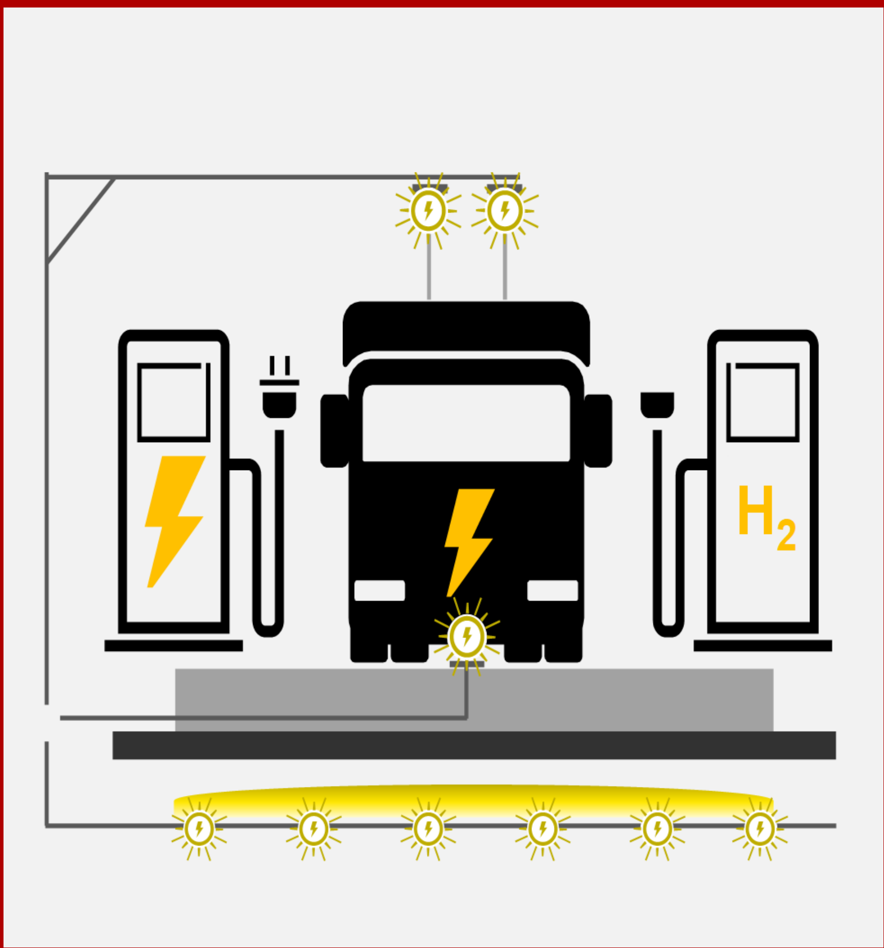
REPORT

Electrification of Heavy Road Transport - business models phase 5

Electrification of Heavy Road Transport
– Analysis of a hydrogen and fuel cell system and comparisons of alternative options for electrification



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Preface

The final sub-report in the Swedish Transport Administration's Programme for Electrification of Heavy Road Traffic on the National Road Network (the Electrification Programme) is presented here within the field of Business Models – financing and organisation. This is report number five within this area of analysis.

During the latter part of 2020 and the beginning of 2021, the efforts have focused on two main areas.

- Firstly, based on previously published reports (Phases 1-4) of this subproject, to deepen a comparative analysis of the electrification alternative options: electric road systems (ERS) and battery-powered vehicles (BEV) with a charging infrastructure. This includes an analysis of what the stakeholder networks look like or how they may be designed in the future, what role parties in the public sector and in the private sector might have, and what financial incentives the parties may need to make investments in the different technologies. This analysis shows that a faster introduction of electrification for heavy vehicles can be achieved with the battery/charging infrastructure solutions than with electric road systems, and that the reduction of CO_2 emissions may be greater.

- Secondly, an initial analysis of and the beginning of a financial calculation model for the hydrogen and fuel cell alternative has been conducted. This analysis has been built up in a similar way as for electric road systems and charging infrastructure, with a stakeholder network and with a breakdown into the different submarkets (long-distance, regional and local). A marginal calculation is also made for the hydrogen alternative compared to diesel as a fuel. The subcomponents included in the system being analysed include hydrogen refuelling stations and vehicles.

  The preliminary analysis suggests that the price of hydrogen users encounter is crucial for the viability of the system, for owners of refuelling station and for vehicle owners. It also shows that the hydrogen and fuel cell alternative could become a competitive alternative to operation with diesel and the other electrification technologies. The hydrogen alternative is in an early development phase and the assessments in this analysis are therefore surrounded by relatively high uncertainty.

The work with the analysis has been conducted in close collaboration with the client and project manager Björn Hasselgren. Elin Näsström and Magnus Lindgren at the Swedish Transport Administration have also participated in the assignment. Lisa Eriksson, currently a soon to graduate student at KTH, is working on a degree project revolving around hydrogen and fuel cells, and she has also participated in the project.

The Swedish Transport Administration and the Consultant (EY) have conducted the project in close collaboration with parties at both regional and national levels, as well as with relevant parties in other countries. The Swedish Transport Administration wishes to thank everyone involved for a productive and open cooperation in the collaboration.

The Swedish Transport Administration publishes the report, however as an agency it does not necessarily agree with all parts of the analyses and conclusions in the reports. The conclusions do however form an important foundation in the Swedish Transport Administration's continued efforts to assess and further develop the possibilities with the electrification of heavy road traffic.

Stockholm in April 2021,

Björn Hasselgren

Senior Advisor

Electrification of Heavy Road Transport – analysis of a hydrogen and fuel cell system and comparisons of alternative options for electrification

22/03/2021

Client: Trafikverket/Swedish Transport Administration, via Björn Hasselgren
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Summary background

This investigation follows four previous phases of studies into business models for electrification of heavy road traffic. The study includes (i) a description of electrification technologies and their systems, focusing on fuel cells as a heavy transport electrification technology and the fuel cell calculation model developed during the assignment, (ii) a comparison between the different electrification technologies and their characteristics, (iii) an analysis of possible combinations between electrification technologies, with a focus on electric road systems (ERS) and stationary charging, and (iv) conclusions and suggestions for further analysis.

As technology develops, it has become clear that several different electrification technologies (ERS, stationary charging, and hydrogen and fuel cells) have the potential to electrify parts of the vehicle fleet for heavy vehicles. It is therefore likely that different electrification technologies for heavy road vehicles will be established and simultaneously co-exist in the future, thereby influencing each other from a system perspective. This is one of the starting points for this investigation phase, phase 5.

Electrification of heavy-duty vehicles with fuel cells

A financial calculation model for a hydrogen/fuel cell system has been developed during this phase. The calculation model aims to enable a financial analysis for the actors involved and at the system level, with various sizes of the system and related costs. The calculation model is based on two stakeholder groups: hauliers and owners of refuelling stations. Similar to the ERS and stationary charging calculation models presented in previous reports, this is a marginal calculation where calculations are compared to a diesel system. The ambition has been that the developing of a calculation model will help to establish an overall understanding of the logic and incentive structures of a system for hydrogen and fuel cells.

Fuel cells is an electrification technology that has the potential to electrify heavy vehicles. Fuel cell electric vehicles use hydrogen as their fuel, which is converted into electricity in the vehicle, which has an electric powertrain. Since the energy carrier for fuel cell electric vehicles is hydrogen, a new type of hydrogen distribution infrastructure is required to enable hydrogen refuelling that does not exist today.

It would be possible to assume that this type of infrastructure may in some respects be similar to today’s diesel refuelling station infrastructure, with refuelling stations scattered across the country, focusing on where hydrogen vehicles are common. Since this refuelling station network is not yet developed, there is, however, uncertainty about what the development of a distribution system might look like and the extent of the investments needed to develop it.

If fuel cells are to be a climate-neutral electrification solution, hydrogen needs to be produced fossil-free. This can be done by means of electrolysis of water with green electricity (fossil-free electricity) or by steam reforming with carbon capture and storage (CCS). This type of production needs to be significantly scaled up so as to respond to the volumes assumed to be needed in the future for the transport sector and other energy-intensive applications, such as fossil-free steel production. This, together with the need to develop a distribution network, makes forecasting for future hydrogen prices to users somewhat uncertain.

The different electrification technologies have different characteristics

The three analysed electrification technologies, ERS, stationary charging and fuel cells, can be seen at an overall level as best suited for different types of vehicle segments or applications, even though technological developments are still ongoing.

- *ERS* can be assumed to be advantageous for vehicles travelling longer distances with heavy loads and over specific stretches of road.
- *Stationary charging* can be assumed in the near future to be primarily suitable for local and regional transport and some long-distance transport.
- *Fuel* cells can be assumed to be an electrification technology suitable for vehicles that are difficult to electrify with ERS and stationary charging. For example, the heaviest vehicles that drive long distances on low-traffic roads, such as timber haulage vehicles.

The practical function of fuel cell technology in various applications is likely to need to continue to be developed, for example in terms of reliability in use with high levels of vibration.

Stationary charging and fuel cell systems are, on the one hand, based on charging and refuelling stations. These can be expanded in stages, depending upon geographical needs and needs related to capacity. On the other hand, for ERS the ERS infrastructure is likely to be expanded before adapted electric vehicles will exist in large numbers.

Electrical charging of charging-while-stationary vehicles and hydrogen refuelling of fuel cell vehicles requires the vehicle to be stationary. A big difference between these two systems is that in the future hydrogen refuelling is expected to take only a few minutes, roughly the equivalent the refuelling time for diesel, while the charging of batteries can take between a few minutes up to several hours, depending on the effect of the charger and on the charging needs.

The infrastructure for electricity and hydrogen has different prerequisites. The electricity network and system, with the production and distribution of electricity, has been long established. Additions to the electricity networks and power grids at the local level may be presumed to be needed in the deployment of an expanded of stationary charging infrastructure and ERS infrastructure. At times, these additions can take some time to achieve and will be costly, however they fall within the framework of the basic operational logic of the electricity grid.

Hydrogen requires the establishment of both a production and distribution system to be able to supply the system’s hydrogen refuelling stations with fossil-free hydrogen. Whether such a system should be based on distribution in tankers (fuel trucks) or via more investment-heavy hydrogen pipelines is one of the issues under discussion, but not focused on here. One factor to consider in this context is that Sweden’s energy system is based only to a relatively limited extent on carriers of energy in gaseous form.

The breakdown of cost items into the Total Cost of Ownership (TCO) of the vehicle differs somewhat between electrification technologies. For ERS vehicles and stationary charged vehicles, a large part of the total cost of ownership lies in the investment to purchase the vehicle, while the cost of fuel accounts for a smaller part. On the other hand, fuel cell electric vehicles have a larger share of their costs in the cost of fuel, making the fuel cell system more sensitive to the price for hydrogen, which in itself is a major future uncertainty. From a cost perspective, electrification via fuel cells is thus similar to the diesel alternative.

It is likely that a combination of some or all of the analysed electrification technologies with a focus on different submarkets and types of vehicles will characterise heavy road traffic in the coming decades. Analyses of combination scenarios for ERS and stationary charging have therefore been conducted in this phase. These combination scenarios show that the different systems can both interact and compete, over time and for different submarkets. It is an area in which continuing investigation will be useful to increase understanding.

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1 Introduction

1.1 Background and purpose

In 2018, heavy-duty vehicles accounted for some 21 percent of greenhouse gas emissions from domestic road transport [1]. In 2017, the Swedish Parliament established a target of reducing the climate impact from domestic transport by 70 percent by year 2030 (compared to 2010 levels) and to eliminate these emissions altogether by the year 2045. One of the means to achieve Sweden's climate goals is the electrification of road transport, where electrification of heavy transport will be a significant part [2] [3].

On behalf of, and in collaboration with the Swedish Transport Administration, EY has investigated business models for electrification of heavy vehicles in five phases since 2018, within the framework of the Programme for Electrification of Heavy Road Traffic on the National Road Network (formerly the "Programme for Electric Road Systems," hereafter referred to as the "Electrification Programme"). Phases one to four have investigated business models and systems for ERS and stationary charging for heavy vehicles, including charging infrastructure. The phases have also included the development of financial calculation models for these systems, as tools for system- and actor analysis for the respective electrification technology.

Four reports on business models, stakeholders and systems for stationary charging and ERS have earlier been published. The first report, *(Business models and financing for the development of electric roads in Sweden)* was published in August 2018. [4] The second report (*Roles, actor relations and risks in the electric roads market*) was published in February 2019 and dealt with roles, actor relationships and risks in a future electrified road market [5]. Subsequently, a report for the third phase (*operator's role, financial assessments and payment systems*) was published in September 2019 together with a calculation model for ERS. It dealt with an additional role as an operator in an electrified road system as well as the financial prerequisites for ERS where the financial calculation model was developed for the purpose of calculating the financial viability of an electrified road system [6].

The fourth report (*Organising an electric road system and calculation model for stationary charging*) was published in June 2020, and dealt with the organisation of an electrified road system. It also included an analysis of the financial prerequisites for stationary charging using a financial calculation model, developed to calculate the financial viability of a stationary charging system [7].

As technology has developed, it has become clear that other electrification technologies in addition to ERS, such as stationary charging and fuel cells, have the potential to electrify parts of the heavy vehicle fleet. It is also likely that different electrification technologies for heavy vehicles will coexist in the future. This phase five is a continuing investigation phase aimed at broadening the analysis of electrification of heavy road transport, by analysing combinations of different electrification technologies, focusing on ERS and stationary charging. The analysis includes comparisons of electrification technologies from a financial and stakeholder incentive perspective.

In addition to ERS and stationary charging solutions, electrification solutions are being developed for heavy vehicles with fuel cells, where hydrogen is the energy carrier. This report studies fuel cell technology to create a deeper understanding of the technology and a potential traffic infrastructure system for fuel cell electric vehicles. The work in phase five also includes an initial analysis of a fuel cell system for heavy vehicles including the development of a financial calculation model for vehicles with fuel cells.

During the current phase, EY has also submitted documentation to the Swedish Transport Administration for the efforts to answer the two government assignments on initial planning of an electric road system in Sweden and public charging infrastructure along the major roads in Sweden, which were submitted to the government in February 2021.

1.2 Methodology

The assignment has been conducted during the period June 2020 to March 2021. This report has been prepared in close collaboration with the Swedish Transport Administration. Björn Hasselgren has been the client and together, he along with Elin Näsström and Magnus Lindgren at the Swedish Transport Administration and EY, has been part of the project group.

The project has gathered knowledge via the assimilation of previously produced documentation in the Electrification Programme, reports from electrification projects in Sweden and other countries, as well as articles, exchanges and dialogues with researchers in other countries such as Germany and the US. Working meetings have been held regularly during the work. The working group has regularly reported to the Electrification Programme and coordinated with the programme's other projects and work, primarily on technology issues and cost-benefit analyses. Regular dialogues with several parties have been conducted during the implementation of the assignment. This is to gain a deeper understanding of the market and the development that takes place for each electrification technology, both within the area of business models for electrification technologies and linked to technology development.

As a first step in the analysis of combinations of different electrification technologies, the financial calculation models for ERS and stationary charging from previous phases have been further developed. The calculation models have also been updated to be consistent with each other, as well as to handle new data and information about the electrification technologies and the market for heavy vehicles.

Adjustments to the input data have been made in cases where new data has emerged that has been regarded as being considered more up-to-date. The input has been updated in accordance with the calculation methodology for cost benefit analyses (ASEK) latest version, Version 7 [8]. In addition, updates have been made to the input data for initial investment costs and operation and maintenance for ERS as well as for battery costs for electrified vehicles.

The calculation models have also been updated computationally, where the calculation model for ERS has been adjusted so that dynamic charged electric vehicles are assumed to be fully electric, i.e. they also run on electricity when not on electric road stretches with a battery for energy storage. Previously, it was assumed that the vehicles would be hybrid vehicles that run on diesel when not on the electric road. The calculations for CO_2 emissions have been updated to include foreign vehicles for stationary charging, as well as to include the entire distance driven by electric vehicles using the ERS infrastructure, including when not on electric road stretches (reduction of emissions when on an electrified road and when not on an electrified road is reported separately).

For more detailed accounts on the structure, design, and functionality of the calculation models, refer to the manual for the calculation model for ERS [9] and Chapter 4 of Report 4 [7] for the calculation model for stationary charging. Updated financial calculation models and manuals are expected to be published by the Swedish Transport Administration in spring 2021.

A financial calculation model has been developed for a hydrogen and fuel cell system for heavy vehicles. The calculation model has been based on the structure and logic used in the calculation model for stationary charging, with vehicles and refuelling station infrastructure as two main components. This calculation model is not at this stage intended to be published by the Swedish Transport Administration, as it requires further development.

2 Electrification technologies and their systems

2.1 Analysed electrification technologies

The following sections provide a brief description of the electrification technologies; a more detailed analysis of each technology can be found in previous reports [4] [5] [6] [7]. The technology around fuel cells and hydrogen has been studied at a more general level for the purpose of understanding the system and the relevance of different basic prerequisites with this alternative electrification technology.

2.1.1 Electric road systems

ERS can be described as roads with electricity transmission infrastructure that supplies a vehicle with electricity while travelling on it (dynamic charging). By building the technology into, or adding it to the road infrastructure, the roads can be accessible to both dynamically charged electric vehicles (vehicles using the electricity transmission), as well as to other vehicles powered by other fuels.

The system required to provide the infrastructure and functionality of the ERS can be described in four parts:

1. Electricity network infrastructure – current structure of electricity grids (regional or local networks), electricity grids along the electricity route providing electricity and connection points where the electricity grid is connected to the local or regional electricity grid [10].
2. The ERS infrastructure in the road area – the technology for transmission to the vehicle including systems for measuring usage.
3. Related services – payment service, information management, access control and security systems.
4. Responsibilities – maintenance, operation, financing and ownership.

Electrification via ERS technology requires major investments in infrastructure [4]. The level of both investment for infrastructure and operation and maintenance is high, and to some extent due to the choice of technical solution for the electrified road system [11].

Dynamically charged electric vehicles will need a battery to respond to the energy needs arising on routes when not on the ERS network. The proportion of the distances driven on the electrified road and on non-electrified sections of road depends on the planning of routes, as well as on the purpose for which the vehicle is used. It is likely that, for some vehicles, the distances when not on the electric road system, together with the capacity and power needs of the vehicles, will be extensive, which means that a relatively large battery will be required [11].

2.1.2 Stationary charging

Electrification by means of stationary charging means that the vehicle's powertrain is supplied with electricity stored in batteries in the vehicle. The battery is charged when the vehicle is stationary, unlike a road-powered electric vehicle that can also be charged while driving. Since the electrical charging takes place before travelling, the battery capacity determines the vehicle's range per charge.

Battery-powered heavy vehicles for stationary charging are being developed by several different manufacturers and the production rate is expected to increase in the coming years [12] [13]. Initially these are light truck types with short and medium daily driving distances, up to 40 tons and with distances driven up to about 300 km per charge, although in the near future the range is expected to increase [14, 11].

Stationary charging can be divided into different market segments depending upon where, when and with what power the battery is charging. In this study, the charging is divided into three different types:

- Depot charging – charging that occurs when the vehicle is in the depot, for example overnight. Transfer with a lower charging effect for a long period of time.
- Semi-public charging – electrical charging that takes place, for instance at an intended destination, such as when unloading and loading goods at logistics centres and requires higher charging effects.
- Public charging – electrical charging that takes place in public places, for example during lunch breaks. This type of public charging takes place during short periods of time and therefore also requires the highest charging effects among the three categories. [15]

These types of stationary charging have previously been analysed in phase 4 [7]. Major initial investments in charging infrastructure are regarded as being necessary in order to expand the stationary charging system for the long term. Investments in public charging infrastructure are expected to be made by private operators, such as the relevant fuel companies or parties active in the electricity market.

2.1.3 Hydrogen and fuel cells

In a similar way to stationary charging in combination with battery-equipped vehicles, fuel cells is a technology that in recent years has rapidly developed. This has now started to establish itself as a possible future electrification technology not only for heavy-duty vehicles but also for ships and work vehicles, for example. Fuel cells are an electrification technology that in the future may have the potential to electrify those vehicles that are more challenging to electrify by means of stationary charging or ERS. For example, these may be the heaviest vehicles that drive over long distances and often in areas with lower traffic flows [12]. One example of this is timber transports.

Fuel cells convert hydrogen into electricity. The vehicle therefore has an electric powertrain in the same way as vehicles for ERS and stationary charging. The fuel cell system consists of three main components that are integrated into the vehicle:

- Hydrogen tank – used to store the hydrogen used as an energy carrier for the fuel cell system.
- Fuel cell stack – the fuel cell stack produces electricity via a reaction that converts hydrogen and oxygen into water, while creating an electric current. This power is fed to the vehicle's electric motor and battery.
- Battery – even if the energy is primarily stored as hydrogen, a small battery is needed to be able to respond to higher effect peaks that can arise, for instance when accelerating the vehicle and to take advantage of regenerative braking energy. [16]

Since hydrogen has a higher energy density compared to batteries, calculated by unit of weight, fuel cell technology provides a longer range than charging-while-stationary vehicles, as well as the ability to electrify even the heavier types of trucks, which have longer driving distances.

It is likely that a hydrogen and fuel cell system for heavy-duty vehicles could be broadly similar to the current one for diesel-operated trucks, with hydrogen refuelling stations along the road network. Correspondingly, it is possible that a future business model for the sale and distribution of hydrogen will also be similar to that of diesel and to some extent also that of stationary charging, with refuelling station operators established beyond limited geographical areas [12]. However, it is difficult to assess how many refuelling stations might be part of a hydrogen system in Sweden, and their capacity.

An infrastructure system with hydrogen as an energy carrier and with fuel cells in heavy vehicles can be described in three parts, or cost components, Figure 1:

1. Production of hydrogen
2. Distribution of hydrogen
3. Hydrogen refuelling stations

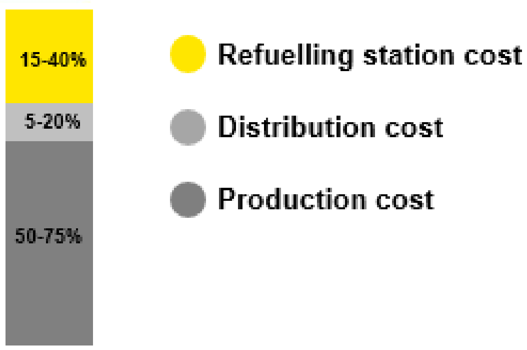

Figure 1. Illustration of main cost components for hydrogen [17].

Hydrogen is currently produced primarily via steam reforming of natural gas, which is a fossil-fuel raw material. In order for the hydrogen, and in turn the fuel cell electric vehicle, to be fossil-free, the hydrogen needs to be produced fossil-free (also called green or blue hydrogen). This can be done by means of electrolysis of water with renewable electricity or by steam reforming with CCS [18]. Renewable hydrogen production by electrolysis is a production method chosen by the European Commission to prioritise the rapid expansion of during the 2020s. [19]

The production of fossil-free hydrogen by electrolysis currently accounts for less than 2 percent of total hydrogen production in Europe [20]. The production cost of fossil-free hydrogen is about SEK 40-50 per kg, while fossil fuel hydrogen costs SEK 10-20 per kg. In order to be able to supply the volumes of fossil-free hydrogen that road vehicles and other applications are expected to demand by 2030, a comprehensive expansion of fossil-free production capacity is likely to be required [21].

The cost of fossil-free hydrogen is projected to decrease to levels competitive with fossil hydrogen by year 2030. This is partly via technology development regarding electrolysis stacks that reduce investment costs, and partly via efficiency improvements and economies of scale at higher production volumes compared to today [17]. Projections for the cost of fossil-free hydrogen include major uncertainties at the various stages of the hydrogen production system, which in turn has a direct impact on the calculations for a fuel cell system.

Demand for fossil-free hydrogen is expected to significantly increase in the future as other sectors also transition to fossil-free energy carriers, while new applications for hydrogen may emerge. Examples of this can be seen in the steel and chemical industries. The significant need for hydrogen at a societal level is another factor that contributes to difficulties and uncertainties in predicting the price level of hydrogen in the future [21].

The distribution of hydrogen from production facilities to hydrogen refuelling stations may be done by means of tankers/fuel trucks (in liquid form or as pressurised gas), by tanker ships and/or by pipelines depending upon the geographical preconditions [17]. In some cases, the production of hydrogen may also take place locally, in direct or close proximity to hydrogen refuelling stations.

The last infrastructure component of a fuel cell system is the refuelling stations themselves, which supply hydrogen to fuel cell electric vehicles. Unlike diesel refuelling stations, hydrogen refuelling stations require compressors and gas tanks to pressurise and store the gas at 700 bar, where the compressor alone can account for up to 60 percent of the investment expenditure for the refuelling station [22]. Even for refuelling stations, significant investments are expected to be required to create a refuelling station network for heavy transport, as only a few hydrogen refuelling stations exist today [22].

Even though the hydrogen refuelling and distribution infrastructure for a heavy-duty fuel cell system is not yet developed, some standards for refuelling passenger cars and transporting hydrogen already exist today, as hydrogen is already used in other applications, primarily in the chemical industry [18]. However, further product development and standardisation is necessary, including in terms of pressure in tanks and transfer technologies from the refuelling station to vehicles. All in all, the establishment of a fuel cell system requires extensive investments at all stages, from production via distribution to hydrogen refuelling stations.

The production and distribution of hydrogen has not been included in section 3, below, nor in the analyses conducted. The focus of this study is instead on the end-use of hydrogen for fuel cell-equipped heavy vehicles. Production and distribution are indirectly included via the use of a hydrogen price that includes production and distribution costs. Hydrogen price forecasts that include requisite investments in the production and distribution of hydrogen have been used in the analysis. Similarly, electricity generation and distribution were not included in the previously conducted analyses of ERS and stationary charging.

The price of fossil-free hydrogen at heavy vehicle refuelling stations and the uncertainty about price developments are today one of several limiting factors for the expansion of this electrification alternative options. With the current price for fossil-free hydrogen, most of the evidence suggests that the total cost of fuel cell electric vehicles and hydrogen will be higher not only than for equivalent conventional vehicles, but also compared to other electrification technologies [12]. The development of hydrogen prices in the future is therefore likely to be one of the decisive factors in establishing fuel cell technology.

In the case of electrification by fuel cell electric vehicles, it is assumed that the electricity demand will be greater compared to the corresponding electrification by ERS or stationary charging. This is because the fuel cell system has greater losses from the production of hydrogen by electrolysis with renewable electricity to the electric propulsion of the vehicle, than other electrification technologies. The losses occur partly in the production of hydrogen and partly in the conversion of the hydrogen into electricity in the fuel cell itself. The total demand for electricity has therefore been estimated to be about twice as large for fuel cell electric vehicles compared to electrified road or stationary charging vehicles [23].

2.2 Parties in each system

2.2.1 Comparison of stakeholders for ERS and stationary charging

Both an electrified road system and a stationary charging system will require involvement and interaction between several parties. Some of these parties can be expected to be involved in the development of both of these systems, while some stakeholders may be deemed to be specific depending on electrification technology and related technical systems. The identified parties likely to be involved in both systems are: *Vehicle manufacturers, hauliers and freight forwarders, electricity grid owners, electricity trading companies, road owners, technology suppliers* and *operators of ERS* or *charging station owners for stationary charging.* Further description and analysis of these parties can be found in the reports for the previous investigation phases [5] [6] [7].

The connection between the operators of the electrified road system is illustrated in Figure 2 and for stationary charging in Figure 3.

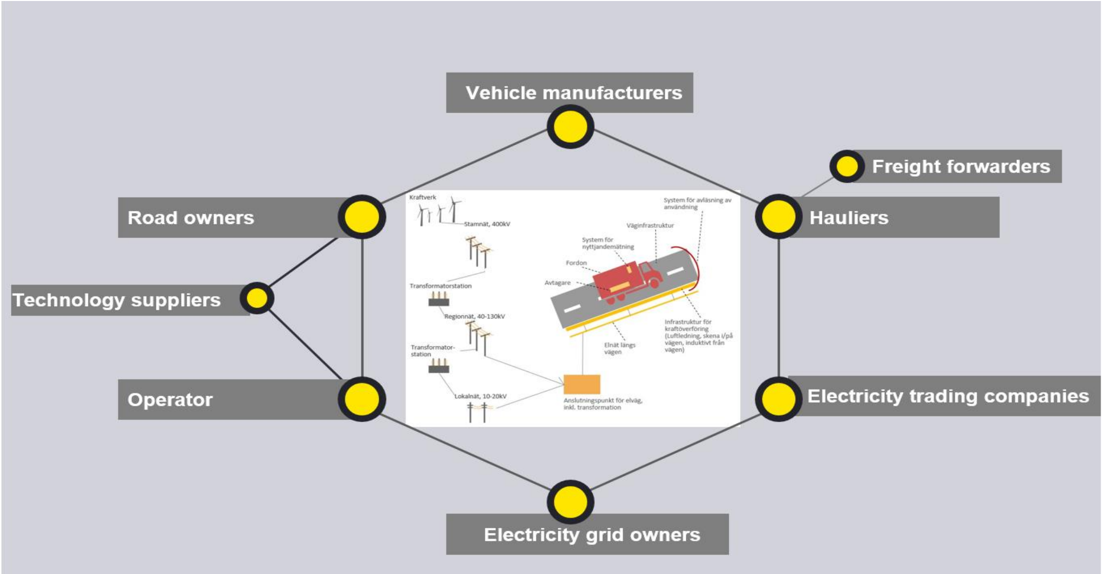

Figure 2. Operators in an electric road system.

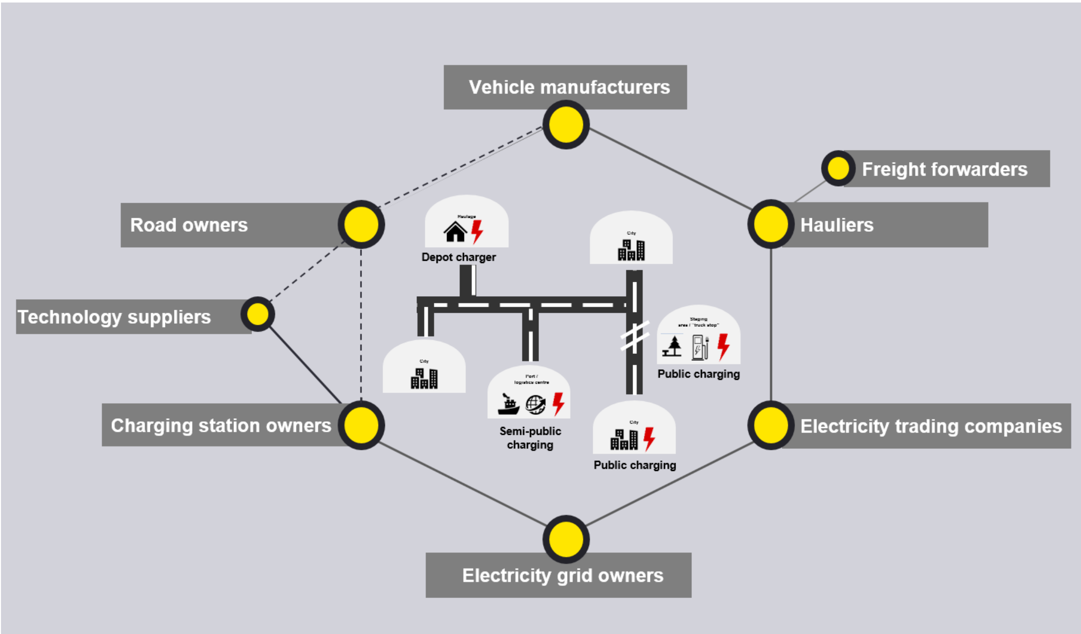

Figure 3. Operators in a stationary charging system.

There are two primary differences between stakeholders in an electric road system and a stationary charging system. One difference concerns the operator role. As public charging of passenger cars is being established, there is already a certain system for stationary charging, including operators in the market who act as charging station owners. Whether the designs being established for the passenger car market will also be relevant for the heavy road vehicles remains to be seen, however there is an initial market development to be based on for operators. The corresponding operator role has not yet been established for ERS, as ERS have not yet been built for public use. This makes it unclear what an operator role for ERS would look like in practice.

The second difference between the electrification technologies concerns the role of the road owners in the system. The construction and operation of ERS has a direct impact on the road system and the road infrastructure. This, together with the requirements for roadside devices, means that the involvement of the road owner needs to be significant in an electric road system.

The Swedish Government's directive outlining the assignment (I2020/02590) to the Swedish Transport Administration for the planning of an expansion of ERS, presumes that the road owner (the Swedish Transport Administration) takes the operator role in the event of an expansion of ERS [24]. The same starting point applies to the legal analysis of ERS in the investigation of the legal aspects of ERS initiated by the Swedish Government in October 2020 [25].

In a stationary charging system, the Swedish Transport Administration as a road owner has a less central role due to that the charging infrastructure is expected to be mostly provided on land outside the Swedish Transport Administration's area of responsibility. However, charging infrastructure at the Swedish Transport Administration's roadside rest areas may be established to a greater extent in the future. The Swedish Transport Administration may also have a continued role in the promotion or coordinating of the establishment of a charging infrastructure. Local government may however become more involved via the need to build charging stations in cities.

2.2.2 Parties working with fuel cells

The parties of a fuel cell system have not been analysed in detail at this stage, however the system may consist of similar roles as for a stationary charging system or current diesel system. It is likely that the distribution system will be built up in a similar manner as with service stations along the road network. As with diesel refuelling, it is also reasonable to assume that these would be specific to heavy-duty vehicles and would not be combined with refuelling for passenger cars. It is therefore likely that two primary actors in the system would be hauliers and refuelling station owners.

A major difference from the electric road system and charging infrastructure systems is that in a fuel cell system the focus on electricity grids and electricity distribution does not have the same importance. Rather, the focus will be on the production of hydrogen and distribution and technology suppliers, which are responsible for technical solutions that enable hydrogen refuelling.

2.3 Submarkets analysed

When analysing types of vehicles, a division into four different submarkets has been made. These are intended to reflect the varying distance driven and driving patterns of the vehicles in each submarket. The fleet of heavy-duty vehicles has been divided into the following four submarkets (for further descriptions of these submarkets, refer to the report for Phase 4 [7]):

- Long-distance transport
- Regional transport
- Local transport
- Foreign-registered vehicles

Long-distance transport is defined as the heavy-duty vehicles with the longest distances driven. Vehicles used primarily in long-distance transport are assumed to use depot charging for most of their energy demand, however to some extent also semi-public and public charging. For ERS, all vehicles are assumed to be long-distance vehicles, including foreign-registered ones. The dynamically charged electric vehicles are also believed to supplement the energy supply via depot charging to be able to drive when not on an electrified road [11]. Long-distance transport is the submarket that is largely assumed to use fuel cells and is assumed to refuel hydrogen at hydrogen refuelling stations. However, as has been pointed out above, hydrogen and fuel cells can also be an option for special markets such as timber transporters.

Regional transports are defined as heavy-duty vehicles with a shorter daily distance than long-distance vehicles and with a lower demand on power and energy. They operate within a limited geographical area and most of their distance driven is not on the largest roads identified as suitable for ERS infrastructure. Regional transport is likely to be able to cover its energy needs more from depot charging compared to the long-distance vehicles.

The local transport submarket is defined as vehicles used in urban distribution and local driving with the shortest daily distances driven. This allows the vehicles supplying the local transport segment to cover most of the energy demand from depot charging, which is also the most cost-effective form of charging for a haulage contractor.

Foreign-registered vehicles are engaged in some of the traffic on Swedish roads. It is likely that some of these vehicles may use stationary charging in Sweden in an expanded system. For foreign-registered vehicles to be able to be operated on ERS in Sweden, it is necessary that the technology is developed in neighbouring countries and that the same standards for power consumption are used. It is also possible that the electrification of heavy-duty vehicles takes place more quickly in surrounding countries, and that foreign vehicles can be a motivating force in the expansion of an electrification infrastructure for heavy vehicles.

3 A financial calculation model for hydrogen and fuel cells

A financial calculation model has been developed to enable the analysis of a fuel cell system for heavy vehicles. In the calculation model, the fuel cell system for vehicles as an independent system is analysed. The calculation model has been based on a similar approach as previous models for ERS and stationary charging, so as to enable comparisons and future combination scenarios with ERS and stationary charging.

The calculations conducted in the model are margin calculations where a fuel cell system is compared on the margin against a corresponding diesel system. The aim is to understand whether there are incentives from a financial perspective to use vehicles with fuel cells instead of diesel vehicles. Completed analyses of a fuel cell system for heavy vehicles have focused on a relatively mature and expanded system, rather than an initial system under expansion. This is to enable comparisons with systems for charging-while-stationary vehicles and ERS.

The calculation model shall primarily be used as a basis for discussion and to gain an understanding of the economic viability of a fuel cell electric vehicle system from a financial perspective, given various scenarios for the size of the system and costs. The model enables scenario analyses with different input values and the assessment of results for the system as a whole and for individual parties.

The calculation model consists of two main components:

- fuel cell electric vehicles and
- hydrogen refuelling stations.

The input data components used in the fuel cell calculation model are illustrated in Figure 4.

The size of the system can be freely selected in the calculation model via specifying the number of vehicles to be composed of the system. Foreign-registered vehicles are also added as a percentage of the Swedish-registered vehicles. Input data for the vehicles, such as additional cost vis-à-vis diesel vehicles, fuel consumption and distance driven, are adjusted according to the type of vehicle analysed.

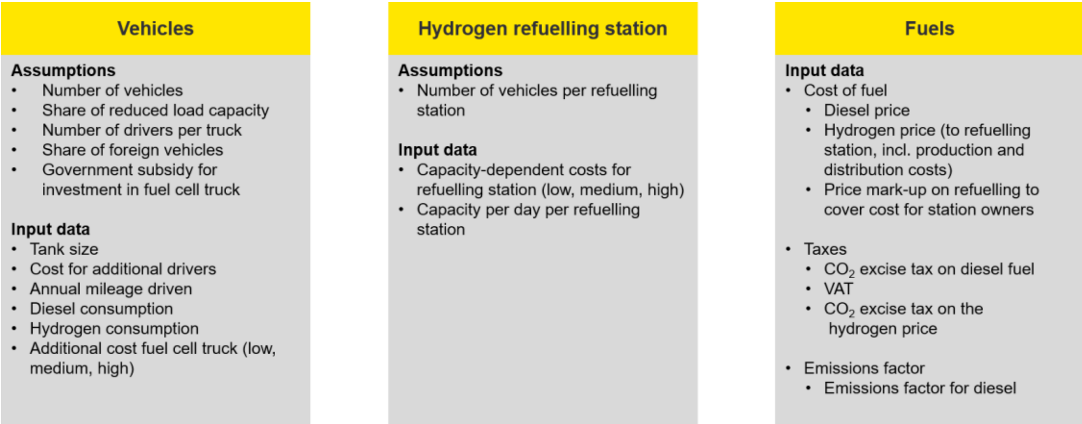

Figure 4. Input data components used in the fuel cell calculation model.

A function is inserted in the calculation model to select the percentage reduction of load capacity depending upon the volume of the fuel cell system on the vehicle, which in the event that such a reduction in load capacity occurs is compensated by additional vehicles and drivers. The investment cost for the vehicles is indicated as an additional cost relative to diesel vehicles and can be adjusted between a low, medium and high level of investment.

The number of hydrogen refuelling stations is set by an adjustable factor for the number of vehicles per hydrogen refuelling station. The number of hydrogen refuelling stations is thus adapted to the number of vehicles in the system. The capacity of hydrogen stations is measured in the number of kg of hydrogen that the refuelling station can supply fuel cell electric vehicles with per day (kg /day). Investments in hydrogen refuelling stations depend on the daily capacity of the refuelling station and are measured in SEK per kg of daily capacity.

The price of diesel and hydrogen is indicated in the model depending upon the scenario analysis and year. By means of sensitivity analysis, these have been identified as having a major impact on the result as the calculation model is based on margin calculations.

One conclusion from initial analysis of the calculation model is that the price for hydrogen is the factor that has the greatest impact on the system's performance and is crucial for the financial viability of the fuel cell system. Sensitivity analyses have also been conducted for the level of the refuelling station investment, the number of vehicles per refuelling station and hydrogen consumption.

4 Characteristic features of different electrification technologies

4.1 Infrastructure and driving patterns

ERS requires substantial investment in infrastructure. Achieving an economically viable system from a financial perspective requires a high rate of utilisation of the system and thus high traffic flows on the electrified routes. An electrified road system is probably best suited for electrifying vehicles in the heaviest vehicle classes that drive long distances on specific roads on a daily basis. This allows ERS to be regarded as being best suited for high traffic roads where a high proportion of the total distance driven by the vehicles consists of specific routes, see Figure 5.

Figure 5. Illustration of an electrified road.

A stationary charging system provides greater flexibility in infrastructure investments, due to that the system can be expanded with charging stations in stages in the geographical areas where a need exists. Such that more locally developed geographical coverage areas can be merged and expanded over time (see Figure 6). Investments in charging infrastructure can be made by both private operators and governmental, as well as on privately-owned or publicly-owned/controlled land. Stationary charging of vehicles allows vehicles to maintain flexibility regarding driving patterns, as the need for charging infrastructure exists only when the vehicle is stationary and charging, i.e. not while driving. On the other hand however, the driving possibilities are limited by the range that the batteries allow after a charge in combination with additional charging.

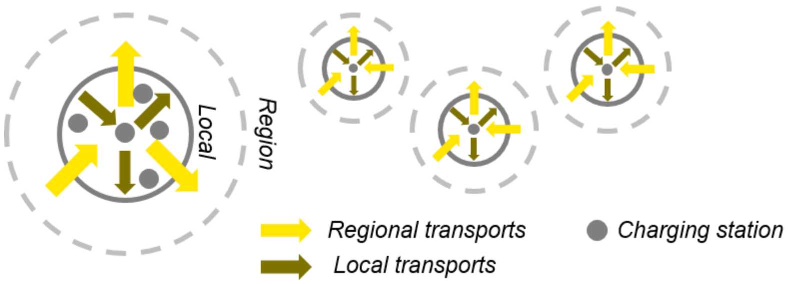

Figure 6. Illustration of a stationary charging system, where charging infrastructure can be gradually expanded.

All in all, this means that stationary charging can be assumed to be best suited for vehicle segments where the vehicles have different driving distances and patterns among each other but within a specific geographical area and with regular driving patterns for the individual vehicles. The shorter the daily distance driven, the less battery capacity is needed; batteries that account for a relatively large part of the vehicle's total cost of ownership. Driving distances of up to 300 km per charge are already possible for light- and medium-duty trucks.

It is likely that a *fuel cell* system will have similar characteristics as a diesel system and stationary charging systems in such a way that it is not linked to specific stretches of road infrastructure. Compared to stationary charging, the time it takes to refuel a fuel cell electric vehicle with hydrogen is shorter. Hydrogen refuelling is almost as fast as refuelling diesel. Fuel cell electric vehicles also have a longer range than stationary charging vehicles, already up to 1,000 km per tank [26].

The likely market for fuel cell electric vehicles is primarily long-distance vehicles that drive over long distances with heavy loads where battery operation is not possible. It may also be a beneficial electrification technology for vehicles with irregular driving distances. Compared to ERS, fuel cells are a more suitable technology in areas without proximity to the electricity grid or in areas where the volume of traffic is too small to justify the investment in ERS technology, and that fuel cells provide greater flexibility in driving patterns and changes in them.

Other types of applications that are regarded as being difficult to electrify in other ways may also be relevant for fuel cells. This applies, for instance, to heavy machinery in forestry and mining.

For fuel cell electric vehicles, as for diesel vehicles, the fuel accounts for a large part of the total cost of ownership of the vehicle, which means that the hydrogen price is of great importance compared to the electricity price of charging-while-stationary vehicles and dynamically charged electric vehicles. At low prices for hydrogen, it is possible that fuel cells can compete with ERS and stationary charging for other types of vehicles as well, while a higher price of hydrogen is likely to make primarily types of vehicles that cannot be electrified in other ways relevant to fuel cells.

Similar to charging infrastructure and diesel refuelling stations, a hydrogen tank infrastructure can also be expanded in stages and over the geographical areas where needs arise, see Figure 7. This provides some flexibility to adapt and develop the system as time goes on.

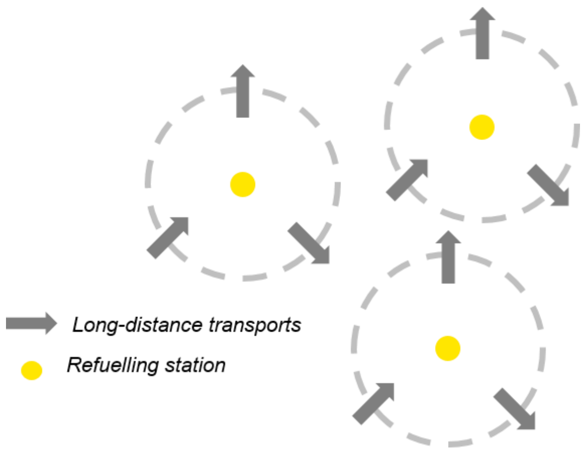

Figure 7. Illustration of a fuel cell system based on hydrogen refuelling stations.

The systems for fuel cell and charging-while-stationary vehicles can both be deployed in stages, where the infrastructure is expanded in the event of increased capacity and geographical dispersion. This means that stationary charging and fuel cells enable electrification on both low and high traffic routes, which is a difference from the ERS option. At a construction stage, smaller fuel cell systems with locally produced electricity may be established. The construction of refuelling stations in close proximity to local electricity production could lead to a lower price of hydrogen, which increases the competitiveness of the hydrogen alternative.

For ERS, the electrified road infrastructure is instead expanded as a first step, after which the system can then be used by vehicles adapted for the ERS. Therefore, an electrified road system does not have the same type of short-term capacity limitation as a fuel cell or stationary charging system. However, as dynamically charged electric vehicles are assumed to need a battery for driving distances when not on an electrified road, the electric road system needs to be complemented by a stationary charging system to make driving on these routes possible. Therefore an electrified road cannot be regarded as being an independent system in the same way as stationary charging and fuel cells.

ERS and stationary charging are both electrification technologies that can be connected to existing power grids, although extensive additions may be required in some locations. Modification and expansion needs for the distribution of electricity vary between technologies. Even though the levels of investment differ, both of these technologies are based on the backbone networks and electricity systems that in essence already exist, with existing regulation and markets. In this respect, fuel cells differ as it is an electrification technology based on the production and distribution of hydrogen, which is not presently available in Sweden for this purpose. This in turn gives rise to greater uncertainty about estimates of the expansion of the fuel cell system and entails a greater risk.

For vehicles adapted for ERS and/or stationary charging, the cost of batteries is a large part of the vehicle's total cost of ownership. The vehicle investment will be higher than for diesel vehicles, while the cost of fuel (electricity) over the life of the vehicle is lower compared to the cost of fuel for a diesel vehicle. Fuel cell electric vehicles, on the other hand, have a higher fuel cost however a lower level of investment than vehicles with large batteries. The fact that operating costs account for a greater share of the total cost of ownership of fuel cells also makes these vehicles more sensitive to adjustments in the price of hydrogen. In this way, fuel cell-powered vehicles are similar to today's diesel vehicles, as fuel costs account for a larger part of the vehicle's total cost of ownership.

Table 1 shows a summary of the characteristics of electrification technologies, see below.

Table 1. Summary table of the characteristics of the different electrification technologies.

	ERS	Stationary charging	Hydrogen and fuel cell system
Suitable driving patterns	Long distances, heavily trafficked routes	Geographically varying, primarily shorter driving distances	Long distances, irregular driving distances
Submarkets	Long-distance vehicles	Local, regional and long-distance vehicles	Long-distance and special vehicles
System expansion	Expansion in stages, infrastructure is completed first	Flexible, expansion in stages	Flexible, expansion in stages
TCO for vehicles	Greater emphasis on vehicle investment	Greater emphasis on vehicle investment	Greater emphasis on the cost of fuel

4.2 Batteries

All electrification technologies covered in this report are based on vehicles with batteries. In the event of a significant increase in the number of battery-electrified vehicles, the need for the number of batteries produced is also increasing. The size of the batteries differs between the electrification technologies because the function of the battery varies between them.

Since stationary charging is distinctively a battery electric vehicle technology, battery-powered vehicles have been assumed to need the largest batteries, which in this analysis is assumed to be up to 600 kWh by 2030 on average for vehicles travelling long distances [15]. Dynamically charged electric vehicles are also expected to use relatively large batteries, up to half the size of the largest batteries for stationary charging, or 300 kWh [11]. Fuel cell electric vehicles use smaller-sized batteries to cope with the power peaks that occur while driving and to utilise the amounts of energy generated by braking (braking energy). In conversations with market participants, these have been estimated to need to be up to 50 kWh.

Heavy battery equipped vehicles for stationary charging are currently in early phases of industrial production and production is likely to increase in scope in the future. Heavy fuel cell electric vehicles are also in production today however seem set to be scaled up only towards the end of the 2020s [13]. In this respect, electric road system vehicles differ, where no plans for the future industrial production of dynamically charged vehicles have been communicated from major market participants.

The primary sustainability aspects linked to the electrification of heavy vehicles by ERS, stationary charging and fuel cells concern electricity generation, hydrogen production and battery production. The production of batteries involves environmental risks, mainly linked to the mining and processing of the metals and minerals used in the batteries. It is relevant to point out that the batteries required to electrify the 85,000 heavy-duty vehicles in Sweden today are a relatively small amount compared to the five million passenger cars that are also potentially to be electrified using batteries [27].

The availability of specific earth elements and minerals needed for the production of batteries is somewhat limited today, and is expected to decrease even further in the future. So as to counteract this lack of natural resources, and to reduce the environmental impact of the extraction of these metals, an increased degree of circularity in the battery system is required. This can be accelerated by the Directives developed by the European Commission where batteries over two kWh must have a minimum level of recycled material for specified substances. For example, it is proposed that at least 20 percent of the cobalt used in the production of new batteries should be recycled [28]. There are also suggestions for recycling rates from scrapped batteries. For lithium, 35 percent is proposed for 2025 and 70 percent by year 2030. For copper, nickel and cobalt, a 90 percent recycling rate is proposed by 2025 and 95 percent by year 2030 [29].

The environmental risks associated with electricity and hydrogen production depend primarily on the choice of energy source (and also the production method) and the greenhouse gas emissions associated with it. In the financial calculation models for ERS and stationary charging, electricity is presumed to be produced from renewable sources.

5 Combinations of electrification technologies

5.1 Submarkets and electrification technologies

There is not one single obvious electrification technology that is best suited for all submarkets and applications. Therefore, it is likely that in the future we will see a combination of some or all of the analysed electrification technologies with a focus on different submarkets and geographical spread, see Figure 8. Considering that previous phases have analysed ERS and stationary charging as individual systems, it is relevant to broaden the analysis to understand what parallel establishment of electrification technologies might look like.

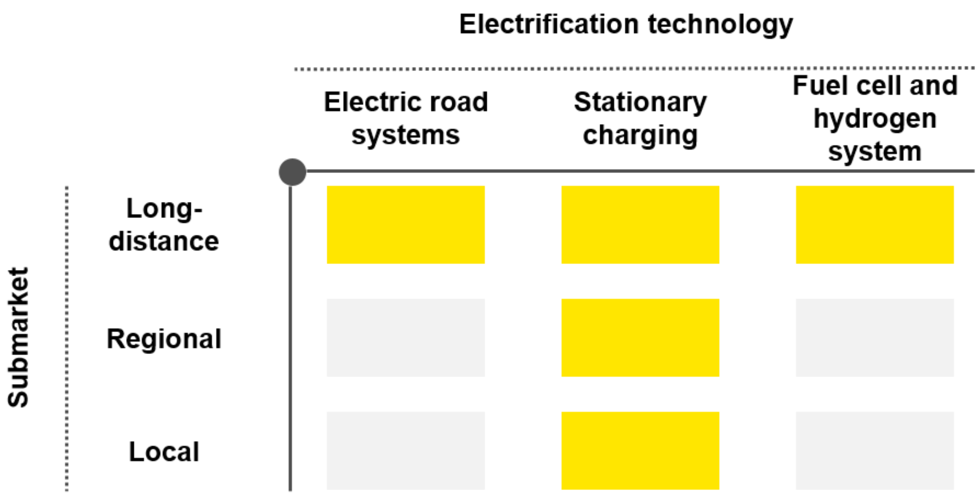

Figure 8. Illustration of likely primary submarkets for each electrification technology

One conclusion from previous analyses is that it is likely that a possible construction of an electric road system could take place on the roads connecting Stockholm-Gothenburg-Malmö, in order to reach as high traffic volumes as possible. A high rate of utilisation is needed to achieve economic viability for an electric road system. In addition, long-distance vehicles that travel long distances on specific routes are assumed to be most suitable for ERS.

Even though, due to the current range of battery-powered trucks, the initial focus on stationary charging is expected to be in the local and regional submarkets, development in battery technology in the coming years are expected to make it possible for some parts of the long-distance market to switch to battery-powered vehicles for stationary charging. This means that it is possible, that some overlap may be the case between ERS and stationary charging, where technicians compete for the same submarket.

Stationary charging is the electrification technology that has so far come the furthest in establishing itself in the heavy vehicle market. Production of battery-powered heavy vehicles has begun and components for the system are available from various technology suppliers, such as charging infrastructure components, even if the further development of technology remains to be done and is ongoing. This means that any introduction of ERS would most likely take place in a market where stationary charging has already been established, and reached a certain maturity. This is especially so, given that an introduction of ERS technology on the main roads in Sweden could potentially take many years due to long lead times in planning and construction.

Vehicles with a driving pattern and a technical design that makes them suitable for ERS will therefore most likely have already been electrified using charging infrastructure. Such a market cycle may reduce the market potential of the ERS solution, reducing the economic viability of that option.

Even though a competitive situation may arise in this way between ERS and stationary charging, the two technologies are to some extent interdependent. The interdependence is clearer from ERS technology to the alternative of charging infrastructure and battery vehicles than vice versa. Dynamically charged electric vehicles, for example, need relatively large batteries to be able to cope with driving distances when not on the ERS, which in reality can often account for a relatively large part of the total distances driven [11].

In the event there is a need for a diversion of electrified road traffic, for example in the event of traffic disruptions or roadworks, it must also be possible to provide alternatives with charging stations for otherwise dynamically charged electric vehicles with short notice. Either such charging infrastructure can be provided by means of mobile equipment, or by setting up fixed pre-planned diversion routes in parallel with the roads being electrified.

Both alternative options accentuate the need to supply even ERS trucks with relatively large batteries, and this contributes to a higher vehicle cost and/or investment expenditure for ERS. This interdependency, where stationary charging is to some extent also a prerequisite for ERS, while stationary charging is an electrification technology during ongoing establishment, makes it likely that stationary charging will account for large parts of the market for electrified heavy vehicles. Therefore it is not unreasonable to have a future scenario in which ERS are given the role of alternative electrification technology in cases where no other electrification technologies are established for the heaviest vehicle segments, which run on the highly trafficked routes primarily between the country's metropolitan areas or between important transport nodes.

In recent years, there has been a rapid development of batteries, where we have seen reduced costs, higher energy density and total capacity. If this development continues to reduce battery costs at a high pace while expanding the range of battery vehicles, it provides an additional advantage for stationary charging, which can further reduce the potential markets for ERS and fuel cell equipped electric vehicles.

No deeper analysis of combination scenarios combining stationary charging and ERS with a fuel cell and hydrogen system has been conducted. However, it is reasonable to assume that several different electrification technologies may be relevant for the heaviest vehicles. For the competitiveness of the fuel cell option vis-à-vis stationary charging and ERS, the future price of hydrogen is crucial. At a high price for hydrogen, fuel cells are less likely to become a competitive solution for electrifying vehicles, which can also be electrified using other electrification technologies. In this case, fuel cells are likely to be primarily used in applications and types of vehicles where other electrification technologies are not possible.

Irrespective of the choice of electrification technology, an electrified heavy vehicle in this analysis has been given zero CO_2 emissions on the assumption that electricity and hydrogen are produced with renewable energy sources and that all electrified vehicles are fully electric, i.e. they are not diesel hybrids. Therefore, if we look at absolute emissions in the analysis of CO_2 emissions, the electrified vehicles do not generate any CO_2 (this is at the vehicle level; a situation that may look different if the analysis is extended to a life cycle option for the different electrification alternative options).

On the other hand, if we choose to compare the reduction of CO_2 with a vehicle fleet that has not been electrified, consisting primarily of diesel vehicles, the share of bio fuel involvement in diesel plays a major role because a large share of bio fuels in diesel means that total emissions from the fleet are lower than otherwise. Therefore in this case, where the Swedish Government has decided on a large share of bio fuel involvement, there is a smaller amount of CO_2 emissions that need to be reduced, for instance by means of electrification. In this way, electrification of the vehicle fleet with a high level of bio fuel involvement in diesel results in a lower additional CO_2 reduction in absolute terms, compared to lower levels of bio fuel. This illustrates that different policy measures and the possibilities of technological development need to be seen in a context in order to achieve cost-effective measures.

5.2 Analysis of combinations with the financial calculation models

The calculated models that have been developed can be used to analyse scenarios with combinations of ERS, stationary charging, and fuel cells as electrification technologies. The following analyses are based on analysis of combination scenarios for ERS and stationary charging. However, fuel cells should be included in future combination analyses as it is relevant to analyse a combined system with all three electrification technologies.

By selecting input data in the model for possible combination scenarios for ERS and stationary charging, including the proportion of vehicles for each electrification technology (annual average daily traffic (AADT) for ERS and number of stationary charging vehicles), total results can be compiled. Both calculation models, as well as the previous version of the financial calculation model for ERS, have functionalities that makes the adjustment of investment levels, fuel costs, and infrastructure and vehicle data possible. In this way, different scenarios can be developed for specific levels of annual average daily traffic and electrified vehicles for stationary charging together with different price forecasts for the price of diesel, the level of bio fuel involvement in diesel and emission factors at selected years.

Uncertainties in future forecasts make it urgent to develop several possible scenarios. By carrying out scenario analyses, crucial aspects can be identified and studied in greater detail, while at the same time providing an understanding of the different relationships that can be assumed to exist in the systems. Examples of parameters that may be relevant to study are the total cost of ownership and investments, results for the combined system additional to the technologies separately, and the total reduction of CO_2 for a combined system.

Comparisons can also be made for investment expenditure per CO_2 equivalent depending on the choice of electrification technology and the scope of the expansion alternatives. Further analyses that can be made are comparisons of the additional costs incurred by hauliers in transitioning from diesel to an electrified fleet of vehicles, i.e. additional costs for vehicles, infrastructure, and electricity.

The foreign-registered vehicles included as an aspect within the calculation models affect the system by contributing to an additional revenue stream for charging infrastructure owners for semi-public and public charging. The additional foreign-registered vehicles may also result in a higher rate of utilisation for existing semi-public and public charging stations that could bring incentives for additional charging stations needing to be added to the system. Similarly, the foreign-registered vehicles provide a higher annual average daily traffic for the electrified road system, which can provide both increased revenues and higher investment needs to respond to the additional demand for, for example, electrical power.

5.3 Incentives for a transition to electrified vehicles

Electrified vehicles so far have a higher price than conventional trucks, which means that the total cost of ownership of an electrified vehicle in the coming years is assumed to be higher, despite an expectation of lower fuel costs and lower maintenance costs for electric vehicles. This is especially true for dynamically charged electric vehicles and stationary charging vehicles equipped with large batteries. In order to reduce the difference between the total cost of ownership of the different types of vehicles, electric trucks can be subsidised by the central government, for example with an environmental truck premium, similar to that already introduced [30]. Subsidies of this type create incentives for investments in an electrified vehicle fleet for vehicle manufacturers, as well as for hauliers and freight forwarders.

As the difference in purchase price between an electrified vehicle and a conventional vehicle narrows, other aspects are likely to play a greater role in establishing incentives for a transition to electrified vehicles. For example, the above-mentioned lower fuel cost, especially for charging-while-stationary vehicles that can charge in depots during the night.

Lower maintenance costs and lower levels of noise, which makes it possible for a greater utilisation of the vehicles at night, are also aspects that provide clear benefits.

From the perspective of an electricity grid owner or an electricity trading company, a trend towards a greater number of electrified heavy vehicles is beneficial as this increases the demand for electricity and network services. This should generally incentivise these network operators to monitor and accelerate the transition to electrification, although inertia may occur in the deployment of electricity networks and charging stations in certain locations.

Stationary charging of vehicles is currently available to some extent for passenger cars and to a limited extent also for heavy vehicles. The regulations and standards surrounding these systems are already developed and used, while they are still under development for ERS. For fuel cells, there are certain standards and regulations for refuelling and distributing hydrogen, however these need to be developed to enable higher capacity in both refuelling and storage.

Subsidies from the central government during an introduction of charging infrastructure are already being used to some extent, for example by means of a Regulation (2020:577) that allows the Swedish Transport Administration to provide investment support for the construction of fast charging public infrastructure along major roads. For hydrogen systems, both for vehicles and infrastructure, corresponding forms of support may be required.

5.4 Possibilities, opportunities, and risks

The high level of investments needed and the long construction time for ERS pose a risk in a market where technology development is taking place quickly. A slow pace of expansion risks leading to a situation where the technologies that various parties are making efforts to establish are outcompeted by technologies that are more competitive than ERS, partly because they may be faster and easier to introduce to the market [29].

The expansion of ERS would require major investments in the electricity grid along the routes being developed. Such investments, in turn, require coordination between the various electricity network owners established along the particular routes being developed. The introduction of ERS technologies that can be used by both heavy-duty vehicles and passenger cars can make the system more efficient with regard to the requisite investments.

Compared to ERS, stationary charging and the fuel cell option provide greater possibilities to flexibly adapt the system as it expands and needs change. This can be done via point-of-point investments in electricity networks, charging infrastructure or hydrogen refuelling stations. Investments can also be made at both regional or local levels, for example with important charging and tank nodes. The issues related to the electricity network capacity and challenges with power in the power grids are also significant for the charging infrastructure option.

Irrespective of the choice of electrification technology, a greater electrification of the vehicle fleet is assumed to increase the demand for electricity. This, together with the fact that electrification is expected to take place in other sectors as well, means that the total consumption of electricity is expected to significantly increase [31]. A large increase in electricity consumption presents challenges in both electricity generation and distribution. Stationary charging can enable the introduction of various forms of grid services, where the installed battery capacity of the vehicles is used during periods when the vehicles are not in use, something which may reduce the load on the electricity grid. This may also be relevant for ERS trucks in the event they are equipped with relatively large batteries.

As mentioned in the previous section, in an overall assessment of the financial viability of the different electrification alternatives, the costs of electrified vehicles compared to conventional diesel vehicles are an important factor. Part of the total cost of ownership of the vehicles is the cost of fuel. In order not to increase the costs with the usage of electrified vehicles, it is important that electricity prices do not rise sharply, for example as a result of an underdimensioned electricity system. At the same time, costs resulting from future and substantial investments in the electricity network and system can lead to higher electricity prices. Similarly, this is particularly relevant for fuel cell electric vehicles and the price of hydrogen as the cost of fuel accounts for an even greater share of the total cost of ownership of the vehicle.

6 Summary conclusions and continued analysis

This and previous phases have analysed and modelled systems for ERS, stationary charging, and fuel cells. Analyses have also been conducted on how ERS and stationary charging may affect each other when combinations of them occur on the market. With the possible introduction of fuel cells, the complexity of assessing the future development of the vehicle fleet further increases. At the same time, the electrification of heavy-duty vehicles needs to be rapid in order to achieve the stated objectives of significantly reducing and ultimately eliminating CO_2 emissions from domestic transport. In doing so, it is important to create a deeper understanding of the complexity of a fuel cell system, to produce combination scenarios that include fuel cells and to investigate how the electrification of the vehicle fleet can be accelerated, for instance by means of various incentive-enhancing measures.

The analysis should be deepened in order to gain a better understanding of the hydrogen system as a whole, including the demand for hydrogen and its distribution possibilities and infrastructure. This is important in order to be able to assess the structure and scope of a future hydrogen system that is reasonable to expect. A continued dialogue with market participants regarding reasoning and input data can also contribute to strengthening the understanding of the system's development and essential mechanisms.

The systems of the analysed electrification technologies differ in several ways where ERS, which is extended in specific routes and thus has a geographical limitation, depends on high traffic to reach financial viability. In addition, ERS depend on stationary charging for driving when not on these stretches of road. On the other hand, stationary charging and fuel cell systems can be expanded in stages and provide a different flexibility in driving patterns.

Another characteristic difference lies in the different vehicles' total cost of ownership. Stationary charging and ERS vehicles have a larger share of the total cost of ownership associated with the investment of the vehicle, due to the battery cost. Fuel cell electric vehicles differ, in the sense that in the future the investment in the vehicle itself is not expected to be much higher than conventional diesel vehicles. Instead, the bulk of the vehicle's total cost of ownership lies in the cost of fuel. This makes the fuel cell system more sensitive to the price of fuel than vehicles intended for stationary charging and ERS. How a system combined with these electrification technologies can be developed, and the competitive situation between them, is therefore relevant to analyse.

Several truck manufacturers already offer charging-while-stationary vehicles for sale and even more are in development. The development of new, more powerful and less expensive batteries is underway, and experiencing rapid progress, which will mean that the vehicle's range will gradually increase, while fuel cell styles are expected to be produced on a larger scale from the mid-2020s [13]. This rapid further development means that the prerequisites for the electrification of heavy vehicles can change in the future as technological development progresses.

To be able to be in a position to achieve the CO_2 reduction targets established by the Swedish Government, it is important that the electrification of the vehicle fleet takes off as quickly as possible. Stationary charging is the most advanced electrification technology, where new vehicles are about to be rolled out on a larger scale. This is especially true not only for the light trucks in local but also partly in regional distribution. It is therefore important to identify how a rapid expansion of stationary charging infrastructure can be effectively promoted, while analysing possible incentives and instruments that can be used to accelerate the expansion.

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