a signal to vehicle manufacturers to develop suitable vehicles. Singh [2016] and Interviewpartner B [2017] assumes that the decrease of costs for Li-ion batteries and at the same time the increase of energy density correlates with the attractiveness and therefore higher share of EVs on the road which enhances the potential implementation of ERSs. Furthermore, the implementation of ERS might lead to smaller on-board batteries of the EV and decrease the environmental impact from battery production through dematerialization [Interviewpartner E, 2017].

Industry experts presume that battery costs have to reach USD150/kW, before EVs can compete with internal combustion vehicles [Nykvist and
Nilsson, 2015]. Though cost for batteries are not published by EV manufacturers, it can be said that the development of price and energy density show declining costs and increasing energy densities [Thielmann et al., 2015]. A similar result regarding the cost development has been obtained by Nykvist and Nilsson [2015] who showed that cost estimations declined by 14% annually between 2007 and 2014 which led to costs of battery packs, that have been used by market-leading EV manufacturers, of USD300/kW in 2014. In addition they are showing that costs decline between 6 and 9%, if production is cumulative doubling [Nykvist and Nilsson, 2015]. Considering that a forecast by Roland Berger regarding the global automotive Lithium-ion battery market expects a growth from USD10 billion in 2015 to approximately USD50 billion by 2020 [Chen et al., 2015], it may be only a matter of time until the threshold of USD150/kW is reached.

**Early Adopter**

It is expected that commercial operators, especially road haulage companies, will be among the first users of an ERS. While it is most likely that first ERS vehicles are retrofitted with the required technology, vehicle manufacturer’s support has to be gained to develop vehicles that are able to connect to the ERS in the long term. Retrofitting vehicles should not be a long term solution [England, 2015]. Decision makers at Toyota Motor Corporation have shown with start of development of one of the first hybrid vehicles, the Toyota Prius, that being an early adopter might constitute a threat but also an opportunity. Though, at this time the demand for hybrid vehicles has been rather low, stricter regulations have been expected by decision makers which led to the development of the model Prius. From taking that risk, Toyota gained a competitive advantage in the development of hybrid vehicles [Interviewpartner D, 2017]. An analogy could be represented by the ERS and the according vehicle development.

**Ownership**

Highways England [2015] sees a next challenge that has to be solved in the ownership of the ERS infrastructure. It is unclear, which institution is best suited for an ownership. This issue has been already tackled by Abdulhadi and Vitez in 2016 with the result that it remains unclear, how the ERS infrastructure should be owned and financed. This is due to the complexity of an ERS which led Abdulhadi and Vitez [2016] to the suggestion decreasing the system’s complexity and increase stakeholder cooperation, through
cross-sectorial suppliers as for example construction firms, truck manufacturers, petroleum firms etc. who served in the present transportation as sub-system suppliers to the system designers as the Swedish government and the Swedish Transport Administration. It also has to be considered that energy suppliers may have monopolies in certain regions in Sweden [Interviewpartner D, 2017] which contributes to the system’s complexity and ownership question.

**Payment and Detection System**

Interviewpartner A and B [2017] expect that the payment and associated vehicle detection system of an ERS could be operated by a third party. Such a system has to be developed and tested before start of operation [England, 2015] in order to avoid operation delay as seen during the introduction of the German toll collect system. The detection and payment system on highways for road freight transportation vehicles in Germany resulted in defaults in payment due to a not ready for operation system in the early 2000s [Löding, 2003].

**Standardization**

Swedish roads are also integrated in legal frameworks by the EU, as Andersson and Edfeldt [2013] state. Experts are discussing, if it’s better to wait for a union wide standard, while others see an opportunity for Sweden being the forerunner [Andersson and Edfeldt, 2013]. However, standardization of the system is an important issue as Interviewpartner B [2017] states. Viktoria Swedish ICT [ICT, 2013a] requests to work with standardization and legal issues at an early development stage to avoid delays in the implementation process while Interviewpartner C [2017] adds that also energy providers, energy retailers and vehicle drivers will have to adapt to certain new frameworks and policies.
Chapter 5

Analysis of the Results

5.1 CO₂ Emission Reduction Options

It was one of the purposes of this thesis to prove that despite certain challenges of EVs, electrification of road transportation in combination with ERSs has the biggest potential to meet the aspired goal of a 70% reduction of CO₂ emissions. Therefore, alternative solutions to reduce carbon emissions in the transportation sector have been investigated to verify the need of ERSs in Sweden.

Even though, concerns of more hazardous tailpipe emissions could be discarded and a rather large reduction of CO₂ emission of up to 38% in the lifecycle of biofuels could be confirmed, problems on a global scale as land change, acidification and rising poverty will be a likely result. On the other hand, it has to be considered that it is possible to produce sustainable biofuels in Europe and in Sweden too. The negative impacts of biofuels produced in Sweden may be smaller on global scale than impacts of imported biofuels and should be subject of closer investigation. Nonetheless, especially figure 4.5 indicates that it is rather doubtful that produced amounts of biofuels in Sweden will be able to satisfy demand, or if the country will still rely on imported biofuels in the future. However, biofuels contribute to reduced climate gas emissions in the transportation sector and even though, they should not be seen as a long-term solution, they may be seen as an interim solution, if the production can be carried out more sustainable.

Another promising solution to reduce GHG emissions has been introduced with fuel cells which are the only propulsion method next to pure electric
propulsion with zero tailpipe emission. Unfortunately, it could be shown that fuel cells have not yet reached the level of technological maturity to be used in passenger vehicles which is seen as a first step to drive long haulage trucks in the future. Hence, it is rather uncertain, if fuel cells will be used for vehicle propulsion in the future.

Another issue has been stated by the present production of hydrogen, which is mainly done in connection to the fossil fuel production. However, with an increased share of renewable energy power plants, surplus energy may be used to produce hydrogen through the rather energy demanding method of electrolysis which allows extracting hydrogen from water rather than fossil fuels. Hence, fuel cells have the ability of reducing emissions of the road transportation sector by the pursued 70% and should not be given up yet.

Hybrid vehicles combine, to some extent, the advantages of both, fossil fuel and electric propulsion. Even though, the reduction of GHGs is not sufficient to reach the government’s goal of a fossil fuel independent vehicle fleet by 2030, hybrid vehicles have already reached a high level of technological maturity, are seen in many car manufacturers portfolios and fulfill the prerequisites to connect to an ERS.

If hybrid vehicles are propellul with biofuels from sustainable production and electrical energy, produced from renewable energies, the technology constitutes the propulsion method with the currently biggest potential of large CO₂ reductions.

Given low readiness of fuel cells, limited availability and CO₂ reduction potential of biofuels and currently limited potential of batteries, reaching the goal of reducing CO₂ emissions by 70% until 2030, will most likely only be enabled through large scale implementation of ERSs.

5.2 Characteristics of ERSs

In the following analysis, each ERS is compared to all other ERS on each characteristic. For purposes of clarity, tables are created for each characteristic that allow an overview about the performance relationships among each ERS. Tables are meant to be interpreted from row to column. This
means that the mean of comparison which have been introduced in this thesis’ methodology describes the performance of the ERS in the row to the ERS in the column.

Construction Measures

The assessed systems differ substantially through changes in road structure and required infrastructure as for example power poles and road restraint systems. While the eHighway system requires probably more resources than roadbound system, it is unclear, if this makes the system’s construction requirements more laborious. Therefore, as can be seen in table 5.1, a sound assessment of this characteristic among evaluated ERSs can not be achieved with gathered results.

Table 5.1: Comparison of the characteristic Construction Measures

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<tr>
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Efficiency

Though, data availability for the Elways system has been rather limited, gathered results from literature and interviews show that especially the degree of efficiency of conductive ERSs as for example, eHighway, APS and Elways is better than the degree of efficiency of an inductive ERS, as Bombardier’s Primove system. Table 5.2 shows that the conductive ERS have a similar degree of efficiency, while the inductive system performs worse.

Table 5.2: Comparison of the characteristic Efficiency

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Cost

Literature and interview partners claimed that the Elways system is rather cost-efficient, even though, the costs are based on an expected large scale implementation. Nonetheless, also Alstom’s ERS showed similar cost expectations, which is why both systems are rated as equal to each other in this characteristic as can be seen in table 5.3. In addition, one can see that even though, cost estimations on Siemens’ ERS range tremendously, it can be settled in between the roadbound conductive systems and Bombardie’s Primove which seems to be the most expensive one.

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Safety

Bombardier’s Primove system is expected to be the safest ERS option among the evaluated systems. This is due to two reasons. Firstly, no power lines are required that constitute a danger for pedestrians or motorcycle riders to be electrified. Secondly, required infrastructure can be installed within a safety distance that avoids vehicles to collide with it.

As table 5.4 shows, Elways tends to be the safer roadbound conductive option, as the power line is not as easy reachable as in the case of Alstom’s APS and in addition does not change the roads friction. However, it has been desisted from comparing the OH system with Elways and Alstom, as it has not been considered sound to compare the differing potential hazards of the systems, as for example power poles to change of road friction and overhead line to in-road power line.
Table 5.4: Comparison of the characteristic Safety

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Maintenance

As can be seen in table 5.5 and derived from the results, information and data regarding the characteristic maintenance has been too vague to describe a performance tendency.

Table 5.5: Comparison of the characteristic Maintenance

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Vehicle

It is assumed that required changes on the vehicle will be the smallest for such that are enabled to connect to the Elways system, followed by APS. Consequently, table 5.6 shows that Elways performs better than Alstom. In addition, the Siemens and Bombardier system do require more extensive changes compared to the conductive roadbound systems. On the other side, it has been desisted from formulating a performance tendency for the comparison of Bombardier to Siemens, as both systems require broad changes but published data does not permit a sound comparison.
Summary of the ERS characteristic

Table 5.7 shows all means of comparison that the respective ERS collected within the certain category. It can be seen that Elways performed better in two categories than Alstom, while Alstom performed better in two categories compared to Siemens and in three categories compared to Bombardier. In comparison with Bombarider, Siemens performed better in two categories.

Hence, if a ranking based on here evaluated characteristics is done, Elways performs best, followed by Alstom, Siemens and Bombardier.

Table 5.7: Summary of ERS Performance

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5.3 Technological Maturity of ERSs

Among here assessed ERSs, Siemens eHighway constitutes the system with the highest TRL, followed by Elways, Alstom APS and Bombardier Primove which share the same TRL. Nonetheless, it is expected that Elways will join Siemens TRL with start of operation of eRoadArlanda in 2017.

5.4 Assessment of the Potential of ERSs

As pointed out, passenger vehicles are easier to electrify and are able to drive rather large distances that overcome the daily travelled distance of
34km in 2016 by far. In addition, the need for passenger vehicles can be further decreased with an improved public transport offer and extended bicycle paths. Hence, the ERS should be chosen to meet the demands of long haulage vehicles with a weight of 40t that can’t be propulsed differently. However, the contribution of passenger vehicles to the financing of the ERS has to be evaluated, before an ERS is chosen that excludes passenger vehicles.

Nonetheless, with regards to the required electrification of long haulage trucks, the ERS should be able to transfer rather larger amounts of energy while losses are reduced to a minimum in a financial feasible manner. It is expected that all conductive ERSs are able to transfer a minimum of 120kW, while the inductive ERS, Bombardier Primove has to prove its transfer capacity. The transfer efficiency of energy should not be neglected and energy losses within the ERS avoided. Even though, it is assumed that energy is produced by renewable sources and the energy efficiency is higher than the efficiency of conventional fossil fuel vehicles, energy production facilities require resources that constitute an environmental impact and could be saved, if a more energy efficient system is chosen.

Hence, due to the rather low efficiency of the energy transfer, high investment costs and not yet proven required transmission capacity, Bombardier’s Primove system can not compete with presented conductive ERSs.
Chapter 6

Discussion

6.1 CO₂ Emission Reduction Options

Biofuels constitute a sensitive topic and even though they have been given more consideration within this thesis work than other CO₂ emission reduction options, the results are worthy of discussion. Though, the results show that biofuels are not seen as a preferable long term solution, it should be clear that increased poverty, acidification and land use change are unacceptable, it has to be considered that global warming, which comes along with CO₂ emissions, does also affect people and ecosystems on a global level. Therefore, it has to be evaluated, how decreased CO₂ emissions can be compared to acidification, land use change and increased poverty. As it is assumed that biofuels, produced in Sweden, do perform better in certain characteristics and have a smaller impact, for example on acidification, the production potential and long term effects should be analysed.

In this thesis, the biofuels used for the evaluation of tailpipe emissions and lifecycle CO₂ emission differ. As no reports have been found that include both, comparisons of tailpipe emissions and lifecycle CO₂ emission of the same biofuel, the actual results of those impacts compared to fossil fuels may differ to some extent. However, a similar tendency is expected. Next to liquid biofuel as biodiesel and bioethanol, also biogas could have been considered to round up the biofuel section.

The conclusion of this thesis’ results indicates that under current circumstances only ERSs have the potential to reduce CO₂ emissions by more than 70% as stated by Andersson and Edfeldt [Andersson and Edfeldt, 2013]. A
scenario, in which a certain road or even a complete road network is fully covered by ERSs and all vehicles are receiving their energy needs is rather unlikely. Nonetheless, ERSs show the biggest potential and even if the road network is only partly covered with this technology the largest CO\textsubscript{2} emission reductions are possible. As current data availability does not allow a full LCA on currently available ERS, the life cycle emissions, including resource usage and maintenance are unknown. It is expected that life cycle CO\textsubscript{2} emission are reduced, even though the hereby required break-even point is not known or not published but rather useful, considering the purpose of an ERS, reducing emissions.

To strengthen the conclusion that ERSs are the most viable option to decrease CO\textsubscript{2} emissions, also future means of freight transportation, as for example drones and autonomous vehicles, could have been included in the thesis’ framework.

6.2 Characteristics of ERSs

Construction Measures

As Interviewpartner A [2017] stated, public acceptance is crucial for new infrastructure projects, as the implementation of ERSs. Public acceptance is accompanied by required construction measures and most likely linked to visual changes of the road environment. An inductive ERS, which is not seen on the road might therefore receive higher acceptance than overhead catenary lines. On the other hand, rather low investment costs of the visible conductive systems may improve public acceptance again. This, topic has not yet been looked into in reviewed literature but will matter to decision makers. Thus, matters of public acceptance should be investigated and included in decision making and planning processes.

Efficiency

Sufficient data has been available for the systems from Siemens, Alstom and Bombardier. Though, it is expected that Elways will have a similar degree of efficiency as Alstom’s APS, not much data is published in a transparent way as seen for the competitive systems.

The degree of efficiency of wireless energy transfer is supposed to decrease with increasing higher amounts of energy that is transferred. Unfortunately,
available literature on Bombardier’s Primove system does not communicate this issue clearly. It would have been interesting to see the degree of efficiency for rather large amounts of energy of 120kW that will be required for the propulsion of long haulage trucks.

Cost

Investigated costs for different ERSs constitute another characteristic with large uncertainties. Besides Siemens eHighway, none of the ERS have been implemented on a public road and even for this respective system estimations range rather wide.

In addition, it has not been stated clearly in the reviewed literature which components of the ERS actually are included in the respective cost estimations. For example, no source describes, if the required road restraint system has been considered in the cost estimations.

Hence, a sound ranking, regarding the most economic feasible ERS could not be carried out, even though, previous reports and statements from interviewpartners indicate the inductive charging systems are generally more expensive than conductive charging systems. Hence, no more than a tendency of the investment costs is presented in the results of this thesis.

Maintenance

Furthermore, a comparison between costs for maintenance and investment costs of a system will be crucial. Investment costs alone can not be used as a single reference for this characteristic but has to be rounded up with cost for maintenance and other operating cost. An ERS that has rather low investment costs but requires frequent maintenance and surveillance may become more expensive in the long run. Required data will probably only be available, when the systems are tested on public roads under realistic utilisation circumstances.

Additionally, optional functions as heating components that avoid icing of power lines have to be considered. Such an ability of an ERS may not only decrease cost for deicing but also cost for maintenance and can lead to the prevention of frost damages in the road. So far, heating components in ERSs have not been tested on public roads but show a potential to decrease
maintenance cost but will most likely increase operating and investment costs.

Roadbound systems change a road’s structure. Some informants share the opinion that, if the road is adapted to the ERS and the following stresses, the road’s lifetime is not affected, it means that further financial burdens will be added to the implementation of an ERS. Hence, wear and tear of roads that are equipped with roadbound systems have to be investigated on tracks within real traffic conditions. Due to currently rather expensive retrofitting of vehicles with the required ERS equipment, only a few vehicles can connect to the available ERS which does not equal common usage behaviour. Hence, available data regarding maintenance requirements is too uncertain to be used for closer evaluation and comparison.

Safety

Reviewed literature does not reveal all required information to compare the systems accordingly. This may be due to the TRL of the respective ERS. So far, solely Siemens, which has the highest TRL, published information regarding safety tests in hazardous situations of their eHighway system. It would be crucial to see how different systems perform in similar hazardous situations as for example within a moose test.

Vehicle

All of the tested vehicles have been retrofitted with required equipment, which means that not only the vehicles but also the current collectors and other components are prototypes. Hence, weight and cost estimations may differ in future due to mass production and maturation of the technology. Unfortunately, no data has been published that points out to the weight of a pantograf for an overhead system.

Summary

Above discussed characteristics showed that uncertainties are still wide spread in almost all of the assessed characteristics. This may be due to the fact that most of the data from available literature is derived from test tracks and pilot projects. If ERSs are implemented on public roads and can be tested within real traffic situations and stresses, knowledge gaps can be closed. On the other hand, much available data could not be used within this thesis as it has been only published in reports that were directly published.
by the ERS suppliers themself and lacked transparency and referencing. Hence, it has not been able to add quantifiable values to the single ERS characteristic, what would have been necessary for the envisaged potential assessment.

In addition, the investigated characteristics have to be valued, as it can be expected that some characteristics are from more interest to decision makers than others. Furthermore, gathered results have to be brought in relation to the respective TRL of the ERSs to be able creating a more representative ranking.

In addition, the question, if it is necessary to connect passenger vehicles to an ERS has to be responded. In comparison to road freight transportation, several alternative options are currently available to substitute the need for passenger vehicles. Assumed that an ERS should be chosen, that matches the needs of long haulage vehicles, the decision making process would gain a new dynamic.

6.3 Technological Maturity of ERSs

It can be observed that the investigated ERSs have different levels of technological maturity. This method and allocation has to be followed up, as more and extended test tracks are developed and pilot projects in real road environments are implemented and operated which may leads to an increase of the technological maturity of a single ERSs. The significance of the method itself can be discussed. On the one hand, it constitutes an opportunity to rank the systems, on the other hand, it gives the illusion that the highest ranked ERS represents the best and most likely to implement solution. The risk for decision makers is given to assess the ERSs based on their TRLs while ERSs on lower TRLs should be given more time to develop to make a sound decision. Hence, it has to be discussed, how much time can be given to ERSs on low TRLs to develop with regard to the goal of a 70% reduction of CO\textsubscript{2} emissions by 2030.

6.4 Assessment of the Potential of ERSs

As earlier discussed, investment costs of an ERS do only represent one side of the coin, while also maintenance cost, the potential for energy expansion and transfer efficiency have to be considered within the cost calculation
as well. Such a calculation on the other hand can only be conducted, if uncertainties can be eliminated. Even though, other authors as for example Singh [Singh, 2016], have already made a recommendation based on CO₂ saving potential and economic feasibility, the results of this thesis suggest that uncertainties are currently too big to make a sound recommendation on which ERS is the most suitable for a large scale implementation.

Hence, especially further tests on public roads are required to collect more data and share information. Following, in this thesis qualitative investigated ERSs and their characteristics can and have to be combined with quantified methods to determine the ERS that has the largest potential to reach Sweden’s transportation goals by 2030.

6.5 Critique of the Sources

It may be common that at this rather low state of technological maturity, as here presented ERSs, suppliers of the respective technology are the most comprehensive and often single available data source. Unfortunately, reviewed published reports and test results do not always comply with scientific standards, as for example references that have as the author’s name Siemens, Alstom, Bombardier or Elways. The same applies to Interview-partner A and B, who are representatives of ERS suppliers. However, it is not expected that suppliers are publishing false information, it has to be considered that every supplier has certain interests which might affect the objectivity of the published information.
Chapter 7

Conclusion

From the research that has been carried out, it could be shown that electrification through an ERS of road freight transportation vehicles constitutes the most achievable way of meeting the goal of a 70% reduction of CO$_2$ emissions. Though, achieving this goal within the time horizon 2030 will be challenging.

It is most likely that hybrid vehicles will be the first choice for the connection to the ERS due to their mature technology and rather high system efficiency and CO$_2$ emission saving potential, if biofuel is chosen, compared to pure EVs. The electrification of heavy vehicles should also constitute the basis for decision makers on which ERS will be implemented on large scale in Sweden, as passenger vehicles can be substituted easier by more environmental friendlier means of transportation.

Even though, the single ERSs from Siemens, Bombardier, Alstom and Elways have been evaluated based on relevant characteristics, it has not been possible to connect this qualitative evaluation with quantified methods in order to find the ERS with the largest overall potential. This is due to severe uncertainties in crucial characteristics as cost and maintenance estimations. It is expected that those uncertainties can be eliminated with further tests of the ERSs, especially on public roads with realistic traffic stresses.

However, based on this thesis’ methods and results, it is shown that conductive ERSs perform better than dynamic inductive charging systems in crucial characteristics as cost and efficiency. Hence, inductive ERSs do not
constitute the ERS technology that should be used for large scale implementation.

If the required, missing data and information has been collected, this thesis work can be used as a basis to combine the qualitative research results with quantified methods in order to determine the ERS with the largest total potential to meet Sweden’s sustainable transportation goal.
Bibliography


[eRoadArlanda, 2017] eRoadArlanda (2017). About the project.


The impacts of biofuels on the economy, environment, and poverty.
Appendices
Appendix A

ERS Projects

A.1 eRoad Arlanda

Additional project participants of eRoadArlanda are:
Kilenkrysset (construction operations and property management),
ABT Bolagen (machinery and transport services),
Airport City Stockholm (operated by Swedavia, Sigtuna Municipality and Arlandastad Holding AB to build Sweden’s first airport city),
Swedavia Airports (airport operator),
Sigtuna kommun (municipality in the greater Stockholm area),
Bilprovningen (vehicle inspection company),
e-Traction (e-mobility technologies; has developed a solution for direct electrical drive through vehicle’s axles),
DAF (manufacturer of utility vehicles),
Cosmo Truckcenter AB (agent for DAF trucks in Sweden; sales and service points throughout the country),
VTI (Swedish Road and Transport Research Institute),
PostNord (supplier of communications and logistics solutions in the Nordic region),
WSP (analyst and technological consultancies),
Vattenfall (power producer),
Gävle Container Terminal (container port).

A.2 SELECT

The multi-university research center SELECT is partnered by:
Utah State University,
Purdue University,
University of Colorado Boulder,
Olin College,
University of Colorado Colorado Springs

A.3 FABRIC

Vehicle Manufacturers  CRF (Italy), VOLVO, SCANIA

Energy Operators  IRE (Italy)

Road Managers  TECNO (Italy), SNF (France)

Technology suppliers  VeDeCom (France), SAET (Italy), HITACHI (Hitachi Europe)

Research Institutes  ICCS (Greece), TRL (United Kingdom), TNO (United Kingdom), CEA (France), FKA (Germany), UNIGE-DITEN (Italy), CIRCE (Spain), POLITO (Italy), KTH (Sweden), TU Berlin (Germany)

Small and medium sized enterprises  QIE (Spain), ENIDE (Spain), ATA (Italy), MECT (Italy), AMET (Italy)

Association  ERTICO (Belgium)

A.4 SINTEF

Project owner  Norwegian Public Roads Administration

Project Management  SINTEF

Partners  Norwegian Public Road Administration, (Research Company) SINTEF,

Research Partners  NTNU, Universitet i Stavanger, (research institute) IRIS, (strategy and innovation coonsulting)
Industry Partners  Miles Ahead, (leading supplier in Nordic Region within building, operating and maintaining critical infrastructure) Infratek, (Norwegian Logistics and Freight Association) NHO Logistikk og Transport, Volvo, Siemens, Lyse
Appendix B

Interviews

B.1 Interviewpartner A - Siemens AG - 06 April 2017 - Phone Interview

Q: Warum hat sich Siemens für die Entwicklung von Oberleitungssystemen entschieden, und zum Beispiel nicht für die Entwicklung von in-road konduktiven oder induktiven Systemen?

A:


- Alle Optionen (induktiv und konduktiv; Schiene und Oberleitung) wurden bezüglich deren Entwicklungsrisiken sorgfältig abgewägt.

- OH stellte sich als vielversprechendstes System heraus.

• PKWs und LKWs haben verschiedene Wirkungsgrade und könnten bspw. durch inductive in-road Systeme nicht gleich effizient geladen werden.

• Alternative Kraftstoffe können genutzt werden um PKWs auf größeren Distanzen mit Energie zu versorgen.

Q: Siemens benutzt Diesel-Elektrische-Hybrid-LKW von Scania, sehen Sie die Zukunft in dieser Technologie oder eher in kleineren on-board Batterien bzw. Brennstoffzellen, Biodiesel?

A:

• Entwicklung der Hybridfahrzeuge obliegt den Fahrzeugherstellern.

• Siemens setzt auf den höchsten Wirkungsgrad des Hybrid-Fahrzeuges. Allerdings werden Diesel und Biodiesel nicht als Kraftstoffe der Zukunft angesehen.

Vielmehr PtG und PtL wie zum Beispiel Wasserstoff, Methan und weitere Flüssigkraftstoffe.

• Eine komplette Elektrifizierung der Fahrzeuge würde von Siemens begrüßt werden.

Rein elektrisch betriebene LKWs können allerdings nur auf Strecken genutzt werden, die durch ERS abgedeckt sind und die Distanz außerhalb des ERSs durch die Batterie im Fahrzeug überbrückt werden kann.

Rein elektrisch betriebene LKW werden auf der Versuchsstrecke in Kalifornien, USA zum Einsatz kommen.

Q: Was muss geschehen, dass ERSs im großen Stil zu implementieren? Sehen Sie die Probleme eher in der Politik, Technologie, Kosten?

A:

• Technologie des ERS ist ausgereift wie auf verschiedenen Teststrecken bewiesen wurde. Die Energiebereitstellung für ein solches System muss aber gesichert sein. Die Lösung hierfür wird auf politischer Ebene entschieden. Herausforderung der großflächigen Implementierung liegen daher eher auf politischer Ebene und in der Kostenträgerschaft.
• Pilotprojekte dienen auch dazu den Behörden die Alltagsverträglichkeit des Oberleitungssystems zu demonstrieren (Einbeziehung des allgemeinen Straßenverkehrs)

• Bundesländer müssten sich auf ein ERS einigen, um Insellösungen zu vermeiden.

• So würde auch ein wichtiges Signal an LKW-Produzenten gesendet werden, sodass diese Planungssicherheit haben und entsprechende Fahrzeuge entwickeln können.

Q: Hessen und Schleswig-Holstein erhalten bis 2019 elektrifizierte Autobahnabschnitte. Ist dies ein weiteres Pilotprojekt, um das System zu testen oder um das System bekannter zu machen bzw. seine Zuverlässigkeit zu demonstrieren (selbiges gilt für Strecke in Kalifornien)?

A:

• Die beiden Bundesländer werden die Projekte und entsprechende Fördergelder ausschreiben.

• ERS-Anbieter, wie z.B. Siemens, können sich auf diese Ausschreibungen bewerben.

• Fest stehen bisher nur, dass die beiden Länder Oberleitungen testen wollen.

• Die Systeme sollen kommerziell genutzt werden. D.h. Transportdienstleister werden sich an diesen Projekten beteiligen (auch wenn diese ebenfalls Fördergelder erhalten können) und Kosten für die Nutzung des Systems tragen.

• Mit diesen Projekten in Deutschland soll die Alltagsverträglichkeit und die positive Umweltwirkung nachgewiesen werden. Gleichzeitig dienen solche Projekte der Bekanntmachung der Technologie.

Q: Wann wird man ein erstes kommerziell genutztes System sehen?

A:

Q: Die Autobahn A1 führt nach Dänemark. Ist dies bereits ein erster Schritt zur Internationalisierung von ERSs (im Kontext des Treffens von Angela Merkel und Stefan Löfven)?

A:
- Rein zufällig. Die Bewerbungsphase der Bundesländer für die Fördergelder lag deutlich vor dem Treffen zwischen dem schwedischen und deutschen Regierungsoberhaupt.

Q: Ist ein ERS über Staatsgrenzen hinweg dennoch ein mögliches Vorhaben?

A:
- Potential für ein solches Vorhaben ist vorhanden.
- Interoperabilität ist notwendig (Vergleich Probleme mit Bahnnetzen).
- Wirtschaftlichkeitserwägung muss dennoch berücksichtigt werden und Akzeptanz des Systems im jeweiligen Land muss vorhanden sein.

Q: Wie hoch schätzen sind die Kosten des Siemens OH-Systems für die Elektrifizierung von BABs?

A:
- Große Teile der Infrastrukturkosten hängen mit der Energiebereitstellung zusammen.
- Verschiedene Quellen (nicht unbedingt Siemens' Abschätzung) gehen von 2,5 Mio EUR/km aus (Komplett, inklusive: externe Energieversorgung, Energieverteilung, Unterwerke etc.)
  Elektrifizierung einer Fahrspur je Richtung.
  Hängt auch von der zu elektrifizierenden Strecke ab (bauliche Sondermaßnahmen aufgrund von Brücken, Tunneln etc.)

Q: Wann wird die Teststrecke in Kalifornien, USA in Betrieb genommen?

A:
- Voraussichtlich im Frühsommer, Sommer 2017
**B.2 Interviewpartner B - Elways - 25 April 2017 - Face-to-Face Interview**

**Q:** All road users are included. Is there a power limit of the system? (40t-truck uphill can be powered 100% through ERS) A passenger vehicle requires 20kW, a heavy truck 120kW on average to be moved. Isn’t there an energy loss in the system or rather an inefficient use of energy?

**A:**

- The system can supply the vehicle with a maximum of approximately 200kW. If the vehicle requires more power, the on-board battery will supply the vehicle with the remaining required power.

**Q:** What is the degree of efficiency from the ERS to the car (loss due to energy transfer)?

**A:**

- The losses of the energy transfer from the ERS to the vehicle are small and depend on the used material and size of the power cable. Thus, the efficiency of the system can be further improved, if the losses of the system justify costlier usage of material.

**Q:** Only the segments that the cars are driving on are electrified. As the current supply is under the road, does the reason for the segmentation is to safe energy or due to safety issues?

**A:**

- Elways is using 50m segments that are electrified if a car with a current collector is driving on it. This is due to two reasons; first because of safety reasons and second due to energy saving reasons.

- Therefore, the switching cycles of single segments are not as high as they are for other on-road conductive ERSs.

- The segments have a drainage system.

**Q:** Every road user constitutes a risk to the system. How do you think will the reliability of your ERS work out? (e.g. faulty current collector)
A:

- The system has mechanical resistance to faulty current collectors.

Q: How much will the system cost per kilometre and what is included in the cost calculation?

A:

- If implemented on large scale, 5,000,000SEK/km for two lanes in both directions
- The required infrastructure of the ERS is included (stations from high voltage to medium voltage are included as well as other infrastructure but for example no units for charging the cost of electricity.

Q: Do you see a safety hazard due to lower friction on rail?

A:

- No, there’s asphalt on top of the rail which. So, no friction problems.

Q: The electrical rail changes the road structure which will lead to (probably) increased maintenance costs. Do you have a plan for that?

A:

- Maintenance cost will only increase for electric rail. NCC says there is no problem for road structure, as the rail shows very good inherence with the surrounding asphalt.
- Tests on four different tracks in 2012, 2014, 2016 and 2017 have been conducted on a total test track length of 600m.
- No problems of the road structure have been detected since the tests in 2014.

Q: Considering the three available methods for dynamic charging (Inductive, conductive in-road/overhead). Where do you see benefits and drawbacks of the other system in comparison to Elways system?
A:

- Availability of all vehicles is a benefit of the Elways system.
- Other conductive in-road ERS have safety issues.
- Inductive ERS are very expensive.
- Additional weight of equipment in car will be only a few kg. Truck: +30kg; Passenger vehicle: less than 30kg.

Q: Do you see a connection between the development of batteries and ERS?

A:

- Yes, they are interrelated!
- If everybody would use an electric car, the cost of an solution with ERS and small batteries would be much lower than only big batteries.

Q: When will we see the first commercial used ERS (so far only test tracks and pilot projects)?

A:

- Within a few years hopefully.

Q: What are remaining challenges of your ERS, before you can implement it in large scale?

A:

- Technology has to be proven in real environment which will happen at eRoad Arlanda.
- Costs of the system have to be brought down which will happen if the system is implemented at large scale.
- Plans for payment methods and car identification have to be developed which only constitutes a minor challenge. Elways can hereby assist a third party but will most likely not work on these issues on its own.
Q: What do you think are the main challenges that have to be overcome before ERS can be implemented in large scale?

A:

• Standards for the system are the most important issue.

B.3 Interviewpartner C - Fabric Project - 28 April 2017 - Phone Interview

Q: Who is the supplier of the inductive charging systems?

A:

• Test side in Sweden is using conductive charging solution.

• Test side in France is supplied with inductive charging system by Qualcomm. Politecnico di Torino developed an inductive ERS with CRF for Fabric’s test side in Italy.

• The development and implementation of the individual ERSs on the test facilities has been conducted in cooperation with different members of the consortium.

Q: How much power do single segments provide?

A:

• Segments provide 20kW power which is a typical rate for passenger vehicles.

• Bigger vehicles have need for higher energy rates. Therefore, the system could be adapted to larger energy transfers, which will increase the costs of the system.

Q: Victoria Swedish ICT [2013] expects cost of 5.8MEUR (120kW power transfer) till 7.2MEUR (200kW power transfer) (This cost includes all necessary wayside components which are - Wayside box – pre-cast concrete housing with lid - Wayside power converters (WPC) – 2 per wayside box - Wayside cooling tower – one per wayside box - Wayside winding material –
all materials including shielding, excluding concrete - Installation and commissioning is included) per km on both sides of the highway. Do you think those numbers are reasonable or do you think they will be lower/ higher?

A:

• The costs for such a system are associated to acceptance and possibility to mass production.

• Dynamic charging will certainly increase the cost of infrastructure but will decrease the operating costs for vehicles.

Q: What is a realistic degree of efficiency of the energy transfer from road to vehicle?

A:

• The degree of efficiency of power transfer from the road to the vehicle or rather from primary to secondary coil is an complex issue. Amongst others, it depends on the alignment of the vehicle with the ERS and the distance between road and the current collector in the vehicle.

• A transfer efficiency of 90% is possible.

• Conductive system’s efficiency will be higher and provide a more stable supply of energy.

Q: Can a single segment provide energy for more than one vehicle?

A:

• More than one vehicle on a segment is possible.

• Auxiliary systems have to be included to ensure the propulsion of the vehicle.

Q: It is estimated that the added compounds for dynamic inductive charging to a heavy truck (40t) will weigh about 550kg [Victoria Swedish ICT, 2013]. Is there a potential to decrease the weight and if so, which components could be lighter? How much do you think the added weight for passenger vehicles will be?
A:

- The weight of the added materials depends on the used material.
- Furthermore, proto types which were basis for this calculation have focus on functionality and less on weight.
- Reduction in size and weight of the required on-board equipment is possible, especially when it comes to the managing of space.

Q: Do you think the road structure will suffer because of the implemented equipment and therefore maintenance costs for roads will increase?

A:

- The costs for road maintenance are possible to increase.
- Though, research is conducted on casing material which will decrease maintenance costs.
- In addition, primary coils in the road could also be used as a heating system that will reduce the risk of frost damages in the winter.

Q: Regarding the lower efficiency of inductive charging systems in comparison to conductive systems and the higher price, do you think it is likely that they will be implemented on large scale to electrify highways for example or is it more likely that they will be used for inner city usage (e.g. for public transport also because of their appearance)?

A:

- Inductive dynamic charging systems are more likely to experience public acceptance.
- Bus lines and routes with steady traffic loads as for example city to airport connections are especially suited for inductive charging systems. Furthermore, charging during short stops as for example on traffic lights.
- However, use cases have to prove themselves before a large scale implementation can be carried out.
• When it comes to static charging, conductive energy transfer is more efficient and reasonable due to a higher energy transmission rate. Additionally, it has to be noted that business models have already been developed for conductive charging systems which is a benefit.

• Inductive charging systems have several advantages and if a suitable economic scenario exists it can be implemented.

Q: What do you think has to happen until ERSs are implemented on large scale (political or technical issues, standardization)?

A:

• Demonstration projects as for example in France and in Italy prove that the technology has reached a high level of maturity. Though it can still be improved to some extent.

• The supply of energy of such an ERS has to be ensured without burdening the electricity grid too much. Though, it has been proved by energy providers that the energy supply can be guaranteed.

• Energy providers, energy retailers and vehicle drivers will have to adapt to certain policies.

• Large investments have to be made which have to be authorised on a political level.

• First the ERS has to be implemented before vehicle owner can and will adapt their vehicles invest in required vehicles.

• As ERSs aim for a reduction of emissions, the supply of energy from renewable energy sources has to be ensured.

• All in all, a large scale implementation of ERSs depends more on political issues than technical issues.

Q: Do you see a potential for ERSs on a cross-border basis?

A:

• Yes, it has to be figured out, what has to be standardized and what the actual value of standardization is.
• Interoperability between different systems can be managed. At Italian
test side, vehicles can receive energy from two different systems.
• Not only technical equipment has to be standardized/ be designed for
interoperability but also charging protocols, paying systems etc.
• Fabric project is already a good example for interoperability as it has
test sides in different European countries and international consortium
members.

B.4 Interviewpartner D - KTH Expert on Power
Electronics - 05 May 2017 - Face-to-Face In-
terview

Q: Dynamic in-road charging systems, as for example Alstom’s APS sys-
tem, consist of different segments that are only powered, if they are covered
by an appropriate vehicle and will turn off if the vehicle leaves the segment.
In ERS applications, due to safety reasons, the segment will also turn off, if
a second vehicle is driving on it. Consequently, the switching cycles of the
single segments are very short, if such a system is used on a much frequented
road. Do you think that the increased amount of switching cycles in a short
amount of time constitutes a technical challenge to the ERS and may lead
to higher maintenance costs?

A:
• No, the increased amount of switching cycles does not constitute a
problem, if the switching is done electronically and not mechanically.
• The state of the art is using power semiconductors which are able
switching on and off at frequent intervals.

For this purpose, power semiconductors have proved themselves to
be reliable and require low-maintenance. Therefore, it cannot be said
that shorter switching cycles will lead to higher maintenance costs.

• A frequency of up to 10 kHz is possible.

Q: Are there any restrictions (technical/ safety) on the amount of energy
that can be transferred from different kinds of ERSs (inductive/ conductive,
in-road/ overhead)? E.g.: the potential of an electric arc that can endanger
pedestrians who come to close to an active conductive segment.
Due to the rather high insulation resistance in the air, the hazard of an electric arc is rather limited. Though, through reckless behaviour of people, it came to accidents due to electric arcs from overhead catenary lines in train applications.

Inductive power transfer is the safest option as the magnetic field decays rather quickly with distance from the source.

Inductive charging systems have physical limitations that correspond to the maximum of power transfer as for example the distance between primary and secondary coil and the potential size of the coil on the bottom of the car.

Inductive and conductive in-road segments can supply up to 200kW to vehicles that are driving on the active segment. A 40t truck requires probably more energy if it goes uphill and therefore has to use its secondary propulsion to provide the necessary amount of energy. Overhead catenary lines on the other hand are not segmented and there is no data (I couldn’t find data) that describes the maximum amount of energy that can be provided. How to figure out the maximum of energy supply that the overhead catenary system can provide?

Several feeding points are possible that supply the ERS with energy, even if the line is connected.

The maximum energy supply can be derived from applications of trolley busses, train applications and test tracks as for example Siemens’ test track in Gävle, Sweden.

All in all, it can be said that OH is more suitable system for the energy transfer of heavy vehicles.

Seen from a cost point of view, required equipment for conductive systems are cheaper if they should be enabled to supply higher amount of energy than it is for inductive systems.
Q: When talking about the required infrastructure of their system, Siemens (overhead catenary system) implies that they need substations, rectifiers and inverters, and the contact line to supply the vehicle with electrical energy. Is there anything else needed to supply the catenary line with energy from the grid system? Can that be applied to other ERSs as well?

A:

• To supply a conductive ERSs (in-road and overhead) with energy a supply line, transformers and rectifiers are required. In the case of an in-road ERS also switching devices are required.

• Inductive ERS require a supply line, transformers, rectifiers, inverters and switching devices.

• On the vehicle side, next to the current collector, also frequency inverters are required to adjust the speed of the electric engine.

Q: Consequently, can I assume that the cost of infrastructure which is required for the supply of energy of the ERS is approximately the same for all the systems?

A:

• It can be assumed that conductive ERS require the same main components for their energy supply (supply line, transformers, rectifiers and for in-road switching devices. Therefore the costs of infrastructure of conductive ERS are approximately the same. Though, the same components of in-road and overhead systems are required, it has to be considered that different constructional measures have to be taken.

Q: How should an ERS be supplied with energy? From the conventional grid or is it more suitable to develop a grid system especially for ERSs (to not burden the conventional grid)?

A:

• Using the conventional grid might lead to fewer infrastructures. The Siemens system might be easier to implement if looking at local feeding points. (you have the poles, it’s simpler to have common feeder line)
• Road bound systems might be a little bit more expensive (infrastructure for energy supply)

• Legal aspects have to be considered, as some energy suppliers may have a monopoly in different areas.

  Technically it would be better having feeding points along the road but not legally.

**Q:** The available ERSs (inductive, conductive in-road and conductive overhead) have different advantages and drawbacks. Only considering the technical aspects (and ignoring the appearance, cost and inclusion of road users), which ERS provides the highest degree of efficiency and is the most suitable for a large scale implementation and why? (In your opinion)

**A:**

• Road bound systems are most flexible ones.

• From a technical point of view, road bound systems are the simplest in sense of power transmission but not in the sense of safety issues and maintenance.

• Overhead catenary systems are limited to heavy vehicles but constitute the most mature technology and for the application of only heavy vehicles the currently most suitable system. Though, solutions could be applied to connect passenger vehicles too.

• Inductive ERS are most likely the safest option but also the most costly one as the cost of the system are directly related to the power.

**Q:** Do you see any problems, if all road users can connect to the ERS (in-road) or do you think it is more practical to have an ERS that can only be used by a limited amount of users (overhead)?

**A:**

• No technical problems but legal and business problems. Payment systems for the use of energy will be more complex, as well as safety aspects.
Q: In your opinion, what has to happen that ERSs can be implemented on a large scale? Do you see the biggest issues on the technological or political level? Do you see other issues?

A:

• Due to the very high investment costs, a clever way has to be found to gradually implement an ERS from a very small system to a large system.

• The uncertainty of such a system is quite high due to many stakeholders.

• Though, in the past, decision makers at Toyota have shown that taking a risk can work out. Stricter regulations have been expected which led to the development of the model Prius. From taking that risk, Toyota gained a competitive advantage in the development of hybrid vehicles.

B.5 Interviewpartner E - Trafikverket - 18 May 2017 - Phone Interview

Q: Sweden has the ambitious goal of a carbon neutral transportation sector by 2030, how do you define carbon neutral and/ or fossil fuel independent?

A:

• In Swedish, it is rather talked about a fossil fuel independent vehicle fleet.

• The government looked into two assignments which proposed at reduction levels of between 60 and 80% compared to 1990.

• Finally, the government agreed on proposal with a reduction of CO2 by 70% reduction of the vehicle fleet in comparison to 1990. the new law is expected to be passed by the Swedish parliament in June 2017.

• Sweden strives to be first CO2 neutral welfare state in the world.
Q: In 2016, passenger vehicles drove an average distance of 34km per day [Trafikanalys, 2017]. Even though some cars drive much bigger distances per day, it can be derived that the majority of passenger vehicles don’t. Such a distance can easily be covered by pure EV and or PHEV. Also fuel cells might be a viable option for such a short distance. Is there even a business case for passenger vehicles in ERSs or do you think other solutions as for example alternative propulsion but also public transport, park and ride, improved bicycle infrastructure would be a better solution for decarbonisation of the passenger transport sector?

A:

• Currently, the passenger car industry is primarily looking for ways to stationary charge cars without using a plug.

• The business case for ERS from the passenger vehicle sector will emerge with a larger share of EVs. An ERS could reduce the on-board battery pack and therefore the required battery capacity, making the car more efficient as the weight is reduced and spare material that would have been used for battery production otherwise. Then, an ERS might become interesting on highly commuted roads as for example Stockholm – Gothenburg.

• Electrification is just one of many measures that have to be fulfilled to cope with climate ambitions within transportation sector. Shifting from cars to bicycles and improving the public transport offer is looked into as well.

Q: Heavy vehicles for road freight transportation purposes are more difficult to decarbonize as passenger vehicles. Which ERS is the most suitable one for the propulsion of heavy vehicles (regarding the system’s efficiency, high demand of energy of heavy vehicles and technological readiness level)?

A:

• ERS has to be adapted to its environment (uphill, downhill, traffic density).

• Uphill, extra propulsion system has to support vehicle, which maybe constitutes a better solution than invest in system with higher peak power.
• Different systems have no problem with transferring more power than it is required by a heavy truck.

Q: Which system is the most technological mature one?

A:

• Siemens’ product is the most mature system. It is the only system that has been built in a real environment so far (Gävle, Sweden). In addition, with its operation begin in the USA in summer 2017 and a potential 6km section on a German highway (Siemens participates with other OH suppliers in this bidding), the system can increase its TRL.

• Beneficial for Siemens is the gathered know-how from already existing systems as for example tramways, railroads and trolleybuses and the potential transmission of safety regulations from those proven systems to its ERS.

• It can be said that if the standard is already in place, as it is the case for Siemens’ but also for Alstom’s ERS, safety issues are easier to adapt.

• On the other side, if a system is new as it is the case for Elways and Elonroad, the development of new standards is necessary.

• Therefore, it can be said that even though, Alstom has no test track of its ERS in a real environment, they have a head start in comparison to Elways and Elonroad as they are going from an already commercialized and proven system without reported accidents due to electricity.

• Elways solution will be evaluated and developed through building of their 2km track on public a road close to Arlanda Airport. That’s one step of development to demonstrate their product in real environment.

Q: How much do you estimate will different ERS cost per km (overhead catenary, conductive in-road, and inductive in-road)? Elways estimates that its system will cost around 5,000,000SEK per km while other systems are much more expensive. Is Elways’ cost estimation feasible?
A:

- Trafikverket doesn’t examine costs of different ERS solutions at the moment.

- Nonetheless, a research platform has been developed in cooperation with RISE, VTI, KTH, Chalmers and others.

  Within this platform nine different work packages are approached as for business model and funding etc.

  However, a pre study has been carried out but the cost aspects are not published yet.

  Next to the investment costs, the system’s lifetime has to be considered. If system costs half as much as a competitor’s system but has a much shorter lifetime, an investment might not be feasible.

  Three different cost sections have been worked out: electric road cost (OH or rail), power grid cost (connection between ERS and power grid and a reinforcement of the grid if necessary), vehicle costs and a potentially fourth section, cost for surveillance and payment method.

  Cost for surveillance and payment method can also be outsourced.

- Road maintenance cost for in-road conductive systems will not be a problem, even though the road structure is changed. It is important to match the quality of the road with the traffic density of road.

Q: If in-road ERSs would be implemented at large scale, potentially every vehicle owner would be enabled to connect to the ERS. Additionally, every vehicle that connects to an ERS also constitutes a thread to the system due to the increased likelihood of human error and/or technical failure due to faulty current collectors. Do you see any problems, if too many users connect to such a system and do you think that further driver training will be required for such an endeavour?

A:

- Present used public roads are open systems and can be used by private and commercial users. An ERS on a public road will not be much different.

- Independent from the system, knowledge information training will be important.
• More individuals are sharing the costs of such a system, if more users are connected to it. Nonetheless, assumed that the failure rate is 1%, the actual number of failure will increase with more users.

• Maintenance of the pick-up will be from great importance to prevent damages of the system. It can be already seen that poor maintained pantographs, brakes and wheels in railroad applications impact the total railway system.

• ERS is nothing different from those systems.

Q: Regarding their rather low energy transfer efficiency, do you see a potential for inductive in-road ERSes?

A:

• Even though, the energy transfer efficiency of an inductive system is lower in comparison to a conductive system, the grade of efficiency in comparison to the use of crude oil is still rather high.

• Trafikverket does not limit their research to only conductive systems. Nonetheless, inductive systems are more costly. Hence, Trafikverket has not been able to afford a long enough test track to evaluate dynamic inductive charging systems.

• Anyways, it is too early to conclude that inductive systems are dead for market!

Car manufacturers are interested in driver independent stationary charging and inductive charging systems are hereby definitely from interest.

Q: Is there a potential for a connected ERS between Sweden, Denmark and Germany or rather between Sweden and Norway because of the larger (freight) border traffic? What is important to realize such a cross border project?

A:

• Before such a cross border project can be approached, ERSes have to prove their technological maturity level and business model.
• Nonetheless, the cross border potential of an electrified road is discussed within Swedish/ German cooperation.

• All in all it can be said that a cross border potential for electrified transportation exist although different systems, not necessarily an ERS are viable options.

Q: Are you familiar with the four-step principle, Rethink, Optimize, Rebuild and Build new? If so, how can those principles be applied on the decarbonisation of road transportation?

A:

• The four step approach is often used to evaluate requests from external entities.

• If applied to the decarbonisation of the road transport sector with the help of ERS. The single principles can be used as follows:

• Rethink:
  Transportation only if it’s necessary and choosing the most environmental friendliest way of transportation.

• Optimize:
  Optimizing the available system. Platooning can be used to safe energy. Furthermore, it is possible to develop more environmental friendly propulsion systems.

• Rebuild:
  Using the available road network and add more functions. In this case, implementing an ERS.

• Build new:
  Using a new mean of transportation that requires a complete new infrastructure. For example a hyper loop as introduced by Elon Musk.