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Techno-economic analysis and design of the charging infrastructure for Electric Heavy Vehicles in Oskarshamn.

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Abstract

Within the most pollutants industries, the energy sector is the most significant contributor to climate change, representing two-thirds of the total Greenhouse Gas (GHG) emissions. One of the main responsible for these emissions is transportation, which accounts for 26% of the world's energy consumption, with crude oil-derived products providing more than 90% of this energy. In Europe, the transport sector is the only sector that has experienced an upward trend of GHG emissions between 1990 and 2017, opposite to all others, such as agriculture, residential, or industry. To cut these growing GHG emissions, transport electrification has been presented as a potential and promising solution for decarbonization thanks to the no tail-pipe emissions and the possibility of using renewable energy to power them. One particularly interesting segment of the transport sector is Heavy Duty Trucks (HDTs) used for freight transport. HDTs are the backbone of the Swedish economy and competitiveness since they represent 45% of its total goods transportation. However, the Swedish transmission grid needs to evolve parallelly to cope with the increase in electricity demand and withstand the Charging Infrastructure (CI) necessary for the electrification of HDTs. Oskarshamn is a Swedish municipality that presents a high potential for electrification of its HDTs, which are currently operated with diesel. Therefore, the objective of this Master Thesis is to study the implementation of Electric Heavy Vehicles (EHVs) CI in Oskarshamn by collaborating with local interested stakeholders. The study is conducted through an analysis of the current status of EHV technologies, as well as CI possibilities, which, together with the information provided by truck operators from Oskarshamn, allows to perform a techno-economic assessment of the solution and analyze the business model of its operation. A virtual model is created with *Python* to simulate the actual operating conditions, which uses all the information gathered and optimizes the CI design while fulfilling all its transport requirements. Additionally, the study seeks to identify potential areas for shared ownership of the CI to increase the project's feasibility. This project's findings demonstrate that electrification of freight transportation brings financial and sustainable benefits for truck operators while presenting a diverse range of options to meet their specific transportation requirements. Furthermore, by effectively negotiating ownership terms and electricity tariffs for CI, there is potential to further enhance business profitability.

Keywords: Electrification, decarbonization, freight transport, heavy duty vehicle, battery electric truck, charging infrastructure, business model assessment.

Sammanfattning

Inom de mest förorenande industrierna är energisektorn den mest betydande bidragsgivaren till klimatförändringarna och står för två tredjedelar av de totala utsläppen av växthusgaser (GHG). En av de huvudsakliga ansvariga för dessa utsläpp är transportsektorn, som står för 26% av världens energiförbrukning, där produkter som härstammar från råolja utgör över 90% av denna energi. I Europa är transportsektorn den enda sektorn som har upplevt en ökande trend av GHG-utsläppen mellan 1990 och 2017, till skillnad från alla andra sektorer. Därför är elektrifiering av transporten en potentiell och lovande lösning för avkolning, tack vare frånvaron av avgasutsläpp och möjligheten att använda förnybar energi för att driva fordonen. En särskilt intressant del av transportsektorn är tunga lastbilar (HDTs) som används för godstransport. HDTs utgör ryggraden i den svenska ekonomin och konkurrenskraften eftersom de står för 45% av den totala godstransporten. Dock behöver det svenska transmissionsnätet utvecklas parallellt för att klara av ökningen av elförbrukningen och klara av laddinfrastrukturen (CI) som krävs för elektrifieringen av HDTs. Oskarshamn är en svensk kommun som har stor potential för elektrifiering av sina HDTs, som för närvarande drivs med diesel. Därför är målet med detta examensarbete att studera implementeringen av laddinfrastruktur för eldrivna tunga fordon (EHVs) i Oskarshamn genom samarbete med lokala intressenter. Studien genomförs genom en analys av den aktuella statusen för EHVs-teknologier, samt CI-möjligheter, vilket, tillsammans med informationen som tillhandahålls av lastbilsoperatörer från Oskarshamn, möjliggör en teknisk-ekonomisk bedömning av lösningen och analyserar affärsmodellen för dess drift. En virtuell modell skapas med hjälp av Python för att simulera de faktiska driftsförhållandena, vilket utnyttjar all insamlad information och optimerar designen av CI samtidigt som alla transportkrav uppfylls. Dessutom syftar studien till att identifiera potentiella områden för delägarskap av CI för att öka projektets genomförbarhet. Denna projekts resultat visar att elektrifiering av godstransport ger ekonomiska och hållbara fördelar för lastbilsoperatörer samtidigt som det presenterar ett brett utbud av alternativ för att möta deras specifika transportkrav. Dessutom finns det potential att ytterligare förbättra affärs lönsamheten genom effektivt förhandla om ägandevillkor och eltariffer för CI.

Nyckelord: Elektrifiering, avkolning, godstransport, tunga fordon, batterielektrisk lastbil, laddinfrastruktur, affärsmodellsbedömning.

List of abbreviations

Alternating Current (AC)

Announced Pledges Scenario (APS)

Battery Electric Vehicles (BEV)

Brushless DC (BLDC)

Certified Emissions Reductions (CERs)

Charging Infrastructure (CI)

Charging Point Operator (CPO)

Charging Stations (CS)

Clean Development Mechanisms (CDM)

Conductive Power Transfer (CPT)

Conference of the Parties (COP)

Direct Current (DC)

Electric Heavy Vehicle (EHV)

Electric Truck (ET)

Electric Vehicle (EV)

Electric Vehicle Service Provider (EVSP)

European Union (EU)

Greenhouse Gasses (GHG)

Gross Trailer Weight (GTW)

Heavy Duty Truck (HDT)

Heavy Duty Vehicle (HDV)

Induction Motor (IM)

Internal Combustion Engine (ICE)

International Energy Agency (IEA)

Level-1 charging type (L1)

Level-2 charging type (L2)

Level-3 charging type (L3)

Level-4 charging type (L4)

Light Duty Vehicles (LDV)

Light-Duty Electric Vehicle (LDEV)

National Renewable Energy Laboratory (NREL)

Nationally Determined Contributions (NDC)

Net Zero Emissions (NZE)

Panel on Climate Change (IPCC)

Paris Agreement (PA)

Permanent Magnet AC (PMAC)

Permanent Magnet Synchronous Motors (PMSM)

Stated Policies Scenario (STEPS)

Sustainable Development Goal (SDG)

United Nations (UN)

United Nations Framework Convention on Climate Change (UNFCCC)

Wireless Power Transfer (WPT)

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1. Introduction

In recent years, the transportation industry has been confronted with a critical challenge: reducing its environmental impact while meeting the increasing demand for goods and services. However, the increase in goods demand has only brought a continuous rise in greenhouse gas emissions. As a result, there has been a growing emphasis on exploring sustainable alternatives to traditional fossil fuel-powered vehicles, particularly in heavy-duty freight transport.

This master's thesis seeks to study the implementation of an Electric Heavy Vehicles (EHVs) Charging Infrastructure (CI) in Oskarshamn to break the correlation between increasing demand for transport and increasing Greenhouse Gas (GHG) emissions. Oskarshamn holds great promise to be at the forefront of building up infrastructure for HDV based on the energy capacity, transport needs, and a municipality with a focus on sustainability. Moreover, Oskarshamn Harbor is a hub for transportation, as it also serves as a terminal for ferries that connect the city to other parts of Sweden, such as with Gotland, which is an essential route for goods transportation.

It is essential to notice that the transport sector contributes to over 30% of Sweden's GHG emissions, with road transport accounting for 92% of those emissions. Furthermore, truck registration is still entirely dominated by diesel-powered trucks.

In this introduction section, an overall view of the transport sector's GHG emissions problem will be presented, starting from where the concern for GHG emissions comes from, followed by the actions that have been taken up to now. Then, the current GHG situation will detail why driving the focus into the transport sector is essential. Finally, the solution that this project brings to address the problem (e.g., transport electrification) will be introduced, as well as the main challenges that still need to be overcome to achieve the objective of this project.

1.1. Historical context

The greenhouse effect is a phenomenon that has been concerning environmental scientists even before the 20th century. In 1896, the Swedish scientist Svante Arrhenius formulated his hypothesis postulating the existence of the greenhouse effect and that increasing levels of atmospheric Greenhouse Gasses (GHGs), such as H_2O, CO_2, or NO_x, would lead to an increase in global temperatures [1]. The greenhouse effect is the process by which GHGs trap heat from the sun and warm the planet's surface, causing temperatures to rise and leading to significant changes in the planet's climate, such as more frequent heat waves, more intense storms, and rising sea levels. Svante Arrhenius was one of the first scientists to suggest a link between human activities, such as burning fossil fuels, and the Earth's climate changes.

GHGs are the main contributor to the well-known phenomena of *climate change*, by which, due to anthropogenic actions, long-term Earth's climate patterns are shifting and endangering life as it is known. Even though climate change can go back to the 1800s, when the use of fossil fuels started to become popular at the beginning of the 2000s, society's awareness has become more significant. The reason behind this consciousness has been the direct relationship between the increase in GHG emissions and the increase in environmental impact, mainly caused due to massive globalization and industrialization [2]. This critical situation has brought many scientists, physicists, and experts from many fields to start acting on the subject, monitoring processes, tracking pollutants, and implementing solutions to prevent pollution worldwide.

The most influential parameter related to climate change is CO_2 emissions. When CO_2 is deployed into the atmosphere, it captures solar radiation reflected by the Earth's surface, increasing Earth's temperature. CO_2 emissions, as well as other GHGs, are generated mainly due to the combustion of fossil fuels, used widely for industrial processes as well as in the energy system. It is for that reason that the regulations for energy transition have been focused on the need for decarbonization of industrial processes [3].

1.2. Dealing with climate change

The United Nations Framework Convention on Climate Change (UNFCCC) entered into force in 1994 with the purpose of stabilizing GHG concentrations to prevent dangerous anthropogenic interference with the climate system. In 1997, the final protocol of the Kyoto conference (Kyoto Protocol to the UNFCCC) aimed to establish GHG emissions reduction targets through the creation of Certified Emissions Reductions (CERs) under the so-called Clean Development Mechanisms (CDM). Between 2005 and 2011, the first carbon market emerged and expanded massively. CDMs allowed developed countries to invest in emissions-reducing projects in developing countries and receive carbon credits in return. These credits could then be used to meet their emissions reduction targets under the Kyoto Protocol [4]. However, these CDM brought big controversy due to that they did not provide clear measurements of the GHG emissions reduction nor assure additionality, permanence, or integration of developing countries [5].

More recently, in 2015, the Paris Agreement (PA) attempted to cover up the failures of the Kyoto Protocol by redefining the CDM, introducing a bottom-up system where governments were to submit their Nationally Determined Contributions (NDCs) [4]. PA aimed at limiting global warming below 2 degrees Celsius above pre-industrial levels and pursuing efforts to limit it to 1.5 degrees Celsius. The Agreement requires countries to submit their NDCs, outlining their plans to reduce greenhouse gas emissions and improve resilience to the impacts of climate change [6]. At the same time, the UN adopted the United Nations Sustainable Development Agenda, also known as the 2030 Agenda, a set of 17 interrelated Sustainable Development Goals (SDGs) to end poverty, protect the planet, and ensure peace and prosperity for all. PA and SDGs, together with the Conference of the Parties (COP), a yearly gathering of representatives from the member countries of the UNFCCC, help countries to come together to address the challenges posed by climate change and to implement international agreements aimed at reducing GHG emissions.

When looking at the future, efforts for achieving global sustainability progress through the SDG lens have been put into short-medium term, with the 2030 Agenda, the Paris Agreement (2050), or the Intergovernmental Panel on Climate Change (IPCC). Although it has to be considered that in some situations, this shorter view can limit the understanding of longer-term progress and delayed or non-linear behavior of slow sustainability trends [7]. In order to help governments and public and private actors to understand the various possible outcomes driven by their actions, the IEA has developed a set of three scenarios to show which are the most appropriated pathways to reach their objectives in the short-medium term. These scenarios display dynamic models where decisions from specific actors influence the development of the overall system, for example, policy choices made by governments, which can shape investment decisions [8]. These three scenarios are detailed in the *World Energy Outlook 2022* [8] and are the following:

- Net Zero Emissions by 2050 (NZE) Scenario, which aims to stabilize global average temperatures at 1.5 °C above pre-industrial levels and reach net zero CO2 emissions by 2050.
- Announced Pledges Scenario (APS), which assumes that governments will meet all of the climate-related commitments that they have announced on time, and it is associated with a temperature rise of 1.7 °C by 2100.
- Stated Policies Scenario (STEPS), which looks not at which measures the governments have stated to implement but at what they are really implementing. This scenario is not expected to reach net zero emissions, and its rise in average temperatures is of around 2.5 °C by 2100.

Thanks to these three scenarios, the IEA provides a framework to conceive the divergence between the setpoints established to achieve carbon neutrality and the real performance of measures implemented by active stakeholders.

1.3. Current situation of GHG emissions

Nowadays, it is clearly stated by organizations worldwide the crucial need to reduce globally and inclusively the use of fossil fuels. In this way, it will be possible to reach climate-neutrality, reducing Greenhouse Gas (GHG) emissions, and in particular CO_2, minimizing the effects of climate change, and establishing human activities based on respect, equity, and sustainability. The need for decarbonization becomes even more important when looking at the energy sector, which accounts for two-thirds of the total GHG worldwide [9]. According to COP 27 celebrated on 11th November, emissions from burning fossil fuels were projected to increase by 1% in 2022, hitting a new record of 37 billion tons of CO_2 [10].

In particular, within the energy sector, the two main contributors to these emissions are the power generation and the transport sectors, which accounted for 44% and 26%, respectively, of the energy sector emissions in 2019 [11]. As claimed by the IEA, in 2020 the contribution of fossil fuels to heat and electricity generation was 88% and 61%, respectively, accounting for approximately 80% of the total energy production [12]. On the other side, the transport sector is the sector with the highest reliance on fossil fuels of all sectors, with crude oil-derived products providing more than 90% of the energy used in this sector [13].

In order to decarbonize the energy sector, the already mentioned Agenda 2030 has set key targets for 2030 of reducing 40% cuts in greenhouse gas emissions (from 1990 levels), having a 32% share for renewable energy, and a 32.5% improvement in energy efficiency [14]. To do so, electrification of the energy system has been defined as the key solution, given that electricity can be produced and distributed with minimal GHG emissions. According to the IEA, electrification will rise from 20% today, reaching more than 50% by mid-century in the NZE Scenario, and in the same way, by mid-century electricity demand is expected to be 75% higher than today in the STEPS, 120% higher in APS and 150% in the NZE Scenario [8].

Renewable technologies, such as wind, solar, and hydro, have been increasing their capacity and contribution to the final electricity mix. Meanwhile, other promising alternatives have been furthered developed to replace fossil fuels in other sectors, such as biofuels or hydrogen. However, the electrification of the energy system is still in its early stages, with many problems arising and new solutions appearing every day. The non-dispatchable nature of many of the renewable systems, such as solar or wind power, do not allow to match demand and production many times, meaning that complementary systems need to be implemented to balance and cover this mismatch, like Hydrogen (H_2) electrolyzers to store and produce electricity. In the same way, the electrification of the transport sector is a promising alternative for decarbonizing this sector, but at the same time, it is very challenging to provide a resilient grid infrastructure with enough power capacity to hold the increase in energy demand while ensuring the reliability of the energy supply for other purposes.

To proceed, the scope of the project will be narrowed down to the transport sector, focusing on the project's topic. It is of special relevance to analyze this sector since it is one of the biggest contributors to GHG emissions and is hence responsible for a big share of the environmental harm caused by anthropogenic activities on the planet.

1.4. Transport sector

Worldwide, the transport sector represents around 26% of the total world's energy consumption, 113.4 EJ out of the total 439.1 EJ consumed [8]. Moreover, the transport sector has the highest reliance on fossil fuels of any sector and accounted for 37% of CO_2 emissions from end-use sectors in 2021, reaching 7.7 Billion tons (Bt) of CO_2 [15]. With the World's population increasing every day and international trade becoming more frequent, the need for transport is constantly increasing. However, the world urgently needs to break the correlation between increasing demand for transport and increasing carbon emissions. To keep the pace of the NZE Scenario, emissions from the transport sector should drop by about 20%, 3% yearly, to less than 6.0 Bt of CO_2 by 2030.

When looking at Europe, opposite to all other sectors' emissions, such as agriculture, residential, or industry, transport is the only one that has experienced an upward trend between 1990 and 2017 [16]. Within its GHG emissions, road transport constitutes the highest proportion of all, accounting for 77% in 2020 of all European Union (EU) transport GHG emissions. However, some subsectors of road transportation present a high pace of decarbonization which will reduce its GHG contribution since the existing and planned measures in the Member States are mainly focused on them [17]. In 2020 in Europe, 818 Mt CO_2-equivalent were emitted by the transport sector, 200 Mt CO_2-equivalent less than in 2019. However, this was mainly due to the COVID-19 pandemic, and they already grew again by 6% in 2021 [18]. According to the report sent by countries to UNFCCC and the EU Greenhouse Gas Monitoring Mechanism, within the road transport emissions, the two subsectors which have contributed the most are passenger cars and Heavy Duty Vehicles (HDVs), with 59% and 27% of these CO_2 emissions respectively [19]. HDVs are defined as road vehicles designed to transport goods or passengers, such as trucks, buses, or coaches, although this definition might vary for countries depending on maximum load weight or maximum weight. Following, Figure 1 and Figure 2 represent the CO_2 emissions share of each kind of transport and the evolution of every sector:

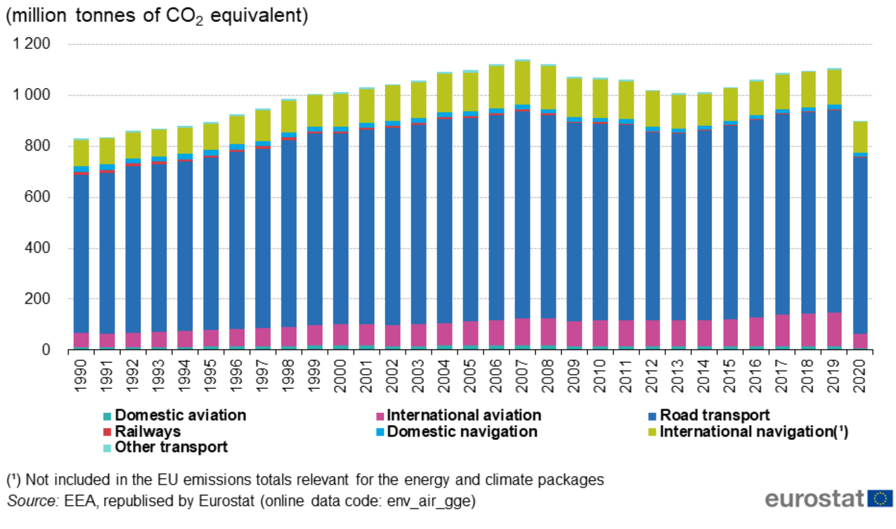

Figure 1. GHG emissions of transport in the EU, 1990-2020 [20].

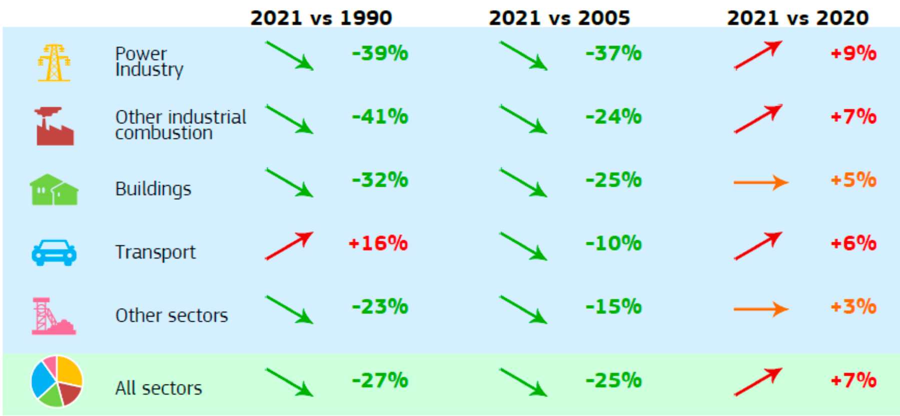

Figure 2. Evolution of GHG emissions per sector in EU, 1990-2021 [18].

In order to decarbonize the transport industry, the EU resolved through Directive 2018/2001 of December 11, 2018, that in every member state, energy from renewable sources used in transport should amount to 14% by 2030 [21]. To do so, electrification of the transport fleet as well as other alternatives to fossil fuels, such as biofuels, hydrogen Internal Combustion Engine (ICE), or hydrogen fuel-cell, have been defined as key solutions. Particularly for HDVs, interurban electric buses have already been demonstrated to be cost-competitive in their application. At the same time, the development of battery technology is making electric long-haul trucks a more attractive alternative [22].

As mentioned before, in this particular project, the focus is drawn to the electrification of the transport sector. In the following subsection, the implications of adopting an electrified transport fleet will be presented.

1.5. Transport electrification

Transport electrification holds immense potential for reducing GHG emissions and transitioning towards a more sustainable transportation system. Moreover, EVs have lower operating costs compared to traditional ICE vehicles, as well as less maintenance requirements. Additionally, the utilization of renewable energy sources for charging EVs can further reduce the overall carbon footprint. These advantages, coupled with advancements in technology and increasing environmental awareness, make vehicle electrification a promising pathway toward a sustainable and efficient transportation future.

However, this transition is not without its challenges. This section will expose why EVs have not been wholly adapted yet, understand the key obstacles that hinder their adoption, and explain why this project brings positive outcomes to incentivize their adoption. The main challenges to EV adoption can be seen in more detail for the Battery Electric Trucks (BETs) in section *3.2.1 Barriers to battery electric trucks*.

When particularly addressing the electrification of the transport fleet, the increasing demand for electricity has presented some challenges. The current electrical infrastructure has not been able to evolve at such a fast pace, raising problems and questions on how further to direct the energy transition within the transport sector. The need for upgrading the electrical infrastructure is crucial if the transport sector is to be decarbonized, but these costs and lead times can disrupt the progress of electrification [22].

Parallelly, the limited Charging Infrastructure (CI) has become a relevant barrier. Establishing an extensive and convenient charging network is crucial to alleviate range anxiety and ensure the practicality of EVs. Without an adequate CI, EV adoption may be slowed down due to concerns about access to charging points and charging times.

Another significant challenge is the cost of electric vehicles. Although the prices of EVs have been decreasing over time, they still tend to be higher than their ICE vehicles. The upfront cost of EVs, coupled with the cost of battery replacements, remains a barrier to their adoption. Furthermore, the limited energy density and range of current battery technology pose challenges, not allowing EVs to operate like ICE vehicles, requiring a more frequent recharging and a more time-consuming charging process, and influencing the maximum vehicle's payload.

Therefore, with these primary limitations and various others, this project aims to deliver an exceptionally optimized configuration for CI necessary to electrify a significant share of Oskarshamn's diesel truck fleet. Thanks to extensive research and collaboration with relevant stakeholders, the project also aims to propose innovative solutions that maximize the feasibility of investments in electrification. Additionally, it presents a comprehensive plan that anticipates future growth in EV adoption, incorporating advanced technologies and intelligent charging algorithms.

By doing all of this, it seeks to reduce the impact of the electrified truck fleet on the grid while streamlining the decision-making process for truck operators, enabling them to successfully transition into BETs and effectively overcome the existing barriers that impede the progress of transport electrification.

2. Objective and methodology

This Master Thesis investigates the potential of implementing Charging Infrastructure (CI) at Oskarshamn to enable the electrification of regional freight transport, particularly Heavy Duty Vehicles (HDV). The main objective pursued by this study is to dimension the CI, which will allow the complete electrification of Oskarshamn's diesel truck fleet without affecting its transport operation schedules. Parallelly, this CI proposed aims to minimize its impact on the local distribution grid to ensure smooth integration and prevent failures or shortages of the energy supply. This project will define the technical, economic, and operational aspects of the CI. Hereby, it provides the most beneficial solution for the stakeholders involved in the project while also considering future trends. Hence, this CI will enable the transition to a cleaner, more affordable, and more efficient transport system.

The following pictogram illustrates the current and final situation of Oskarshamn after the objective of this Master Thesis has been achieved, where the current truck fleet is powered by fossil fuel derivates, and the aim is to be powered by electricity:

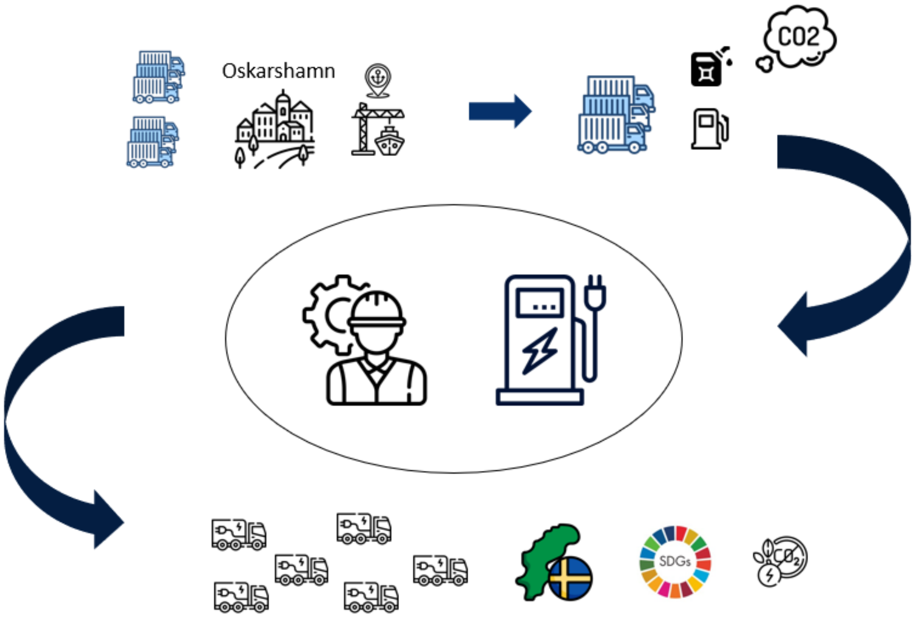

Figure 3. Pictogram of the Master Thesis' objective.

As has been introduced before, due to the high amount of GHG coming from the transport sector, it is crucial to move into the technological shift of electrification, bringing forward the energy transition and reducing the impact of the road transport system on Climate Change. To do so, this study will analyze different configurations of CI to deal with the energy (electric) requirements that this new electrified EHV fleet will have. Next, the following figure represents the flowchart that defines the methodology followed in this project:

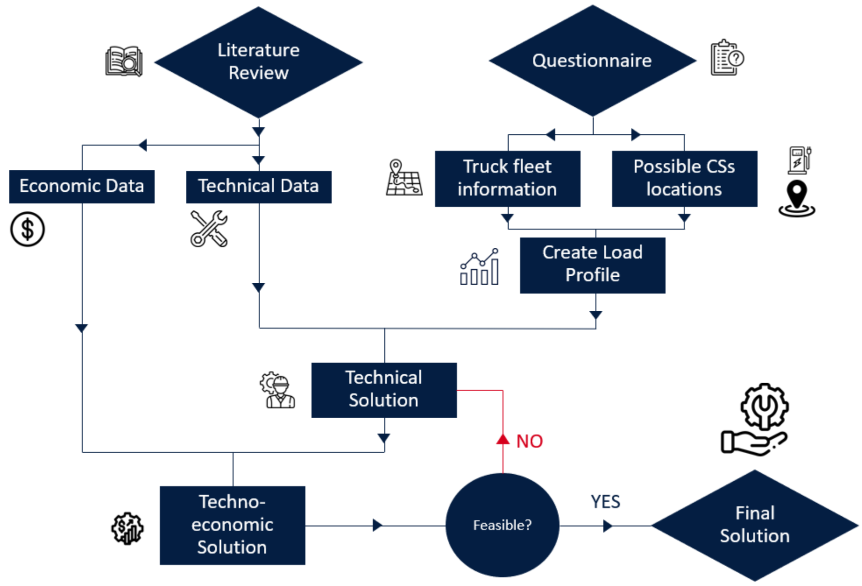

Figure 4. Flowchart of the methodology followed along the project.

This project starts by analyzing the current trends and performance of the Swedish transport sector. Right after, the two big branches shown in Figure 4 will be developed parallelly.

On the one hand, an extended literature review of the state-of-art of Battery Electric Trucks (BETs), in particular trucks used for freight transport, constructs deep knowledge of which are the components that make up a BET, their configuration within the vehicle, and the main trends in the technologies used in this market. It is crucial to understand the status of truck electrification and perceive the advantages that BETs can bring over conventional diesel trucks and which challenges lay ahead. In this sense, the proposed CI system will be built according to current and future BETs requirements. Following, the second section of the literature review will focus on the technical characteristics of CI for Electric Vehicles, such as components, standard models, or charging types, in order to understand their requirements, limitations, and performance. These two sections of the literature review will be accompanied by their respective economic analysis. This assessment will provide not only technical knowledge but also a complete and robust understanding of the operation opportunities of Charging Stations (CSs), assessing current charging strategies in use, possibilities of ownership of the CSs, and the business model of its operation. Within the economic analysis, some of the aspects addressed are Total Cost of Ownership (TCO), Investment Cost, or Operation and Maintenance Costs. All this literature research will enable to build of a strong theoretical background that will be helpful for analyzing the case study from a critical point of view.

On the other hand, the project will analyze the case study of Oskarshamn. To capture the whole picture, a series of steps need to be followed, which involve interested stakeholders from Oskarshamn. First, it is necessary to get in contact with the parties that want to be involved in the project. To do so, during the first steps of this project, a visit to Oskarshamn was made in order to get to know firsthand the parties involved in the project and which are their interests behind this proposal. Thanks to this collaboration among public and private stakeholders from Oskarshamn, contact with truck operators from the municipality and surroundings was established. Additionally, follow-up meetings have been carried out every other week to update all the parties on the status of the project, keep a good track of how procedures are implemented, and jointly define future steps and identify areas of improvement.

Getting in touch with Oskarshamn's actors makes it possible to identify potential stakeholders and define their transport operations. To gather all essential information, a Questionnaire is designed and sent to all truck operators that agreed to collaborate. This Questionnaire aims to principally collect information about truck fleet sizes, itineraries and flows. Additionally, sustainability commitment, the current share of BETs within the fleet of each actor as well as their plans for future electrification, will also be analyzed so that their commitment to energy transition is reflected. Finally, the last section of the Questionnaire will be addressed to identify the preferred CS location, parking spaces, and most frequented routes of transport. More information regarding the methodology and design of the Questionnaire is found in section *4.2 Data collection*.

After thoroughly mapping the transportation needs and operations in Oskarshamn, one of the primary prerequisites that must be met is the seamless integration of truck electrification without disrupting the existing transport chain. Hence, it becomes imperative to determine the specific electrical requirements that the new BET fleet must meet in order to ensure uninterrupted continuity in its operations, mirroring the current system. To do so, the information received from questionnaires will be translated into numerical data to create a virtual model that simulates the real case scenario and characterizes the dynamics of the whole system based on the highly reliable data gathered. This virtual model will optimize the charging schedule of BETs to reduce its impact on the local grid and, at the same time, guarantees that transport operations are carried out in the same way as they are nowadays. Doing so, the model will replicate electric loads per truck, actor, and aggregated at the district level, giving as a result the most optimal power output for the different CSs according to Oskarshamn transport needs. The aggregated load profiles at a district level will depend on the CSs location since CSs could be used by individuals (only one actor) or commonly (more than one actor), which will be decided according to the preferences or possibilities defined in the Questionnaire. So, in summary, this Optimization Model (OM) will replicate electrical loads that are defined in order to provide the most optimal charging schedule to minimize the impact on the grid and to guarantee that transport needs are fulfilled. It will be built using *Python,* and the methodology to develop the optimization of the model can be seen in more detail in section *4.4 Optimization Model*.

Once the electrical requirements of the new BET fleet have been established, the subsequent phase entails formulating the definitive configuration for the charging infrastructure (CI) to effectively fulfill these energy demands. To do so, geographical, technical, and economic aspects are addressed so that the most beneficial solution for the stakeholders is assured. Thus, the results and data obtained from the OM, questionnaires, and literature review will be put together to capture the whole picture and analyze the different alternatives available.

Finally, sizing and placement for the CI will be defined, as well as the economic and operational business model for each CS. This analysis will give customized solutions for each of the stakeholders, including as mentioned before TCO, ownership of the CS, booking and payment system, as well as the economic balance of the whole project along its lifetime.

Overall, this study will provide the necessary CI to install, in terms of power output and number of charging points, the financial cost of each solution, addressing Total Cost of Ownership (TCO), Investment Cost, or Operation and Maintenance Costs, and the business model for the operation opportunities of Charging Stations (CSs), assessing current charging strategies in use and ownership models of the CSs. The electric profile will be derived from authentic data collected from the stakeholders involved in the project, ensuring a thorough and well-informed approach.

3. Literature review

The main purpose of this literature review section is to provide a comprehensive overview of which is the state of Heavy Duty Vehicle (HDV) electrification in Sweden, focusing particularly on Heavy Duty Trucks used for freight transportation. The literature review will address the current status of the most relevant topics in this matter, such as the Swedish road transport sector, HDV electrification, and its barriers, and finally will cover Battery Electric Trucks (BETs) and Charging Infrastructure (CI) technologies, economic aspects and provide a market study with available alternatives. The focus of this review will not only be to offer a basic understanding of these areas but also to delve deep into the technologies used in the BET market. By exploring these areas in detail, this literature review aims to provide a complete understanding of the subject matter, allowing readers to gain insight into the latest developments in the field of BET technology. Whether the reader is an industry expert or a newcomer to the field, this literature review will serve as an essential resource for gaining a complete and deep understanding of the current state of the electrification of HDV used for freight transport.

3.1. Swedish road transport sector

In this section, Swedish transport will be analyzed, collecting information from official national entities, among other sources, in order to completely comprehend its operation conditions, its development towards the future, its contribution to climate change, and the importance of HDV used for freight transport within the Swedish economy.

Swedish road vehicle fleet has been steadily growing over the last years, with passenger cars leading the growth and increasing their number to almost 43,000 units in 2021, 0.9% more cars than the previous year. In terms of vehicle mileage on Swedish roads, passenger cars also have the biggest share covering almost 80% of the total 80,139 million km driven on Swedish roads, followed by light duty trucks (maximum weight of fewer than 3.5 tons), with 12%, and heavy duty trucks (maximum weight of more than 3.5 tons), with 6%. Regarding Heavy Duty Trucks (HDTs), their growth over the last ten years has not been very pronounced, growing only 7% in comparison to the 27% of light trucks [27]. Furthermore, there are only 72 HDTs that run on electricity alone. However, competitive Battery Electric Trucks (BETs) suitable for regional freight transport are already on the market, enhancing the potential for electrification of regional freight transport [28]. In the following Figure 5 and Figure 6, the number in millions of vehicles in 2021 for passenger cars (Personbilar), light duty trucks (Lätta lasbilar), and HDTs (Tunga lastbilar) is shown, as well as the total mileage per vehicle type:

Fordonsslag	*Antal i trafik tusental (procentuell förändring mot föregående år)*	*Antal avställda tusental (procentuell förändring mot föregående år)*
Personbilar	4 987 (+0,9)	1 352 (-0,2)
Lätta lastbilar	606 (+1,7)	211 (-0,9)
Tunga lastbilar	86 (+1,4)	53 (-0,5)
Bussar	14 (+0,8)	6 (-13,0)
Motorcyklar	313 (+0,9)	262 (+1,6)
Mopeder klass I	102 (-0,7)	231 (+3,4)
Traktorer	374 (+4,7)	150 (+3,4)
Snöskotrar	198 (+3,3)	152 (+0,3)
Terräng-hjulingar	104 (+1,5)	24 (+6,3)
Släpvagnar	1 292 (+3,2)	312 (+3,6)

Figure 5. Vehicles in service and withdrawn from service in millions in 2021 by type, number, and percentage of change with respect to 2020 [27].

År 	Summa *Total*	Motorcyklar *Motorcycles*	Personbil *Passenger cars*	Bussar *Buses/Coaches*	Lastbilar max 3,5 ton totalvikt *Lorries max 3.5 tonnes*	Lastbilar 3,501–16 ton totalvikt *Lorries 3.501 – 16 tonnes*	Lastbilar 16,001–26 ton totalvikt *Lorries 16.001 – 26 tonnes*	Lastbilar över 26 ton totalvikt *Lorries over 26 tonnes*
2018	84 536	646	68 639	998	9 393	320	804	3 736
2019	83 674	662	67 816	1 006	9 421	314	741	3 713
2020	77 813	693	62 162	899	9 332	294	679	3 753
2021	80 139	654	63 913	888	9 697	296	683	4 009

Figure 6. Vehicle kilometers on Swedish roads (millions) from 2018 to 2021 [29].

Total GHG emissions in Sweden during 2021 added up to 48.7 Mt CO_2-equivalent [30]. Within these emissions, the transport sector was the most significant contributor, with 15.07 Mt CO_2-equivalent coming from fuel combustion in vehicles, 31.5% of Swedish total GHG emissions [31]. Back in 2020, in the report sent to UNFCCC and the EU Greenhouse Gas Monitoring Mechanism, Sweden's transport sector reported 15.39 Mt CO_2-equivalent, with 91.8% of them coming from road transport accounting for 14.13 Mt CO_2-equivalent. Nonetheless, the trend on GHG emissions from transport sector has already been decreasing during the last years, falling from 20.73 Mt CO_2-equivalent in 2011 to its current value [32]. Figure 7 illustrates the evolution of GHG emissions from the transport sector in Sweden:

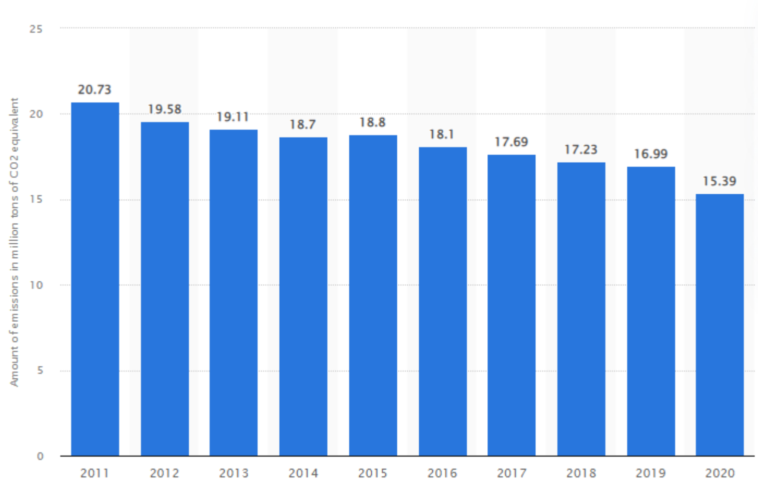

Figure 7. Annual greenhouse gas emissions from fuel combustion in the transport sector in Sweden from 2011 to 2020 [32].

Due to its high contribution to GHG emissions, it is clearly stated a need for further decarbonization of Swedish road transport, which in 2020 represented 25.45% of the total GHG emissions. In order to do so, Sweden is already one of the pioneer countries towards electrification of the transport fleet, being the third country in Europe with the highest market share for new electric car sales in 2021, with 43% for Light Duty Vehicles (LDV) [28].

However, apart from LDV electrification, which is mainly used for road passenger transport, it is also crucial to electrify vehicles used for goods transport. These vehicles are the backbone of the Swedish economy and competitiveness, they are essential for the functioning of the market, and they represent a big share of the GHG emissions within the transport sector. The most common way of freight transport is also road transport, which increased its contribution in 2021 with respect to 2020 from 52% to 54%, while maritime transport decreased by 2% to 26%, railway maintained its contribution of 20%, and aviation remained with a trivial contribution lower than 0.1%. In terms of ton-kilometers, which is the unit used for measuring freight transport, road transport contributed to more than half of the total

106,063 million ton-kilometers of goods transported in 2021 [33]. Next, in Figure 8 and Figure 9, the contribution of road traffic (vägtrafik), railway (bantrafik), shipping (sjöfart), and aviation (luftfart) is shown as a percentage and as total million ton-kilometers:

Trafikslag	Person-transporter	Gods transporte
Vägtrafik	88	5
Bantrafik	8	2
Sjöfart	1	2
Luftfart	3	<0,
Samtliga	**100**	**10**

Figure 8. Share of transport modes in transport work in Sweden as a percentage in 2021.

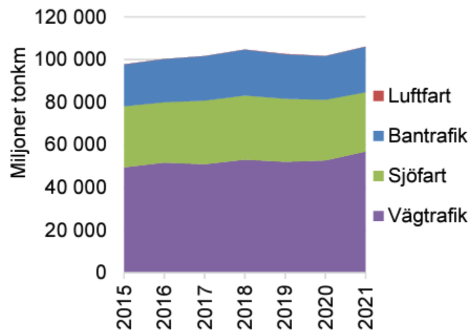

Figure 9. Freight transport in Sweden from 2015 to 2021 in million ton-km [33].

As mentioned before, from the total 106,063 million ton-kilometers of goods transport in 2021, 56,841 million ton-kilometers corresponded to freight road transport. Among these 56,841 million ton-kilometers of freight road transport performed, 78.8% of them were domestic transport carried out by Swedish Heavy Duty Trucks (HDTs), which are considered as those with more than 3.5 tons of maximum load weight [34]. The rest of the freight road transport consisted of domestic traffic with foreign heavy goods vehicles, light goods vehicles, and international traffic. Domestic goods refers to all the products that are produced and intended to be consumed within a region, while domestic transport refers to transport that starts and ends within Swedish boarders. Now it is important to pay attention to the region of Kalmar since Oskarshamn (the municipality where the study will be performed) is located there. 16.35 million tons of goods are transported from Kalmar, with 77.3% of them delivered within the borders of Kalmar county, being only 3.54 million tons transported outside the county. This means that most of the HDTs usually will not need to cover long distances, having a shorter range of operation which will facilitate their replacement for Electric Trucks. Following, Table 1 wraps the contribution of HDTs to goods transportation in Sweden:

Swedish Goods Transport 2021	Domestic Transport		International Transport		Heavy Duty Trucks		Total	
	%	ton-km	%	ton-km	%	ton-km	%	ton-km
Total Goods Transport	64.75%	68,678	35.25%	37,385	44.77%	47,481	100.00%	106,063
Domestic Goods Transport	100.00%	68,678	0.00%	0	65.19%	44,773	100.00%	68,678
International Goods Transport	0.00%	0	100.00%	37,385	7.24%	2,708	100.00%	37,385

Table 1. Goods transportation by category of transport, number (ton-km), and percentage in 2021 [33], [34].

Hence, narrowing down the focus to HDTs due to their notable share, these vehicles transported 44 million goods in 2021, a total of 492 million tons, of which 99% of them were in domestic traffic. Within these domestic transport operations, 65% of them were carried out over distances shorter than 50 km, while only 6% of them were carried out over distances longer than 300 km. In the following Figure 10 and Figure 11, the goods transported by HDTs are shown in number of transports (antal transporter), kilometers driven (körda kilometer), quantity of goods (godsmängd), and transport work (transportarbete) for 2020 and 2021, as well as the evolution of HDTs goods transport from 2012 to 2021:

	2021		2020
Antal transporter, 1 000-tal	**44 023**		**42 591**
inrikes	*43 570*		*42 211*
utrikes	*453*		*381*
Körda kilometer, 1 000-tal km	**3 353 102**	*	**3 115 916**
inrikes	*3 155 493*	*	*2 948 485*
utrikes	*197 608*		*167 431*
Godsmängd, 1 000-tal ton	**492 464**		**475 200**
inrikes	*486 963*		*470 092*
utrikes	*5 501*		*5 108*
Transportarbete, miljoner tonkm	**47 481**	*	**43 183**
inrikes	*44 773*	*	*40 710*
utrikes	*2 708*		*2 473*

Figure 10. Swedish goods transported by HDTs in freight transport in 2021 and 2020 [34].

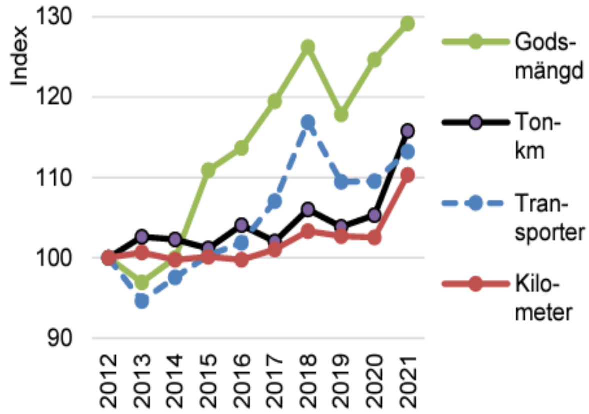

Figure 11. Truck transport with Swedish trucks. Indices (2012=100) for freight volume in tons (godsmängd), tons per km, number of transports, and kilometers driven [34].

In Figure 11, it can be seen that amount of goods as well as total kilometers covered by the truck fleet have been increasing over the last years, and this trend is expected to continue due to a constant increase in demand. It is for that reason that a large share of the goods transport sector in Sweden relies and will rely on HDTs, which is a daunting problem since these vehicles are still highly dependent on fossil fuels, such as conventional ICE diesel trucks.

To approach this problem, two of the leading Swedish climate targets are net zero emissions by 2045, aiming afterward for negative emissions, and a 70% reduction in emissions from domestic transport by 2030. In order to support these objectives, the Commission for Electrification, tasked by the Government, developed a plan together with society and actors from the Electrification Hub. This plan was specifically designed to accelerate the electrification of regional freight transport since, in fact, 73% of all domestic goods transport is done within the same county [34]. The plan consisted of 16 pledges, such as establishing a stronger charging infrastructure, participating in pilot projects, purchasing electric transport services, ensuring local grid capacity, or coordinating stakeholders to accelerate electrification [35].

Finally, regarding electrical Charging Infrastructure (CI), it is expected that by 2030 Sweden will need 1,200 EV charging stations to accommodate the increasing number of Electric Vehicles (EVs). Many of these Charging Stations (CSs) will likely be installed at logistics centers, seaports, and alongside major Swedish roads, where long-distance vehicles, commonly HDTs, will frequently be passing by or stopping at night [36]. Even so, there is exhaustive planning behind the implementation of CS. Logistic operations need to be performed to address their optimal location, investors need certainty that their investment will be paired with investment in EVs, and the power of CSs has to match with charging-time needs and local or regional electrical infrastructure.

3.2. Heavy duty trucks electrification

This section focuses on Heavy Duty Truck (HDT) electrification, which passing through its evolution over the past years will provide a complete picture of which is the current status of

HDTs and their way towards electrification. Finally, it will show which are its crucial advantages over conventional diesel ICE trucks, but also which are the main challenges or barriers to their implementation.

As mentioned previously in section *1.4 Transport sector*, the transport sector is one of the most polluting and challenging to decarbonize, contributing in 2021 to 37 % of CO_2 emissions from end-use sectors and with crude oil-derived products providing more than 90% of the energy used in this sector [13][15]. Within the transport sector in Europe, road transport accounted for more than 75% of this pollution in 2020, with Heavy Duty Vehicles (HDVs) representing a quarter of the Greenhouse Gas (GHG) emissions and increasing every year since 2014 [37]. Worldwide, even though Heavy Duty Trucks (HDTs) used for freight transport only represent 9% of the vehicle stock, their emissions account for 39% of the total road transport emissions [38]. Figure 12 depicts the evolution of CO_2 emissions in Europe from 1990 to 2020:

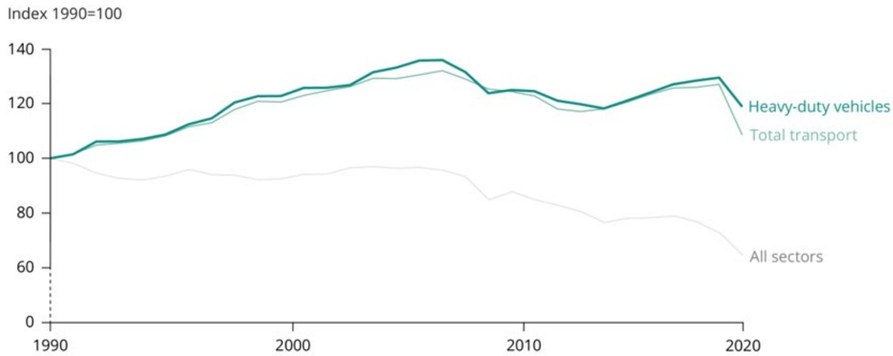

Figure 12. Trends in CO_2 emissions from heavy-duty vehicles in the EU, 1990-2020 [37].

In order to comply with EU climate neutrality policies, a 90% reduction in GHG emissions from transport will be needed; hence a shift to vehicles with lower emissions is needed. Among the possible solutions to decarbonize the transport sector, electrification has emerged as a very promising and attractive solution, and governments have set specific goals in order to define clear pathways for the phase-out of conventional Internal Combustion Engines (ICE) [39]. Another law approved by the European Parliament on the 14th of February of 2023 states that the sale of new petrol and diesel cars will be banned from 2035 on and proposes that 90% of all newly manufactured trucks should run on fossil-free fuels by 2040 [40], [41]. Currently, the sales of Electric Vehicles (EVs) have been growing at a very fast pace. In 2021, 10% of global car sales were electric, adding up to a total of 16.5 million cars on the road worldwide. Europe presents the highest electric car penetration rate, growing 65% year-on-year (2.3 million cars growth) in 2021, having a total of about 5.5 million cars in circulation [42].

However, all this growth needs to be paired together with the development of other industries. For example, when talking about pure Battery Electric Vehicles (BEVs), materials and systems need to be further developed within the battery to enhance the autonomy of BEVs, suppressing the range anxiety that concerns EV drivers for not being able to travel the desired distances. Another potential impediment to the future electrification of road transport is the grid infrastructure. With the enlargement of electricity use in every sector, the need for increasing grid capacity becomes indispensable, nonetheless, the pace of grid capacity growth has not been able to keep up with other sectors. Moreover, an increase in decentralized generation systems, more renewable production, and an increase in load due to transport electrification will require a much more complex need of demand management to ensure grid stability.

These two problems just mentioned arise much larger when referring particularly to Heavy Duty Vehicles (HDVs), which emit around 200 Mt CO_2-equivalent. Among HDVs, HDTs were responsible for about 85% of the emissions, while buses and coaches were responsible for the remainder [37]. HDTs are key elements for the transportation of goods and, therefore, for the economic development of countries and regions. In 2020 in Europe, HDT transport represented 77.4% of the total inland freight transport, which has increased by a 25% since 2000, and it is expected to continue growing [43]. During the period of 2000-2020, HDT transport has risen 31% in comparison to a 5% in railway and inland waterways. In this sense, when approaching the electrification of HDTs, it has become crucial to properly define strategies and develop logistic planning to ensure that the energy needed for the journey will be supplied within the timelines stablished.

In 2021, more than 14,200 electric medium- and heavy-duty trucks were sold worldwide. China accounted for nearly 90% of electric truck registrations, down from almost 100% in 2017 [42]. Electric Truck (ET) stock share worldwide has been growing rapidly in these last years, reaching around 0.11% in 2021, with China as the leading country, with 0.17% of their truck fleet being electric. This has been driven due to an increase in the share of ETs among the total truck sales, being lower than 0.3% of the sales in 2021 but more than double that in 2020, although far from the boom of 2018, where it reached 0.8% [44]. In Europe, the ETs stock share is still lower, with only 0.04% of the truck fleet being electrified in 2021, although it has more than doubled from 2020. This share has also kept a steady growth from 2018 to 2021, reaching 0.19% of the total sales [44]. However, these numbers are far behind reaching the objectives established by the NZE scenario, which attempts to have ETs with a 25% share in sales worldwide, in comparison to the 7% projected by the STEPS and 10% by the APS. Therefore, it is of high importance to continue implementing and developing new policies to put HDTs on the pathway to climate-neutrality by 2050 [42]. Following, Figure 13 shows electric bus and trucks registration from 2015 to 2021:

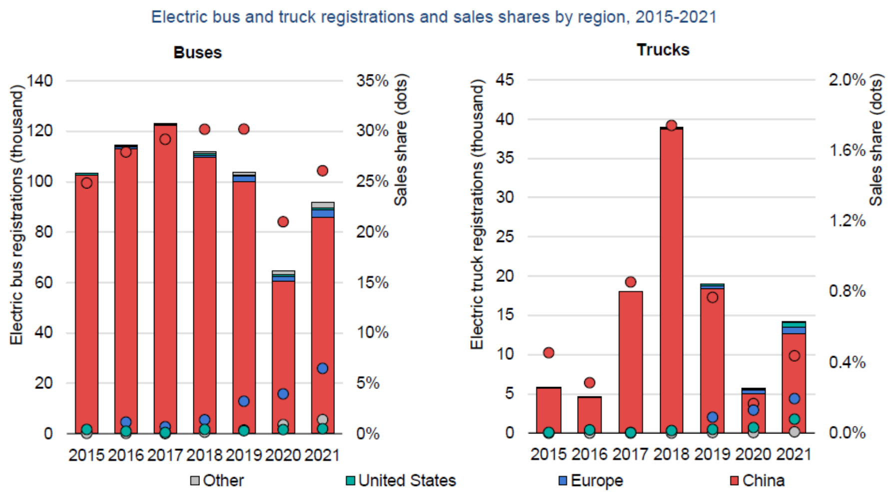

Figure 13. Electric bus and truck registration and sales shares by region, 2015-2021 [42].

Battery Electric Trucks (BETs) can be a turning point to bring down GHG emissions in the freight transport sector, apart from providing advantages for truck managers or owners. BETs are beneficial for the environment since they do not produce any tailpipe emissions. Although the electricity used for powering the BETs could have released GHG, the concentration of these gasses is usually lower than conventional ICE trucks, and they will become cleaner as renewable electricity generation share increases.

Secondly, BETs have lower operating costs than conventional diesel trucks, such as fuel or maintenance costs, which can generate big savings over the lifetime of the vehicle. Also, having a much simpler design reduces not only the maintenance costs but also the average downtime that a truck will spend being repaired. Thirdly, BETs provide the opportunity for potential energy savings thanks to improved efficiency, which reduces the energy needed per kilometer traveled. Better energy use will not only produce economic savings but also improves the productivity of the transport system. Furthermore, BETs can deliver peak torque almost instantly, allowing them to perform very well in towing large loads [45]. Among other important advantages, it is important to notice that ETs have a quieter operation, which improves the quality of life in urban areas, and flexibility in energy sources since electricity can be produced using many different technologies.

In section *3.5.1 Types of charging*, other alternatives to BETs and their conventional charging method will be analyzed, such as road electrification or battery swapping.

3.2.1. Barriers to battery electric trucks

Even though BETs present many positive features or advantages over conventional ICE trucks, there are also big barriers and disadvantages that have complicated the implementation and penetration of them into the market.

First of all, BETs have a high upfront cost and associated tariffs, which can make possible clients reconsider their purchase. Their price is still much higher than conventional ICE trucks. California Air Resources Board (CARB 2019) prediction for the year 2024 states that class 8 BETs will still have an 85% higher cost than conventional ICE trucks [45]. Disaggregating the price of BETs, batteries are the most expensive component. Nonetheless, battery prices have been decreasing by approximately 87% from 2010 to 2019, while their energy density and charging speed are steadily increasing. According to Bloomberg New Energy Finance, heavy-duty electric trucks will achieve cost parity with ICE trucks around 2030 [46]. Another concern regarding batteries is their replacement time since batteries are one of the components with the shortest lifetime and highest price, hence the feasibility of BETs highly depends on them.

Other cost challenges are the electric motor and system management costs, but they are expected to decrease mainly due to the economy of scale. Nonetheless, operational costs for BETs are predicted to decrease as renewable electricity production increases and electrification grows. Meanwhile, operational costs for conventional ICE trucks will keep increasing as fossil fuels taxes become higher due to environmental concerns. This gap between both operational costs will result in a much earlier payback period, bringing BETs to a competitive spot.

Secondly, charging infrastructure processes are costly and relatively complex. BETs have big batteries to ensure enough energy to cover long distances within a timeframe while complying with their itineraries. Charging big-size batteries demands more power or time than for Light-Duty Electric Vehicles (LDEV), hence complicating the process and asking for more specific charging planning. In conventional ICE trucks, such as, for instance, Scania R 620 Class 8 truck, their tank has a capacity of 1,400 liters with an average consumption of 1.25 km per liter, offering a range of up to 1,750 km [47]. With this extended range, conventional ICE trucks have far less need for refueling planning, needing fewer refueling stations along their shipping routes as well as less time to refill their tanks. On the other side, defining an electrical charging network along the shipping routes is currently much more complex, which is a big barrier for ETs [46]. However, even with longer ranges, truck drivers have to stick under hours-of-service regulations [48], limiting their ranges and hence reducing this currently big gap between ETs and ICE trucks. Looking at the future of transportation, autonomous driving should be considered, which will replace the driver removing the need for stops, and usually, EVs are a better fit for this application in terms of stability, reliability, and efficiency [49].

The third barrier for BETs concerns electrical infrastructure and electricity prices. In order to reduce charging time, high-power charger models exist, such as DC fast charging (DCFC) stations, which will be detailed in section *3.5.1 Types of charging* of the literature review. These kinds of chargers are not only very expensive but might also need substantial reinforcements to existing electrical networks, which requires both time and money [45]. The reason why this reinforcement is needed is that connecting BETs to these chargers will suppose heavy loads for local grid networks, which may be forced beyond their capacity leading to disruptions and even blackouts. Disabling access to electricity in entire regions is unacceptable and could bring catastrophic consequences for the economy and society. Furthermore, using fast chargers simultaneously can produce a peak in electricity prices, which will enlarge the operational cost of BETs, bringing down their advantage over ICE trucks. Therefore, it is crucial to take into consideration the need for reinforcement and monitoring of the electrical grid if delays in electrification want to be avoided [46].

Another challenge is model availability. Due to the immaturity of the market, manufacturers do not offer a wide variety of models yet, limiting the freedom to choose for potential customers [50]. However, the market is becoming more and more active, and many countries and regions are coming up with new models with more developed features, as can be seen in Figure 14:

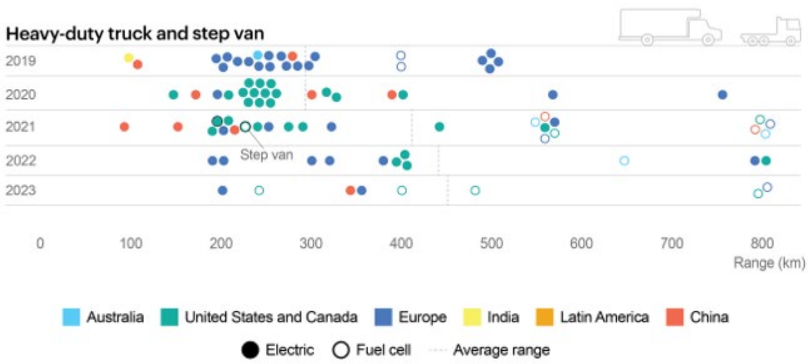

Figure 14. Current and announced zero-emissions commercial vehicle models by range [42].

Other aspects related to the immaturity of the market are a lack of verified data on the Total Cost of Ownership (TCO) and performance specifications, limited access to certified service centers and technicians, and a complicated model of vehicle and facility ownership. In the first place, TCO is crucial for defining the feasibility of business models as well as performance specifications are for ensuring operational requirements. The limited number of BETs under operation restricts data gathered regarding these two factors, making it more difficult for potential customers to analyze the viability of their purchase and to ensure that BETs will continue fulfilling their transport requirements. In the second place, although BETs are less likely to have mechanical failures and have fewer maintenance requirements, access to expert repair centers is still limited. In an industry where time is essential, the uncertainty of the time that a vehicle can be out of service plays an important role, which calls for the need for expert technicians able to assist in place and in time. Finally, although leased BETs are limited, they are expected to expand as the market grows. However, when it comes to ownership of electrical infrastructure, serious limitations appear. In order to invest in electrical infrastructure, the investor wants to be sure that such a big investment is amortized, but this can only occur if the equipment is transferable after the end of the lease or refundable by the facility owner [46]. As stated, these barriers are the cause of immaturity in the market and are predicted to be overcome as the market expands.

3.3. Battery electric trucks

Although it exists a wide variety of electric-propelled vehicles, such as hybrid vehicles or fuel-cell electric vehicles, in this literature review, the focus will only be put on Battery Electric Trucks (BETs) used mainly for freight transport. In this analysis, all the components integrated into a BET will be shown and explained. Besides, a more thorough explanation will be given for the batteries and electric motors, as they are the two main components of the drivetrain, also reviewing their state-of-art. Finally, some models of commercialized BETs already in the market will be provided, detailing the most important parameters of their performance in order to ensure a complete understanding of the maturity level of these vehicles and which are the key indicators that define their state of development.

3.3.1. Drivetrain

A BET drivetrain is a group of systems and subsystems used to turn electrical energy stored in the vehicle's batteries to mechanical torque that is then delivered to the wheels. Generally, the drivetrain in a BET must be able to start from a halt position and repeatedly accelerate smoothly in a short time to overcome the high inertia of the load on various road inclinations. There are different configurations available for the drivetrain of a BET, however, the most common one is formed by a central motor, a single-speed gearbox, and a differential [51]. The single-speed gearbox allows for easier configuration and operation, making this drivetrain configuration a more practical and cost-effective choice for electric trucks. Moreover, they require less space and are lighter than multiple-speed gear boxes, a really important feature for Electric Vehicles (EVs) where weight and space are often at a premium. Using a single-speed is possible in BETs thanks to the very wide torque band of the electric engine, making it possible to achieve a wider range of speeds by adjusting the frequency of the electric motor rather than changing gears. Next, Figure 15 shows the drivetrain configuration already mentioned:

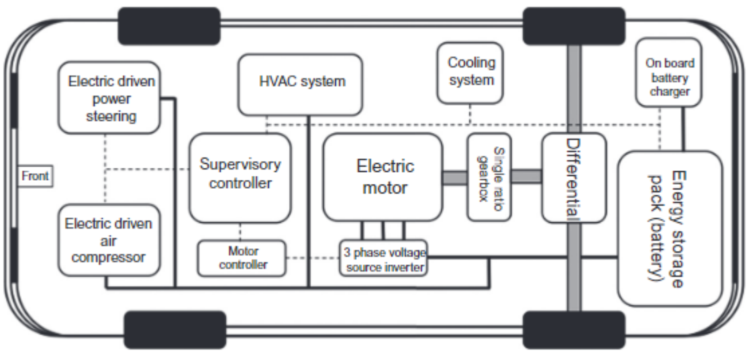

Figure 15. Central motor + single ratio reduction gearbox + differential configuration [51].

Nevertheless, there are also other potential drivetrains that can bring different advantages over the configuration already mentioned, such as a central motor with a differential or a two-by-wheel motor with a single ratio gearbox. When looking at a drivetrain, the most important characteristics to consider are efficiency, modularity, control, retrofitting simplicity, ease of servicing, low mass and volume, low vibration and acoustic noise, low cost, and high market availability [51].

Now, to get a better understanding of BET systems, in Figure 16, the fundamental components of a real truck design are shown. However, it has to be noticed that some of them are not numbered, although they will be explained after the image in order to capture the whole picture of a BET drivetrain.

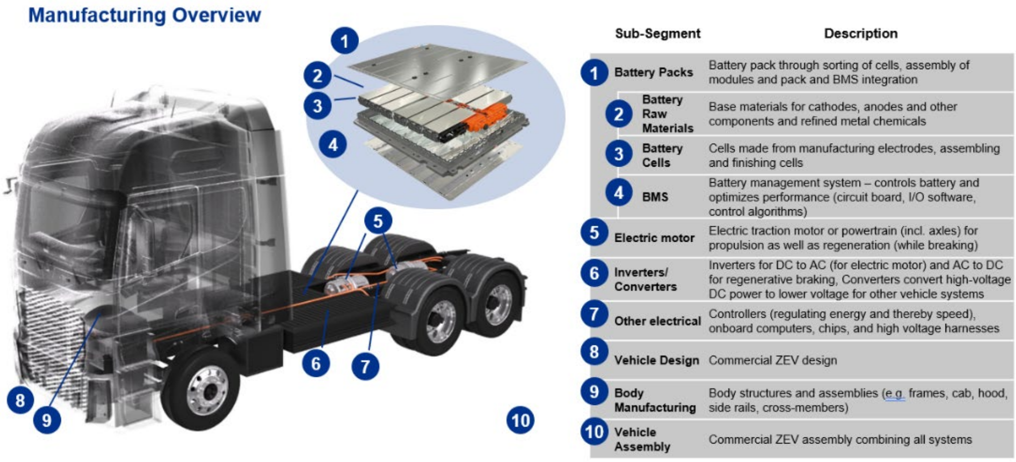

Figure 16. Main components of a BET drivetrain [52].

On the first hand, focusing on power electronics, these components include controllers that are in charge of regulating the energy flow between batteries, motors, auxiliary systems and others, and hence the speed of the vehicle. Power electronics are really important for the functioning of the BET since they are in charge of optimizing the vehicle's performance, for example, the battery management system used to ensure the longest lifetime of the battery.

Secondly, DC-DC converters are responsible for regulating the voltage to an appropriate level in order to be used by the different components, such as auxiliary systems. On the other side, inverters (or frequency controllers) are in charge of converting DC power coming from the batteries to AC power that will be used in the electric engine. Another important function of the inverter is to turn AC power generated thanks to the regenerative braking system to DC power to charge the batteries while driving.

Thirdly but not depicted in the picture, the charging system. The charging system is made up of a charging port, on-board charger, and charging cables, and it is in charge of supplying the electrical energy that will be stored in batteries. The charge port connects the electric vehicle to an external supply, and the onboard charger is responsible, in case of AC charging, for turning AC supplied from the charge port to DC supply.

Following, the Thermal Management System is in charge of guaranteeing that the operational temperatures of components are always within limits, using thermoelectric cooling, forced air cooling, liquid cooling, or a combination of these. Thermal management is also crucial to maximize the performance and lifespan of components.

Finally, it is also important to mention the existence of auxiliary batteries, which are a backup source of energy to avoid voltage drop at the start of the engine, and they are also used to power the auxiliary systems such as HVAC system or lighting [53].

To continue with the literature review, as mentioned before, a thorough analysis of the battery and electric engine will be conducted.

3.3.2. Battery

Batteries are the most important component in a BET, which are the primary power source for the electric motor. Many battery cells are assembled together to provide high voltage and capacity, creating the so-called battery pack. Currently, the battery sector is clearly dominated by Li-ion batteries, given that they provide higher specific energy, uphold higher capacity, have a more stable voltage level, and can reach longer driving ranges [54]. When it comes to battery pack prices, they have been falling down along these last years, going from around $US750-1000/kWh [55] to $US127/kWh in China, and in the US and Europe, 24% and 33% higher, respectively [56]. Nowadays, China controls 80% of the total manufacturing industry, and the demand for lithium-ion batteries has grown by over 1,600% from 2020 levels [57]. The following Figure 17 and Figure 18 show first the evolution of the total battery price while distinguishing between battery pack (light blue) and cell (dark blue) and second the top 10 countries in battery manufacturing for EVs.

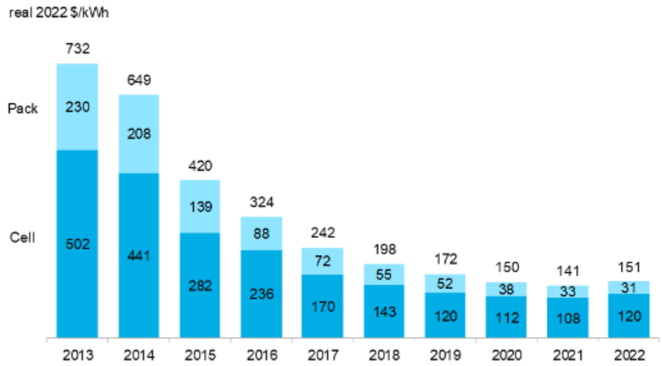

Figure 17. Volume-weighted average lithium-ion battery pack and cell price split [56].

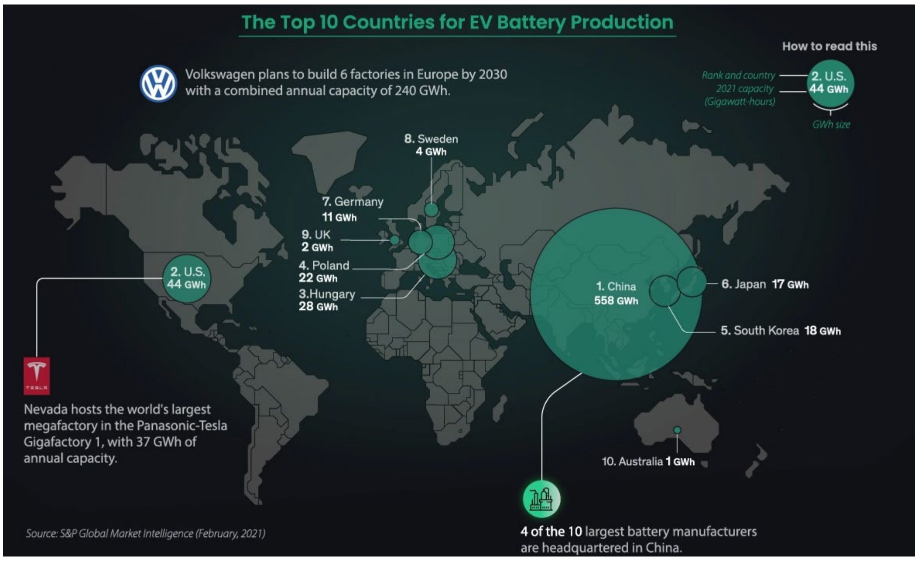

Figure 18. Top 10 Countries for EV battery production in 2021 [57].

Initially in 1999, Lithium iron phosphate (LFP) batteries were used due to their durability, safety, and reliance on eco-friendly materials. However, LFPs have relatively low specific energy, which has made High-Nickel-based Li-ion batteries with higher specific energy gain popularity, e.g., lithium nickel cobalt aluminum oxide (NCA) or lithium nickel manganese cobalt oxide (NMC). Nevertheless, some of the biggest battery manufacturers in China are betting again on LFP batteries, and the global LFP batteries market is expected to grow at a Constant Average Growing Rate of 14.8% in the forecast period of 2022-2027 [58]. LFP have a low specific energy of 90-140 Wh/kg but a long life that can endure up to 2000 cycles, NCA have 200–250 Wh/kg, can endure 1000-1500 cycles, and are currently used by Tesla EVs, and finally, NMC have 140-200 Wh/kg, can endure 1000-2000 cycles and are currently the mainstream of EV applications and particularly in BET [59]. With these characteristics, on average LFPs are stated to travel between 200 and 320 km, meanwhile High-Nickel-BETs stand between 190 and 800 km on one charge, but this is far from other technologies such as Fuel-Cell Electric Trucks with ranges that vary from 400 to 1200 km or diesel trucks with up to 1,750 km [60].

Technology choice in freight transport highly depends on trip distance and type of cargo carried. For BETs to outperform diesel trucks, the main challenges appear due to low specific energy and high cost. BETs have to be dimensioned to supply enough energy to reach their destiny, but big battery sizes are a problem due to the limitations on weight and volume. For transportation below 300 km BETs are already competitive, however, big disadvantages appear for longer distances. For ranges greater than 500 km, battery energies of 900 kWh are required, reducing BETs' average cargo weight capacity by 20% compared to diesel trucks. Another important aspect to consider with big batteries is that, since they require C-rates for charging significantly below 2C (1C means that the battery is completely charged/discharged in an hour), high voltages are necessary to reduce charging time, demanding a strong electrical infrastructure [60].

Furthermore, the range that a battery can provide to BETs is highly affected by cycling degradation, which produces a decrease in the battery energy capacity. Generally, higher temperatures, greater depth of discharge, and high-rate charging/discharging promote cycling degradation and reduce the battery life [61]. Hence, another important aspect to consider is battery durability, which is the number of full cycles that a battery can take before failing to meet its specified end-of-life criteria (normally 80% of the battery's initial capacity). The number of battery replacements needed largely influences the feasibility of BETs since batteries are the most expensive component, and their lifetime is shorter than that of most components on the BET, whose mileage can be greater than 1,200,000 km [61]. For example, for Light Duty Vehicle (LDV) batteries, the replacement cost of the Nissan Leaf electric battery of 24 kWh is around $US5,500, and for the Chevrolet Bolt EV with a 60 kWh battery pack is $US15,734.29 [62].

Apart from the feasibility of a BET, the replacement of batteries has an enormous impact on the total demand for Li-ion batteries. In the paper *Impact of transport electrification on critical metal sustainability with a focus on the heavy-duty segment* [61], four different scenarios are studied in order to analyze the net lithium demand due to the mass electrification of Heavy Duty Vehicles (HDVs). The study concludes that it is very important to decarbonize the HDV sector, not only focusing on BETs so as to prevent strain on the global lithium supply. Hence, a huge effort has to be put into developing a proper Li-ion battery recovery and recycling scheme to reduce the environmental impact of the mining of raw materials, as well as to alleviate material bottlenecks and their price effects, thus assuring a strong ongoing market growth [59].

In order to increase the feasibility of BETs and reduce the gap between them and diesel trucks, there are some alternatives already in place [63]. First of all, using fast charging allows to have smaller battery packs which decreases energy consumption and payload deficits. Other alternatives are secondary uses, which are an optimal way to extend battery life and reduce the cost of EV ownership. For example, in increasingly renewable-integrated electrical grids, second-life battery storage can help alleviate the intermittency problem by improving stability and providing regulatory actions such as frequency regulation, demand response, or energy time shifting [64],[65]. A real case application of second-life batteries is the Nissan project in Melilla in collaboration with Loccioni, a system integrator. Once the batteries of EVs have come to an end, they are recycled and assembled in a large stationary storage system, with the purpose of avoiding the interruption of electricity supply during events of excessive load, improving the reliability of the grid, and securing the continuity of network service to the local population. The back-up generator is composed of 48 used Nissan LEAF batteries and 30 new ones [66]. Another potential improvement in the feasibility of the batteries is to use them in a bidirectional mode (V2G). In this way, the battery is charged and discharged, helping the electrical grid in peak demand hours. Using V2G can potentially reduce the operational cost since the battery will purchase electricity when prices are low and can sell it back to the grid when the prices are higher, increasing profitability and reducing the overall cost of the electricity stored in the battery. However, this operational mode requires a complex protocol of communication and can reduce the lifetime of the battery due to constant charge and discharge [67].

Regarding safety issues, the United Nations (UN) developed the UN DOT 38.3 test methods and procedures to ensure lithium-ion batteries are suitable for transport and to promote the continued growth and adoption of these important energy storage devices. The UN 38.3 standard is designed to simulate many possible extreme conditions and covers a wide range of safety tests, including tests for thermal stability, overcharging, short-circuiting, impact, and vibration. Compliance with the UN 38.3 standard is required by air, sea, and land and is typically indicated by a marking on the battery or packaging [68].

3.3.3. Electric engine

The electric engine of a BET is the other most relevant component since, depending on which type of engine is used, different performance and efficiency levels can be achieved. When selecting the electric engine, it is of high importance to identify for which kind of application it will be used since its characteristics, as well as its control system, will differ. Required power, operating voltage and current, motor torque versus speed characteristics, or control complexity are parameters that must be considered when selecting the appropriate electric engine for a BET [51]. In the following image REFERENCE, a torque-speed and power-speed characteristic curve of a traction motor is depicted, which is of crucial importance for understanding the performance of an electrical engine as it shows the engine's power output, which is directly proportional to the product of its speed and torque.

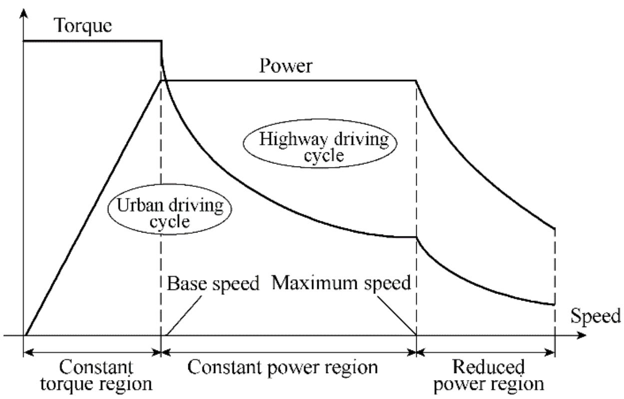

Figure 19. Torque-speed and power-speed characteristic curves of a traction motor [69].

As can be seen, the curve is divided into three different regions starting with the constant torque region, then the constant power region, and finally the reduced power region. In the first region, it is desired that the engine is capable of providing high torque at low speeds to provide a good start and overcome the inertia of heavy loads for different road inclinations. Once the base speed is reached, the maximum power of the engine is achieved in the constant power region, and the torque decreases proportionally to the square of speed. Depending on the type of EV, it will be more beneficial to provide a wide speed range in the constant power region or a higher torque in the constant torque region. Hence, it will be necessary to find the optimal balance between acceleration performance (related to the torque) and the maximum speed necessary. Finally, the reduced power region is generally considered to be an undesirable operating condition for an engine, where it begins to lose synchronism and the output power starts to decrease rapidly, heating up due to the increased current flow and reducing its efficiency [70].

When applying this curve to BETs used for freight transport, it will be important that the engine presents high torque at low speeds in order to be able to start and accelerate with heavy loads. Besides, it should also provide a flat torque curve that can maintain a relatively constant torque output over a wide range of speeds, helping the BET to maintain a consistent speed regardless of road conditions. Finally, a high power output will be needed to ensure that the BET is capable of reaching high speeds in order to drive smoothly along highways. Additionally, other features not directly included in the curve but beneficial for the BET are high efficiency, high instant power, and fast torque response.

With the purpose of providing these characteristics, there are different kinds of electric engines that differ in their configuration. All electric engines are formed by two parts, the stator and the rotor. This last one is the rotating part that transfers the torque to the wheels or gearboxes. Following, the five main types of electric engines are going to be explained using documentation from explanatory videos, scientific magazines, and research articles [51], [71]–[75], [76, p. 12].

Brushed Direct Current Motor

First of all, the brushed Direct Current (DC) motor is the only engine that does not require AC and therefore does not have an inverter. Brushed DC motors use a mechanical commutator and brushes to switch the direction of the current flow in the motor's windings, producing a rotating magnetic field that interacts with the permanent magnets in the rotor to produce torque. Brushed DC motors have a high start torque capability but have a strong drawback which is their maintenance and lack of long-term reliability, due to the need for replacement of brushes and commutators. Currently, this kind of motor is used in Indian railways but not in EVs.

Permanent Magnet Synchronous Motors

Secondly, Brushless DC (BLDC) synchronous motors use electronic commutation to switch the current to the motor windings located in the stator in a precise manner to control the speed and torque of the motor. This kind of motor is very similar to the Permanent Magnet AC (PMAC) synchronous motor, which creates a rotating magnetic field using Alternating Current (AC) in the stator windings to produce a force in the rotor. In both cases, the rotor is attracted by the electromagnetic fields created at the different stator windings. Generally, the rotor is made up of permanent magnets, but in a few applications, it can also be formed by permanent electromagnets created with a DC supply, although it is more complex and expensive to manufacture and maintain. In Figure 20, the scheme of a BLDC motor can be seen:

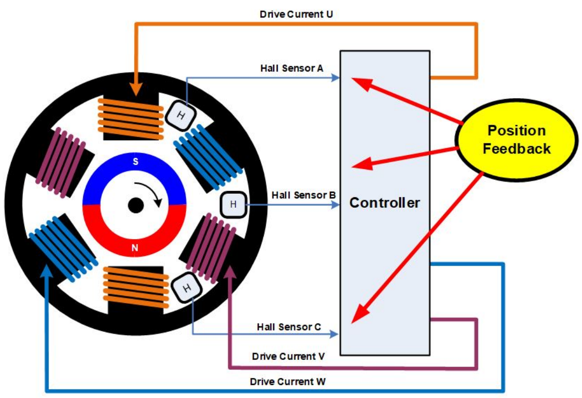

Figure 20. BLDC motor with permanent magnets in the rotor and hall sensor control system [77].

Both BLDC and PMAC motors are known as Permanent Magnet Synchronous Motors (PMSMs). PMSMs present high starting torque, high efficiency of around 95-98%, and high power density. The main differences between them are:

- Speed and torque control method: BLDC uses electronic commutation, whereas PMAC only needs to vary the frequency of the AC wave.
- Efficiency: PMAC has a slightly higher efficiency than BLDC due to a simpler design.
- Torque production: PMAC can produce higher torque at low speeds than BLDC motors.
- Speed range: BLDC can operate at higher speeds than PMAC motors.
- Back Electromotive Force (EMF) waveform: PMAC has sinusoidal back EMF, which allows for smooth and efficient operation, whereas BLDC has trapezoidal back EMF, which requires more complex current waveforms to drive the motor.

The problem with PMSMs is that permanent magnets are made up of rare earth elements, such as Praseodymium (Pr) or Neodymium (Nd), which are scarce, have high prices, and are mainly controlled by China. However, recently the largest deposit of rare earth metals in Europe has been found in Kiruna (Sweden). This has been a key finding in order to avoid the undersupply of these materials and could become a significant building block for producing the critical raw materials to enable the green transition through EVs [78].

PMSMs are the most common alternative of automotive manufacturers, who use these synchronous engines for their hybrid and EVs, but they are also widely seen in heavy-duty applications because of their higher efficiency and power density. Some examples of EVs using these engines are Volvo FE Electric truck model, Man eTGM, Toyota Prius, Chevrolet Bolt EV, zero motorcycles S/SR, Kia EV6, Tesla Model S, 3, X, and Y or BMW i3.

Induction Motor

The fourth type of electric engine is the asynchronous Induction Motor (IM). In IMs, the rotor is a cylindrical core made of stacked laminations of electrically insulated steel or cast aluminum, called a "squirrel cage" rotor. This motor also uses three-phase AC to generate a rotating magnetic field in the stator, which induces a voltage in the rotor. This voltage difference will cause current to flow, creating its own magnetic field, which will follow the rotating magnetic field generated by the stator. The induced magnetic field in the rotor lags behind the rotating magnetic field generated in the stator, creating asynchronism. The difference between these two fields is called “slip” and can be generally up to 5%.

IMs are known for their high power output, robustness, longevity, and resistance to harsh environmental conditions. Compared to synchronous motors, IM are simpler, require less maintenance, have lower costs, and do not require rare earth materials. However, synchronous motors can be more compact and have higher power density, wider speed range, higher efficiency, and more precise control. Some models with IMs in the market are Audi e-Tron SUV, Mercedes-Benz EQC, or Renault Zoe, and they are also used for heavy duty applications such as in the Toyota Mirai fuel cell electric truck, Scania battery electric trailer tractor and rigid truck, and Mercedes eAcros. Initially, the model availability for LDV using IMs was wider, however, many models lately have changed their IM to a PMSM one, such as the Nissan Leaf, BMW i3, or various Tesla models.

Switched Reluctance Motor

Finally, the last kind of electric engine is the Switched Reluctance Motor (SRM) or also known as variable reluctance motor, although they are not as popular as PMSMs or IMs. It has a ferromagnetic rotor with no windings or permanent magnets on it, therefore being cheaper. SRM’s stator winding has electrically independent phases and requires an electronics commutation similar to PMSMs. When AC is applied to the stator, the generated magnetic field is always pulling the rotor towards the next stator pole, minimizing the reluctance in the air gap and increasing the stator winding inductance which results in generating the torque. SRMs are simple, have high reliability, and can offer high torque density and efficiency in certain applications. Their robust nature makes them suitable for high-speed applications. However, they can also be more difficult to control compared to other types of electric motors.

3.4. Current models in the market

After having discussed the main technologies used for EVs and particularly BETs, now a model availability review has been performed in order to show some of the current BETs in the market, specifying their characteristics and showing their potential to replace conventional ICE trucks. To do so, the Zero-Emission Technology Inventory (ZETI) tool, which is an interactive online resource where worldwide commercially available models of zero-emission medium- and heavy-duty vehicles (MHDVs) are shown [73]. Parallelly, several leading European companies in BETs have been analyzed to identify potential trends, such as Scania, Volvo, and Mercedes, among others.

Scania Trailer Tractor and Rigid Truck

Scania Trailer Tractor BET is designed for regional long-haul transportation. It has a triple electric powertrain, which can provide the 40 R/S with a continuous power of 400 kW (540 hp), and the 45 R/S with a power output of 450 kW (610 hp). Scania Trailer Tractor and Scania Rigid Truck use Induction Motors (IMs) with inverter technology for high efficiency and smaller physical size. The battery pack can store 624 kWh, although only 468 kWh of them are usable with a 75% State Of Charge (SOC), and they are lithium-ion NMC batteries. This battery pack allows for up to 350 km range at 40 t Gross Trailer Weight (GTW) and 250 km range at 64 t GTW. It uses a CCS2 (Combined Charging System 2) charger of 375 kW / 500 A DC, being able to fully charge in less than 90 min at 375 kW, but the charging port is also prepared to support MW charging in the future. The next-level Scania electrified trucks will commence production in Q4 2023 [79], [80].

Volvo FM Electric and Volvo FH Electric Trailer Tractors and Rigid Trucks

Volvo FM Electric and Volvo FH Electric Trailer Tractors and Rigid Trucks are designed to manage large volumes between cities or deliver in busy urban environments. These models use two to three Permanent Magnet electric motors (PMAC) with a combined output of 490 kW (665 hp) continuous power. They are equipped with a high-capacity lithium-ion battery pack with a storage capacity of up to 540 kWh, which allows for a range of around 300 km with 44 t GTW ensuring sufficient range for many regional haul assignments. Volvo FM and FH can be charged using both AC or DC, taking 9.5 hours with AC (43 kW) and 2.5 hours with DC (250 kW) [82].

Mercedes Benz eActros 400 6x2

Mercedes Benz also offers BETs, such as the eActros BETs series. Particularly, the model eActros 400 6x2 extended range is designed for urban distribution transport. It uses two three-phase AC asynchronous motors in the rear axle, IMs, which together generate a continuous output of 330 kW (450 hp) and a peak output of 400 kW. It has four lithium-ion batteries with a total energy storage capacity of 448 kWh, 112 kWh each, providing a range of up to 400 km on a single charge under real-world conditions. Its maximum speed is 89 km/h, and the maximum payload allowed is 16.6 t (GTW of 27 t). It uses a CCS2 plug with a charging capacity of 160 kW / 400 A DC which it can go from 20% battery to 80% in around 1.5 hours [83], [84].

Truck MAN eTGM

Truck MAN eTGM is designed for inner-city distribution transport but can even be sufficient for large metropolitan areas. It has a single central electric engine with a maximum power output of 264 kW (360 hp). This engine is a PMSM. eTGM has 12 highly efficient lithium-ion NMC battery packs with an available capacity of 185 kWh. With a 26 t GTW, the battery pack provides a range of up to 190 km, clearly dependent on the area of operation and climatic and topographical conditions. It can be charged using AC or DC. Slow charge is done with a 22 kW AC charge socket which takes 8 hours to fully charge, and in DC the charging power can go up to 150 kW / 800 V, taking only 1 hour to completely charge the battery pack [85].

E-Force EF26

Finally, the last model discussed is from E-Force. The model EF26 is perfectly adapted for local distribution. This model is equipped with hybrid PMSMs having maximum power ratings of 440 kW and 550 kW (750 hp), depending on the configuration. The batteries of the EF26 are NMC-C type, and sizes range from 120 to 310 kWh, and the complete battery pack can reach up to 450 kWh. This energy storage allows the EF26 to drive up to 350 km in urban environments and 200 km on highways, with a payload admission of 26 t (GTW of 44 t). It can also be charged with normal and fast charging. Normal charging uses AC at 44 kW and takes 8 hours to charge completely. On the other side, fast charging uses DC at 350 kW charging the batteries in less than 1 hour [86], [87].

After having reviewed some of the BETs available in the European market, it is crucial to understand where these BETs models are placed with respect to conventional diesel trucks. To get a first overview, Table 2 recaps a comparison of some of the most important indicators:

	Energy Stored (kWh)	**Range (km)**	**Power (kW)**	**GTW (ton)**	**Energy per km (kWh/km)**
Scania Trailer Tractor	624	250	400	64	2.5
Scania Trailer Tractor	624	350	400	40	1.78
Volvo	540	300	490	44	1.8
Mercedes	448	400	330	27	1.12
Man	185	190	264	26	0.97
E-Force	450	200	550	44	2.25
Scania R 620 Class 8 (Diesel)	14075	1750	456	64	8.04

Table 2. Comparison of indicators of long-haul truck models.

As can be seen, even with the diesel truck Scania R 620 Class 8 truck which provides high fuel efficiency, the energy consumption per km is much bigger than for the BET models. This is due to the far lower efficiency of the ICE, ranging from 30 to 40%, with respect to electrical engines, which, as mentioned, can reach up to 98%. However, when it comes to range, Scania R 620 Class 8 truck outcompetes any BET model by more than four times. This happens because even with a lower efficiency in the combustion, diesel presents a high energy density of around 12 kWh/kg, while the battery technologies used in BETs range from 0.14 to 0.25 kWh/kg, as has been discussed. This results in a bigger energy storage capacity for diesel over BETs and, therefore, a wider range.

This comparison has also been made in previous studies where well-designed BETs under full-load conditions were stated to have an energy consumption of 2.05 ± 0.32 kWh/mi or 51.25 ± 8 Wh/ton-mile depending on the road conditions and the duty cycle, whereas conventional diesel trucks consumed about 4.45−6.3 kWh/mile. Furthermore, a comparison with United States electricity and fuel prices provides clear benefits for BETs. The cost per mile for the diesel truck is about US$1.36 ± 0.17/mile, and that of the BET is about US$0.96 ± 0.12/mile [88]. The following Figure 21 and Figure 22 show first a comparison between electricity and diesel price in the United States as well as their energy consumption per mile, and then the operational costs of BETs ($US0.96 ± 0.12/mile) and diesel trucks ($US1.36 ± 0.17/mile), including also repair costs which are expected to increase diesel operational costs around US$[0.12−0.16]/mile.

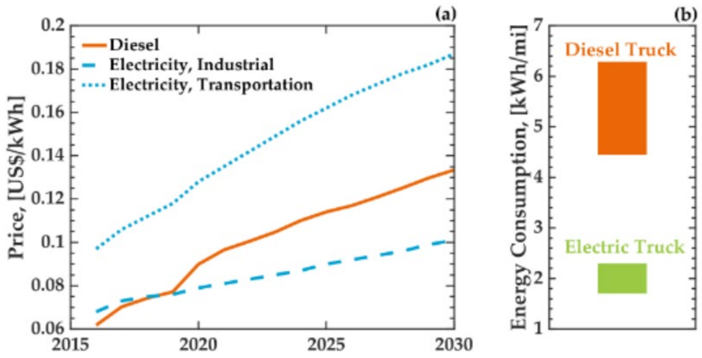

Figure 21. Comparison of the nominal price of fuel per unit of energy of diesel and electricity (transportation and industrial) (a) and the energy consumption per mile (b).

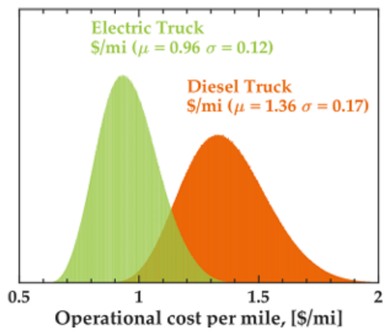

Figure 22. Comparison of the operational cost per mile per truck for a diesel truck fleet and an electric truck fleet.

3.5. Charging stations for electric vehicles

Charging Stations (CSs) for Electric Vehicles (EVs) are refueling stations that provide electricity to charge EVs, and nowadays, most of them are placed at residences and workplaces. Publicly accessible CSs worldwide approached 1.8 million in 2021, with 500,000 new chargers installed and with fast chargers representing already a third of the total CSs. In 2021, fast charging increased slightly more than in 2020 (48% compared with 43%) and slow charging much slower (33% compared with 46%), with China being the global leader in number of publicly available chargers. Europe ranked second with over 300,000 slow chargers, a 30% year-on-year increase. The Netherlands leads in Europe with more than 80,000 slow chargers, followed by 50,000 in France, 40,000 in Germany, 30,000 in the United Kingdom, 20,000 in Italy, and just over 12,000 in both Norway and Sweden. The number of public fast chargers in Europe was up by over 30% to nearly 50,000 units. This includes 9,200 public fast chargers in Germany, 7,700 in the United Kingdom, 6,700 in Norway, 4,500 in France, and 2,600 in Spain and the Netherlands [42].

When designing CSs for EVs, it is of high importance to identify the needs and requirements that it has to fulfill. The determination of the optimal power output or locations for CSs is a challenging multi-objective optimization problem. In order to define the configuration of CSs, some aspects have to be considered, such as EV driver behaviors and driving patterns, predicting evolutionary changes in both EV and EV charging technologies, predicting future EV take-up rates, what investment may or may not occur in private EV Charging Infrastructure (CI), the type of infrastructure required, and whether it is home, work, or public infrastructure [89]. However, these are not the only aspects. Apart from the CS configuration itself, some other external limitations might require consideration, such as legal issues, land tenure, physical, electricity supply capacity, road planning requirements, and financial factors.

In terms of charging and refueling infrastructure, several projects are being developed worldwide. Some examples are Megawatt Charging Systems, such as the CharIn project with up to 3.75 MW charging power [23], battery swapping stations, such as pilot projects being developed in China [25], or electric road systems, such as the Swedish 21 km electrified road [26].

Along this literature review section, power levels, costs, advantages, disadvantages, and other aspects just mentioned will be addressed so as to provide a clear perspective of which is the state-of-art in the development of CI technology for EVs, putting the focus on Battery Electric Trucks (BETs) again.

3.5.1. Types of charging

There are different types of charging classified by the international standard IEC 61,851, the Electric Power Research Institute (EPRI), the Society of Automotive Engineers (SAE), and the International Electro-Technical Commission (IEC) [67]. Depending on the charging type, the CS will have a different power output, which will therefore differentiate them by the charging time required, which is at the same time influenced by the State of Charge (SOC) or the maximum charging rate of the battery.

Level-1 (L1) charging type

Level-1 (L1) charging is the charging type with the lowest power output and hence the least expensive but the slowest of all charging methods. Due to the European standard 230 V residential electricity, this type of charger is unavailable in Europe, however, they are widely used in North America or Asia. L1 charging uses a typical 120 V household outlet with a maximum current allowed of 16 A, providing a maximum power outlet of 1.9 kW [90]. L1 charger takes between 11 to 36 hours to charge a passenger EV battery of 16 to 50 kWh according to its capacity fully, recharging approximately 40 miles (65 km) in 8 hours [67]. For many EV drivers, this works well due to the average driver's 37 miles (60 km) of driving per day. Depending on the price of electricity and the efficiency rating of the EV, L1 charging can cost anywhere from $US2 to 6 per mile [91].

L1 charging can be done using two different technologies. The first option is using a cordset (which usually comes with the EV) that on one end has a standard that plugs into a Level 1 outlet (110–120 V), and on the other end has the standard connector (different across the world) that plugs into the EV. The second method consists of installing a permanent wall-mounted or pedestal-mounted L1 CS, which has a fixed connector, and although this method is more expensive, it reduces the risk of personal property (cordset) theft or damage [92]. For L1 CSs, the type 1 plug *SAE J1772 connector*, also known as the *J-plug*, is widely used in North America and Asia. The main disadvantage of this plug is that it allows the use of only one phase [93].

L1 chargers are mostly used in households and offices since EVs are parked for a long time, reducing the need for fast charging, and given that there is no need for additional infrastructure, they are more economical [67]. The main advantage is that L1 CS can be used with the tariff-based charging system to reduce the charging cost even more, thanks to the lower electricity consumption costs compared to higher power charging options [90]. Furthermore, each utility has its own threshold for demand charges. If a site's power usage exceeds that threshold, the site is charged a fee based on the site's peak demand, and this event is more likely to happen for CSs with higher power than the L1 type [92]. However, the L1 charger also has its limitations, such as the charging time needed to fully charge the battery, which reduces the flexibility of this kind of charger and does not allow the EV driver to use it for quick charges during some daily tasks like shopping, medical appointments and others.

The exact price of the whole installation of an L1 CS differs across studies. Some of these costs are: approximately $US400-900 for the infrastructure [67], simple wall-mounted units that plug into an outlet or can be hardwired to the electrical system cost around $US300–600, and a pedestal unit with access control costs range from $US1,000–3,000, assuming that no major electrical upgrades are needed, and electrician's fees for replacing outlets are in the $US50–75 [92].

Level-2 (L2) charging type

Level-2 (L2) charging is much faster than L1. In North America, it utilizes a 208 V to 240 V AC outlet, with a maximum power output of 19.2 kW. In Europe, this mode has a 230 V (single-phase) AC with a current-handling capacity of 40 A and a 400 V (three-phase) AC supply at 80 A, with a maximum power output of 22 kW. With a power output of 19.2 kW, the L2 CS can take between 2 to 3 hours to charge a battery of 50 kWh [67]. However, L2 chargers can rate from 3 to 22 kW power output, being able to charge from 16 to 120 km per hour. Based on the electricity rate and the vehicle's efficiency, L2 charge costs range from $US2 to 6 per mile [91].

L2 CS can be provided with tethered charging cables (hard-wired to the CS) or untethered with just a socket, but opposite to L1, it cannot be directly connected to the household grid. L2 CS requires being mounted on a wall or pole near the parking spot, running electrical wiring from the electrical panel to the CS, and installing a dedicated circuit (e.g., 230 V outlet with the capacity of at least 16 A on a dedicated circuit) [94]. Overvoltage and overcurrent protection are built into L2 charging systems [91]. When it comes to connectors for L2 CSs, they vary across countries. Standard in Europe is the three-phase *IEC 62196 Type 2 connector*, also known as *Mennekes plug*, which holds the typical 22 kW but can also reach up to 43 kW [95]. In North America (except for Tesla, which provides a charger adapter in every EV sold), they use the same as for L1, the *SAE J1772* connector or *J-plug*. In China, the *GB / T plug*, also known as the *Guobiao/T standard connector*, is the most commonly used [93].

Level-2 CS is the most common and conspicuously used in Europe or North America, used for charging at residential as well as public and private charging facilities (e.g., entrances to businesses, schools, and colleges) since many times it runs on the same voltage as home appliances (i.e., 230-240 V) [90]. Thanks to the higher power outputs, L2 provides more flexibility than L1, allowing EVs to charge faster. This brings two main advantages; first, it allows charging more EVs during the day, and second, it also allows extending the range of the EV more easily. Moreover, L2 charging provides more CS options available, including smart chargers that can be controlled remotely and that can be integrated with other home automation systems [91]. Though L2 charging has many advantages, it has certain drawbacks if it is not monitored, such as the power consumption can surge up to 25%, which can lead to an increase in the charging costs due to exceeding the power tariff [67].

The economic availability of this kind of CS also differs widely. Some references are: pedestal-mounted L2 CS had an average installation cost of $US2,305, with some installations costing over $US4,000 [92]; depending on its brand, power rating, and installation requirements, L2 CS can cost anywhere between $US500 and $US2000 per unit [91], or commercial and public charging stations cost more than $US15,000 [67].

Level-3 (L3) charging type

Level-3 (L3), also called Direct Current Fast Charging (DCFC), is the fastest CS, usually presenting a C-rate between 1 and 2, much greater than for L1 and L2. L3 CS uses AC from the grid, and it requires 400 V (three-phase) AC in Europe (480 V AC in North America) that is first converted to DC from an off-board charger contained in the CS pole and then delivered to the EV, instead of AC used in L1 and L2. DC converted in the off-board charger from the CSs bypasses the on-board charger allowing a faster charge. The main aim of such a station is to provide a similar experience as that of a normal gas filling station by using DC charging facility [90]. Currently, L3 charging provides a voltage range between 200-600 V, some of them reaching even 1000 VDC, and power output ranging between 36-360 kW [96]. Charges for L3 charging can range from $US12 to 25 per mile [91]. It can charge from 190 to more than 2250 km in an hour, obviously depending on the battery energy capacity and availability to withstand higher charging rates. Usually, a DC fast charging takes 15-20 min to charge a battery from 0 to 80% State of Charge (SOC). The 20% left is always charged in slow mode irrespective of the charging level type, considerably slowing in order to prevent overheating or overcharging. For example, it may take just as much time to charge from 80 to 100 percent SOC as it does from 10 to 80 percent [97]. This phenomenon is known as *tapering*, and it happens because the battery can take the maximum power of the charging station when it has a low SOC because the internal resistance is relatively low, which allows to accept more charging power without overheating. However, as the battery charges and the SOC increases, the internal resistance of the battery also increases, which can lead to overheating and damage to the battery if it continues to charge at the same high rate. Although this happens in all CSs, tapering effect is more noticeable in high-power charging stations. Figure 23 illustrates the tapering effect happening in a 50 kW DC Tesla charger:

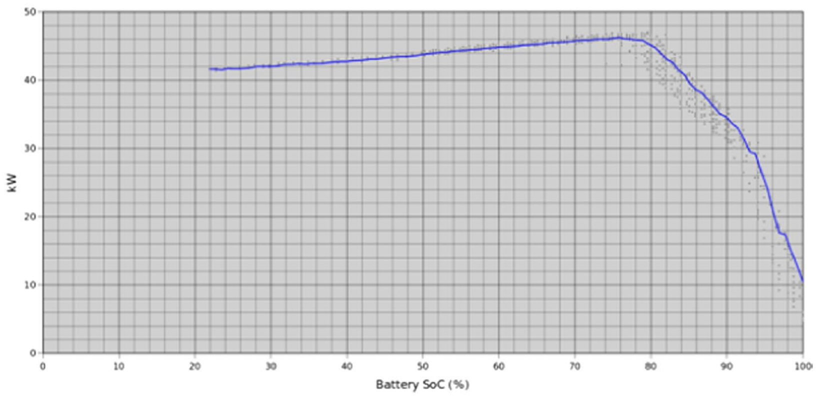

Figure 23. Charging curve for a Tesla Model S on a 50 kW DC charger [89].

Installing an L3 CS requires a dedicated electrical service that can handle the high power demands of the charging station, a dedicated cooling module for high-power electronics, and an AC (from the grid) to DC (for charging the battery) converter. The connectors used in Europe are the *Type 2 CCS (Combined Charging System)*. This connector allows to have only one socket (used for both AC and DC) and supports a charging capacity of up to 350 kW [95]. The design of *Type 2 CCS* is the same as for the *IEC 62196 Type 2 connector*, although for allowing DCFC, it includes two lower pins, and the upper part (*IEC 62196 Type 2 connector*) is used for the communication pin and the earth conductor, as well as for AC charging. In North America, the *Type 1 CCS* is used, and, in the same way as *Type 2 CCS,* it includes two lower pins for DC charging to the current *SAE J1772*. Japan uses the *CHAdeMO plug,* which is gaining international recognition. However, this plug can only be used for DCFC, requiring two sockets instead of one [67]. China has its own standards for DC charging with the *GB / T plug*.

Most L3 CSs are located in high-traffic areas such as logistic hubs, shopping centers, government buildings, distribution centers, airports, and refueling stations. L3 CSs are very suitable for Battery Electric Trucks (BETs) since they are able to provide a fast charge for big battery sizes, allowing freight transport BETs to reduce their refilling time to continue with their journey. Hence, their main advantage is a low time required to charge the EV, resembling gas refills times to which society is used. However, DCFC has a significant drawback due to their high installation costs, apart from being unsuitable for residential places. Furthermore, they might require potential grid improvements, which would take time and money. For instance, a typical Electrify America highway charging station with two 350 kW and four 150 kW chargers will increase the power consumption by 1.2 MW, necessitating the purchase of a more expensive distribution transformer [67].

In the same way as for other charging levels, the economic references found vary widely. Some of these are: it costs between $US30,000 and 160,000, depending on the quality [67], $US80,000 to 120,000 are required to install a DCFC, including investment, infrastructure, and O&M costs [67], the equipment costs is assumed to be $US127,000 (350 kW), $US70,000 (150 kW) and $US30,000 (50 kW) and the installation costs $US15,000 (350 kW), $US8000 (150 kW), $US5000 (50 kW) [89].

Other types of CS

All these previously defined kinds of CSs are categorized as conductive charging, which is considered the most efficient method due to that it has the most efficient way of transferring energy with minimum loss. However, based on charge transfer patterns, there are also other alternatives available in the market that can bring solutions to the existing problems of conductive charging [90].

Electrified Highways (eHighways) are an alternative to conventional charging methods. The principle is that EVs use electricity directly from the electric grid as they travel along the road, rather than relying on the storage capacity of a battery and the need to stop refilling. There are two main types of eHighways, putting specifically the focus on BETs, in-motion Wireless Power Transfer (WPT) and Conductive Power Transfer (CPT). Both of these technologies represent a strong advance and a key feature over conventional ICE trucks used for freight transport since the need for stopping is removed, and this could be potentially applied in future autonomous BETs. Furthermore, the reduction of battery size is also possible thanks to the in-motion charge, reducing the problems with payloads or volume limitations.

WPT can be divided into two categories; capacitive wireless charging, based on electric field coupling, and inductive wireless charging, in which energy is transferred wirelessly through a magnetic field between two coil plates, one in the vehicle and the other embedded in the pavement [98]. One example of the WTP inductive method is the Smartroad Gotland in Sweden, financed by the Swedish Transport Administration and managed by Electreon AB. The electrified road on Gotland makes up a total of 1.6 km of the 4 km long stretch between central Visby and Visby airport, with the charging system installed under the asphalt, used mainly for BETs and buses [99]. Figure 24 and Figure 25 illustrate two kinds of WPT systems:

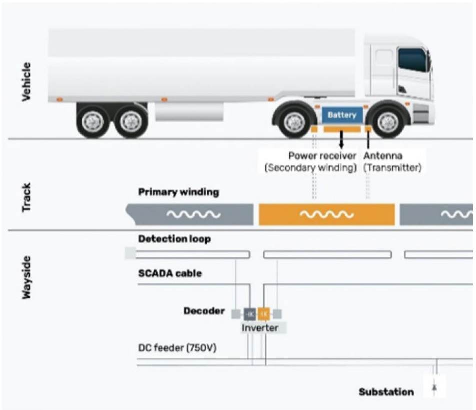

Figure 24. In-motion Wireless Power Transfer (WTP) system [98].

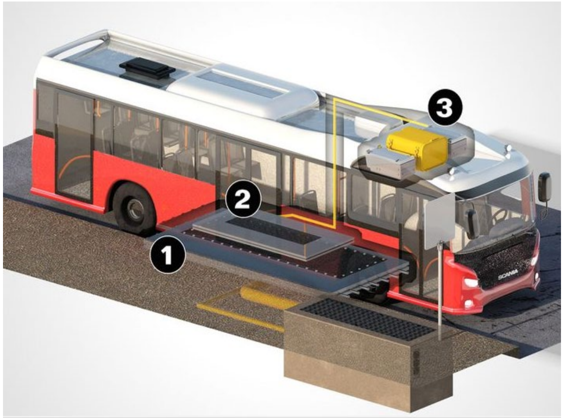

Figure 25. Endpoint Wireless Power Transfer (WTP) system [100].

On the other side, CPT eHighways are systems with efficient energy transfer from overhead wires. For such a CPT system, BETs have a pantograph installed in the upper part of the vehicle, and when needed, the pantograph is deployed to get in contact with two overhead catenaries in charge of supplying the DC electricity. Then, electricity is transferred to the truck through the pantograph charging the BET's battery [98]. An example of this technology is the world's first electric road in the existing public road network, which connects Sandviken and Kungsgården in Sweden [101]. In the following figure, the CPT eHighway system can be seen:

Figure 26. Siemens catenary system with pantograph connector on a Scania truck [101].

Another promising method of EV recharging is battery swapping. This technique consists of a station of battery replacement, known as Battery Swap Station, where batteries are charged as long as they stay in the station. Instead of connecting the EV to a charging network, the empty batteries of EVs are removed from the vehicle, and a charged one from the stationary battery charger is put in its place. This can bring potential advantages such as a longer battery lifetime due to lower charging rates, a higher efficiency thanks to the more optimal charging power used, a reduction in charging time resembling a conventional gas station, or better stability on the electrical grid. However, there are still concerns regarding the ownership of the batteries. In the research article [102], battery swapping method is expected to become more cost-effective than fast charging or superfast charging methods for EBTs when the station utilization rate is higher than 43%, and cost-effectiveness is expected to grow even more due to improvements in battery technology.

Recently, Cafu, a Dubai-based on-demand vehicle service provider, together with Quebec's Innovative Vehicle Institute have developed a new pioneering strategy for EV charging. This method consists of a mobile charging solution, Cafu En Charge, a van equipped with a 140 kWh battery pack that enables 50kW of fast charging. Using their app, an EV owner can book the van and select a meeting point to charge their EV. This method has been considered a very convenient solution for EV owners who may not have access to home charging or who need an extra boost of energy on the go [103].

For all the kinds of CSs discussed, it is important to consider what has already been discussed in previous sections. CSs and BETs entail a huge increase in electrical demand that somehow needs to be paired together with the enhancement of the current electricity infrastructure. Such upgrading of the electricity infrastructure will take both time and money, increasing the complexity of the projects. In order to minimize the time or money needed for these types of projects, it is important to establish strategies for modeling the charging profile of EVs. In the next section, an analysis of the charging management will be addressed so as to understand how the charging process can be adapted and optimized.

3.5.2. Charging station projects

Örnsköldsvik CS

One example of Level-3 CS is the Tesla V3 Supercharger, which for instance, in Örnsköldsvik (Sweden) has twenty CSs capable of delivering 1000 VDC at 425 A each, delivering 250 kW per CS. The Supercharger can recharge up to 200 miles (330 km) in 15 min. Tesla uses the same connector for level 1, level 2, and DC fast charge. Only Tesla vehicles can use their DC fast chargers or also called Superchargers. Even with an adapter cable, it would not be possible to charge a non-tesla EV at a Tesla Supercharger station due to a compulsory authentication process [104]. The following pictures have been taken in place and show this installation:

Figure 27. Pictures from Örnsköldsvik (Sweden) CI with 20 CSs, each delivering up to 250 kW.

SFV Naturhistoriska CS

Another example of CI is the Charging site SFV Naturhistoriska (Stockholm). This smaller CS is able to provide up to 22 kW AC charging, being classified as an L2 CS, operated by eways. It offers five charging posts that use the IEC 62196 Type 2 connector.

Figure 28. Pictures from Naturhistoriska CI, with 5 CSs, each delivering up to 22 kW.

Verkstadsvägen – Södertälje CS

The last example is the 350kW CSs located in Verkstadsvägen – Södertälje (Sweden). The Ionity HPC 350kW Circle K is a project developed by Ionity as a technology supplier, a joint venture between several major automakers that is building a European network of DCFC, with Circle K as the facility owner, a major operator of petrol stations in Sweden that has been expanding its EV CI in recent years. The CS has a power output of up to 350 kW with six sockets available for multiple charging, making it possible to top up the battery to 80 % capacity in less than half an hour [105]. EVs can be charged using CHAdeMO, CCS Type 2, or the standard IEC 62196 Type 2 connector. The following image shows the CS:

Figure 29. Ionity 350kW CSs located in Verkstadsvägen – Södertälje (Sweden) [106].

In order to summarize key information provided in this literature review section, Table 3 shows the main parameters discussed, and Figure 30 shows the types of connectors used for the different charging types and regions.

Charging Level	Output Power Range (kW)	Range per hour charging (km)	Time for 10% to 80% SOC of a 50 kWh battery (hours)	Investment Cost 2016 (SEK) [107]
Level 1	1.4 – 1.9	4 - 11	18 – 25	~15,000
Level 2	3 - 22	16 - 120	1.6 – 11.7	60,000 – 80,000
Level 3	36 - 360	193 – 2250+	0.1 – 1	25,000 (50kW) 800,000 (150kW) 1,200,000 (360kW)

Table 3. Summary of main parameters of CSs.

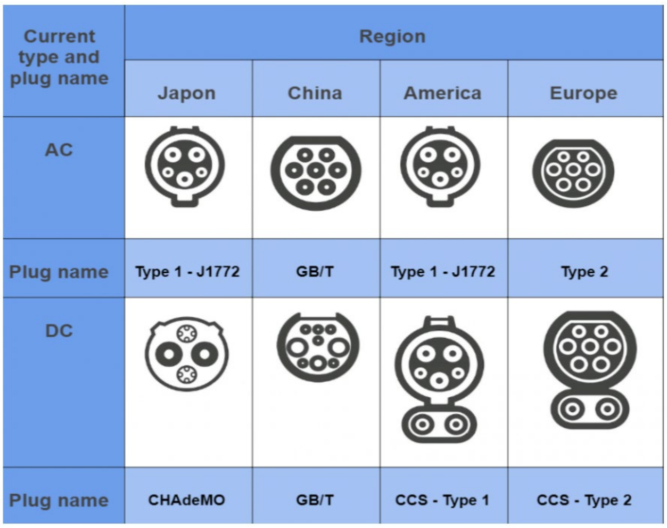

Figure 30. Type of CS connector for every region and charging mode [93].

Finally, it is important to mention that other relevant parameters that might be used in this report can also come from other sources, but a special mention has to be made to the *Analysis of electric vehicle charging station usage and profitability in Germany based on empirical data* [108]. In this article, the feasibility of different CSs is analyzed using real data on energy consumption, arrival times, occupation, and estimated profitability of 22,200 charging stations in Germany. Using this data, the article studies the common patterns of charging for EVs in each kind of CS, defining their average energy supplied and time used, and identifies how, where, and when CSs are used and how profitable they are. Just as an example, the next table extracted from this article shows which is the percentage of profitable CSs depending on the sales price of electricity, understanding as profitable that sales of electricity cover their costs.

		$P < 4$ kW	$4 \leq P < 12$ kW	$12 \leq P < 25$ kW	$25 \leq P < 100$ kW	$100 \leq P < 200$ kW	$P \geq 200$ kW
Investment cost		2,000 €	6,000 €	9,000 €	50,000 €	100,000 €	200,000 €
Lifetime in years		8	8	8	8	8	8
Real interest rate		4%	4%	4%	4%	4%	4%
OpEx in €/a		122.2	76.3	77.2	136.4	128.8	117.6
Number of EVSEs per PCS		3.94	2.41	2.44	3.31	3.12	2.84
PCS EVSEs independent of area type							
Share profitable by sales margin	5 €ct/kWh	21.29%	1.77%	1.04%	0.08%	0.08%	0.11%
	10 €ct/kWh	**37.72%**	**11.63%**	**9.09%**	1.04%	0.42%	0.11%
	15 €ct/kWh	47.23%	23.15%	20.88%	3.07%	6.23%	0.11%
	20 €ct/kWh	52.83%	*33.04%*	*31.12%*	6.93%	14.99%	0.47%
	30 €ct/kWh	63.12%	46.51%	46.62%	**15.57%**	33.13%	6.26%
	40 €ct/kWh	68.99%	55.39%	56.81%	*24.46%*	47.77%	17.53%
	50 €ct/kWh	73.50%	61.40%	64.05%	31.60%	**58.92%**	**29.10%**
	60 €ct/kWh	77.06%	66.47%	69.45%	38.20%	*67.34%*	*40.79%*

Table 4. Estimation of share of profitable CSs [108].

3.6. Charging management

When it comes to charging, EVs alone account for approximately 5% of the total electricity consumption [42]. Therefore, uncontrolled charging of EVs (V0G) affects the power system, causing, as a result, increased thermal overload, instability issues, decrease in power quality, or overloaded transformers and lines, triggering detrimental impacts on distribution grids [109], [110]. Moreover, EV charging costs could exceed diesel fueling costs when high-power charging is subject to high peak demand prices or experiences low utilization [111]. Additionally, without EV charging coordination, residential peak demand hours will overlap with EV charging timeframes, not only causing an impact on the grid but also exceeding the hired power contract and supposing economic compensations [112]. According to the study performed in [113], uncontrolled charging of EVs in the current Australian national grid can support EVs at 5–10% penetration, whereas with controlled charging, the penetration is around 60–70%, and it also reduces electricity cost by up to around 4–6%.

These effects can even be seen enhanced when talking about Battery Electric Trucks (BETs). EV passenger fleets have lower power requirements and longer available parking time periods, in some cases up to 95% of the time, offering a much more flexible charging profile. Whereas BETs present several challenges that make load shifting a complicated operation. First of all, BETs have a stringent operational schedule, complicating their charging during parking time. Secondly, restrictions on the maximum power demand of commercial premises due to different electricity billing strategies limit high power Charging Stations (CSs). And thirdly, their larger battery sizes result in larger impacts on the local network of commercial premises due to higher power consumption, requiring bigger grid reinforcements [114].

However, controlled EV charging strategies can optimize the number of Charging Stations (CSs), which can subsequently lead to reducing the need for grid improvement, reducing costs and time. Optimized charging methods can reduce charging time, improve charging performance and extend the battery life cycle compared with conventional charging methods. Furthermore, the appropriate charging strategies can also produce a reduction in emissions thanks to the use of electricity with a higher share of renewable production. Following, different strategies for charging management are going to be analyzed, showing their potential to benefit EV owners as well as grid operators.

3.6.1. Charging strategies

It is important to take into consideration that the charging strategies that will be presented can be classified into two major categories, user-controlled scheduling and grid-operator-controlled scheduling. The user-controlled scheduling of EVs aims to reduce the charging costs for EV users without considering any provision for grid support, while the grid-operator-controlled scheduling approaches are managed from the system operators' perspectives to provide grid ancillary support such as congestion management and peak shaving [110].

First of all, Time-of-use unidirectional charging method (V1G). In a Time-of-use scheme, electricity usage is priced differently during peak and off-peak hours, with higher prices during periods of peak demand and lower prices during periods of low demand. This encourages EV owners to charge their EVs using electricity generated during off-peak, which can help to balance the load on the power grid and reduce overall electricity costs [115]. Similarly, in the Load Shifting strategy, the charging of EVs is shifted to off-peak hours through the use of scheduling or automated charging algorithms. During low-demand hours, EV charging coordination may be a potential candidate to decrease voltage fluctuation [112].

Vehicle-to-grid (V2G) charging strategy is a bidirectional method. In this strategy, EVs are used not only as consumers of electricity but also as suppliers of electricity back to the power grid, allowing EVs with a sufficient State of Charge (SOC) and parking time to provide grid support. However, the EV owner and the charging station operators must have mutual agreements in such cases [110]. V2G is also viewed as a promising technology for solving the problem that appears due to the non-dispatchable nature of renewable generation, accommodating their intermittent generation via EVs. The common charging management objectives of V2G are to improve the well-being of EV owners thanks to decreasing energy costs and enhancing the satisfaction of charging demand, to increase the profits of charging service operators, and to balance the load [109]. However, this charging strategy, although providing several advantages, requires a very complex communication system and can decrease the lifetime of the battery due to constant charge and discharge operations.

Finally, the last strategy for charging management includes external Battery Energy Storage Systems (BESSs). There are multiple ways to use the batteries to define the charging of EVs. For example, BESSs located at charging parks can help to avoid significant increases in the peak load, apart from relieving individual overloaded or limiting lines [116]. Another kind of charging strategy using batteries is the already discussed battery swapping. Although this strategy may have a higher initial investment, it reduces the charging cost and improves the operational economic benefits [102]. Additionally, if nanogrids with renewable generation systems integrated can supply batteries to a battery swapping station (BSS), it will help establish a novel renewable-energy-to-vehicle system [117].

3.6.2. Ownership and business models of charging stations

The initial investment to install Charging Infrastructure (CI) is currently a huge barrier to EV adoption and even more in this fast-paced industry where flexibility and scalability are absolutely critical. In order to reduce this barrier and incentivize EV adoption, different models of ownership for CI have been developed. On the other side, many different business models have been developed regarding the payment method of the electricity sold in order to capture as many customers as possible. In the same way as charging management, ownership and business model to operate the CSs bring several benefits to many actors, such as EV owners, grid operators, or third parties, depending on who owns them and how they are operated.

Focusing first on ownership possibilities, public ownership is one of the existing choices. Nevertheless, it is less frequently used if compared with charging at home or in workplaces (hybrid or private), but it is still necessary to encourage vehicle drivers to adopt an EV [118]. In this case, CSs are owned and operated by public entities such as municipalities, public utilities, or government agencies. The public authority assumes the cost of the installation and maintenance using public funds or grants, while they will usually not cover any of the charging costs of electricity used by individuals. This business model is beneficial in many ways. First of all, private EV owners will not assume the high investment costs of CI, reducing the cost of ownership of their EVs. Secondly, for the public entity, this will increase energy security, reducing the dependence on imports of fossil fuel, it will also increase air quality while pursuing international climate and environment commitments, and it will guarantee economic development [119].

In the case of private ownership, the CI is completely owned by an actor or alternatively by multiple parties (could be both public and private entities). Depending on who owns or has funded the different parts of the CI, the project can be divided into Business or landowner funded, Hybrid (partially funded), or Fully funded by a third party [120].

Business or landowner funded refers to complete ownership of the CI by the facility owner, which can be one party or, by convenience, shared ownership between more parties. In this model, the facility owner pays the Charging Point Operator (CPO) or Electric Vehicle Service Provider (EVSP) for hardware, installation, and connection costs. Once it is installed, 100% of the profit is kept by the facility owners, or a third party can be included to manage, operate and maintain the CSs, splitting the profits accordingly. In the Hybrid model, the facility owner and CPO or EVSP agree to share the upfront capital costs and the ongoing revenue from the operations. Finally, the Fully Funded CPO or EVSP is interested in the particular location of the project due to factors such as EV driver density, adjacency to highway networks, and other commercial factors and accepts to fully fund the capital outlay for the project. The facility owner and CPO or EVSP will negotiate a custom business agreement and revenue-sharing model. The two main agreements are the Leasing Revenue, in which the landowner receives a rental fee of the land and the CPO or EVSP fees drivers for plugging in their EVs, and the Revenue Sharing, based on sharing the profits between the two parties [121]. Next, Figure 31 illustrates the electric vehicle supply equipment. The green area is the part owned by the grid operator, and the blue is the part belonging to the owner of the CS, depending on the model of ownership.

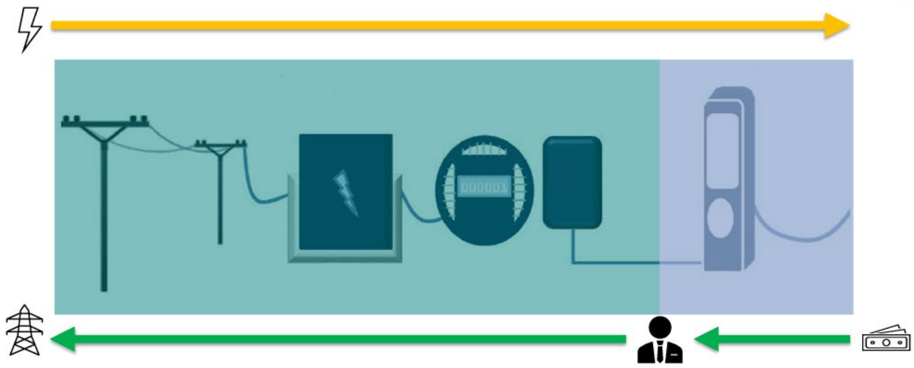

Figure 31. Simplified electric vehicle supply equipment ownership model [119].

Operation of the CI entails a huge responsibility and know-how of the business. While EV drivers benefit from speed and flexibility in charging, electric power providers benefit from predictability and stability in power demand, and many times EV demand and electricity grid requirements do not match, bringing problems for both sides. In order to facilitate this communication between actors, as mentioned just before, a third-party aggregator can be included to serve as a mediator, optimizing services for collective benefit. The third party can own the equipment or not, but it will be responsible for its operation and maintenance. The set of emerging infrastructure ownership and usage models involving third parties is known as ‘‘charging-as-a-service’’ (ChaaS) [111]. This business model can offer perks in multiple ways, such as economic and technical, in exchange for a share of the profits generated. Firstly, it can mitigate economic risks by sharing or having complete ownership. Moreover, the billing process commonly requires the consideration of many factors and strategies that can be otherwise carried out by the ChaaS. Secondly, having the system designed and operated with expert and experienced knowledge reduces risks of an increase in costs or diminished performance, and ChaaS companies can provide design and operations expertise to their customers. Additionally, taking care of the operation and maintenance of the CSs reduces time-intensive responsibilities and the costs of potential errors.

When it comes to the profits generated by pricing electricity sold, many alternatives have been developed, considering aspects such as the kind of visiting driver, type of location of the CI, or typical costs incurred. Depending on the business model implemented, they can be classified into those that do not depend on the electricity consumed, such as Pay by Time or Pricing as Flat Rate, and those that depend on the amount of electricity used, such as Loss Leader Model, Operational Cost or Total Cost Recovery and Profit Making [118], [122].

Within the non-energy dependent, the Pay by Time method only takes into consideration the time that the EV is connected to the CS. The other non-energy dependent pricing method is the Pricing as Flat Rate, in which the user pays a fixed price for a limited period and can charge as often and as much as wanted, or a fixed fee for one charging process, independently of the electricity used and the charging duration.

For energy-dependent methods, depending on the strategy followed, three different business models can be identified. In the Loss Leader Model charging is offered completely free, with the main idea to grow brand loyalty and encourage on-site spending. With the Operational Cost or Total Cost Recovery, it is intended to match the operational costs or recover the total cost thanks to applying a fee to the electricity sold. Further on, the Profit Making method is based on the same strategy but with a higher fee charged to drivers to use the charge points. Nevertheless, with these two last methods prices for electricity sold need to be set within a reasonable frame that drivers find acceptable, and in order to incentivize it, some strategies are applied, such as first hour free, second hour paid, or penalties for peak charging [122]. Some ongoing electrical costs are collected in the following table:

Charger power rating	kWh added per 30 minutes charging	Approx miles of range added per 30 minutes charging for a hypothetical 80kWh BEV	Electrical cost (assuming business paying 12p per kWh)
7kW top-up charging	3.5kWh	12.5	£0.42
50kW rapid charging	25kWh	87.5	£3.00
150kW en route charging	75kWh	262.5	£9.00

Table 5. Ongoing electrical costs in the UK [122].

Having addressed the most crucial aspects of this project, a clear picture and extensive knowledge have been provided, creating a strong theoretical background. Understanding the Swedish transport sector's current development and future plans, HDTs electrification challenges and advantages, BETs technologies, and CI possibilities, it is now possible to proceed with the elaboration of the practical part of the project. The next sections of the report will be focused on the development of the methodology applied to the case study of Oskarshamn. This stage will combine both real information collected from actors involved in the project and data obtained through the exhaustive theoretical analysis done along the literature review. Finally, based on techno-economic indicators and aiming to maximize the feasibility of the project, a solution will be provided that guarantees a CI capable of enabling the complete electrification of Oskarshamn's truck fleet.

4. Oskarshamn Case Study - Modelling

As mentioned previously, this study seeks to investigate the potential of the implementation of a Charging Infrastructure (CI) at Oskarshamn, which will allow the electrification of the regional freight transport, in particular of Heavy Duty Trucks (HDTs) that are fueled with diesel. Oskarshamn is a Swedish municipality located in Kalmar county on the east coast, with a significant and growing maritime industry. Oskarshamn Harbor is a hub for transportation, as it also serves as a terminal for ferries that connect the city to other parts of Sweden, like the route that connects Oskarshamn (Småland) with Gotland.

In section *3.1* Swedish road transport sector*,* it has been shown that 99% of the ton-km of goods transported by the road sector occur in domestic traffic, with 65% of them in distances shorter than 50km. Thanks to the information available in *Trafikanalys* and *Official Statistics of Sweden* [27], [29], [33], [34] specific data from Kalmar region and Oskarshamn has been gathered to understand the behavior and importance of the transport sector for this case study. Out of the 16.4 Mt of goods transported by HDTs in Kalmar region, 12.8 Mt were transported within the county. When looking at which kind of HDTs have transported these goods, the next Figure 32 and Figure 33 show the number of trucks registered by type of fuel:

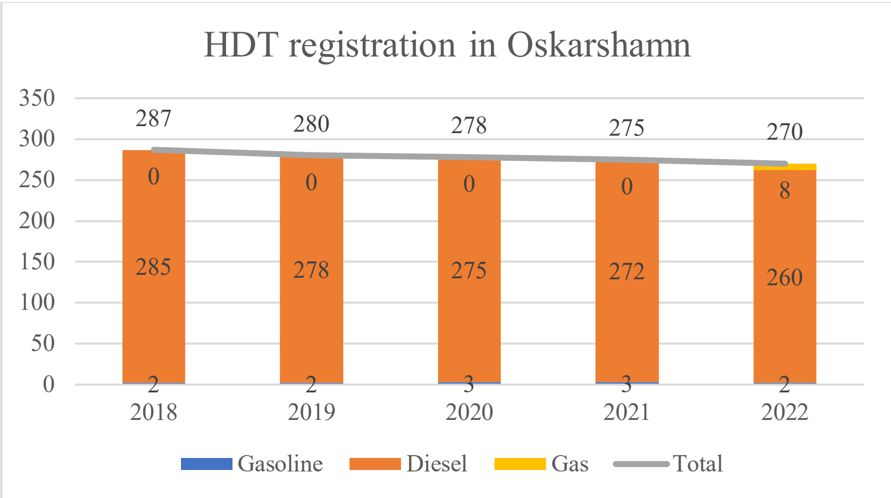

Figure 32. Heavy Duty Truck registration in Oskarshamn from 2018 to 2022.

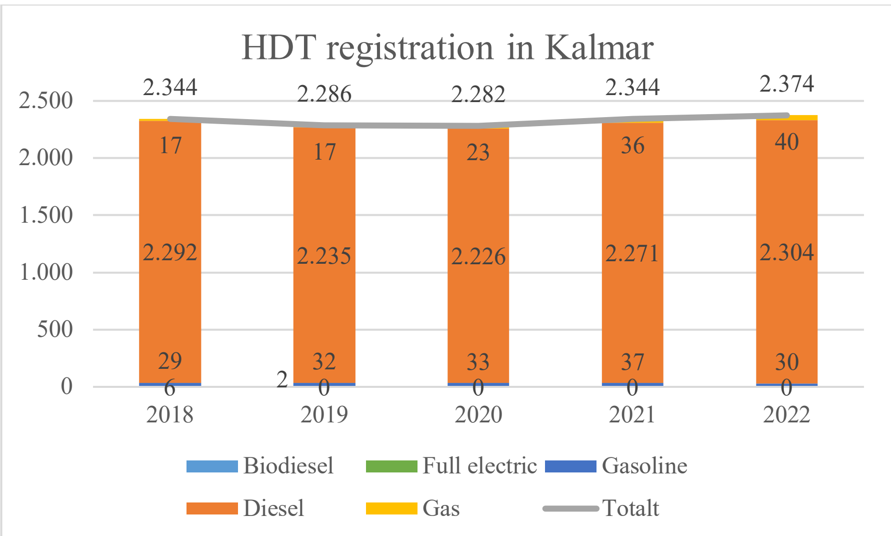

Figure 33. Heavy Duty Truck registration in Kalmar from 2018 to 2022.

As can be seen, the number of Full electric HDTs is deficient, finding only two registrations in Kalmar in 2019. The most predominant powering fuel type, with more than 96% of the truck registered every year, is diesel, followed by far by gasoline and gas. Therefore, the conceivable benefits of replacing a truck fleet heavily based on diesel are huge and can bring many positive impacts on the environment.

In the following sections, the methodology described in section *2 Objective and methodology* will be explained thoroughly, giving examples of its application. Finally, in section *5 Oskarshamn Case Study – Final proposal,* the methodology presented in these next sections will be applied entirely to the case study, providing the most appropriate configuration for the CI in Oskarshamn.

4.1. Main Stakeholders

The interest in this project arose from the willingness of private and public entities from Oskarshamn to collaborate together in order to pursue ambitious objectives to fight climate change. In this sense, Oskarshamn is positioned on the right path to continue fulfilling SDGs, decarbonizing road transport and keeping Sweden as one of the most committed countries in the fight against climate change.

In the first instance, it is necessary to identify who the stakeholders of Oskarshamn are. First of all, the public sector with the municipality actors of Oskarshamn. Oskarshamn municipality is really committed to the energy transition, even though Kalmar county has not presented an electrification pledge, unlike the other regions of Småland och öarna (Jönköping, Kronoberg, and Gotland). Ulrika Zetterberg, development manager in Oskarshamn municipality, states, “We are currently working with an Energy and Climate action plan. Our intention is to set up goals that harmonize with the regional goals of a fossil-fuel-free region in 2030. Electrification is an important part of the development of the municipality and the region. Political leadership has a more diverse agenda to address, and industry wants to electrify, but we need to be able to maintain jobs and welfare. In Oskarshamn’s municipality, approximately 80% of the emissions of CO_2 come from the transport sector. As a municipality, we have limited possibilities to operate on the energy market and install charging points for electric vehicles. We can, however, promote electrification in other ways. We have several companies that are fully and partly owned by the municipality. One of them is Oskarshamn Energi AB, which is allowed to and has the competence to install charging points and sell electricity. Thanks to that, we can negotiate business agreements that result in the development of the charging infrastructure. My ambition is to express goals in the climate action plan that are linked to these types of agreements. However, the plan must eventually be decided upon amongst the political leadership.”. Therefore, as mentioned in Ulrika’s statement, Oskarshamn’s municipality is truly committed to facilitating and helping to develop projects that will bring the region to a fossil-fuel-free region and is willing to put into practice, among other projects, the electrification of Oskarshamn’s truck fleet.

On the other side, there are also many private stakeholders who are interested in carrying out this project since it can bring economic benefits for the company and help them to achieve their goals for fighting climate change. One of these stakeholders is Scania, which has a big factory in Oskarshamn. Scania is willing to build a CI to replace their conventional diesel truck fleet aiming to reduce CO_2 emissions by 50% in internal operations and by 20% in the truck selling process. These two main targets are accompanied by other strategies, such as replacing the fuel used for the painting process from fossil diesel to the biofuel RME (Rapeseed Methyl Ester) and switching internal transport vehicles that were previously operated on fossil diesel to an on-site supply of the renewable biofuel HVO (Hydrotreated Vegetable Oil) [123]. In the same way that Scania, there are many other companies engaged in the project and looking forward to having a CI to replace their fleet with BETs, such as E B Logistik AB or Oskarshamns Logistik AB. Others have also shown high interest in sustainability projects and are interested in the potential benefits of shared ownership of the CI and the replacement of their diesel truck fleet with Battery Electric Trucks (BETs). For example, DB Schenker who have clear environmental goals globally and locally, and also drives with HVO on many of their lines and with electricity on a few of them (e.g., all of their Gotland lines).

4.2. Data collection

Once all the actors are identified, it is crucial to gather all the necessary information that defines the transport operations occurring in Oskarshamn from reliable sources. In order to do so, a Questionnaire has been created, with the main objective of defining the behavior of the truck fleets of each of the actors. By doing so, it guarantees that the necessary CI is properly designed to replace the complete diesel truck fleet with a BET fleet without affecting the transport chain and fulfilling all its requirements. This Questionnaire is directed to truck operators that carry out goods transport operations in Oskarshamn both locally and externally, and it can be found in *Appendix I: Questionnaire*.

First of all, the Questionnaire gathers general information like location and sustainable commitment of the company, also asking about their electrification status. Understanding whether companies have strategies or not on how to address energy transition allows to identify stakeholders who will be more committed to the project.

The second part of the Questionnaire is focused on identifying the volume of operations of the survey respondent. In this section, the size of the truck fleet is obtained, as well as truck models used, their age, their Gross Trailer Weight (GTW), the number of transport operations carried out and their average distance. Each of these parameters allows to obtain a preview of the following:

- *The number of trucks*: a preview of the CI necessary.
- *Age of the truck*: a preview of whether the replacement of trucks will be done in the shorter or longer term.
- *GTW*: an estimation of the consumption per kilometer.
- *Distance of the trip*: an estimation of the size of the battery.

The third part of the Questionnaire is addressed to understand this previously gathered general information in a more precise way. The focus is being put on the itineraries driven by the trucks. The simpler version allows the survey respondent to cross the boxes that represent their answer better. In a more accurate way, distances and schedules are defined. There is a more complex version of this part that asks for specific information on the itineraries (*Logistics questionnaire complex (optional)*). In this more complex version, each itinerary is individually defined by when it is done, by how many trucks, which is their payload and distance covered, and the number of stops. However, although this provides much more reliable data, it is an optional section and has only been filled by some of the companies, while others have opted for the more simplistic way by crossing boxes. Thanks to this section, a really important parameter is defined, the flow. The flow defines the itineraries followed by trucks, and it is the aggregation of all the trucks following the same route.

The fourth and fifth part of the Questionnaire aims to gather information regarding parking availability and potential places for installing the CI. The map of Oskarshamn is depicted in different pictures asking the survey respondent to mark where they park their trucks, where they would prefer to have CI installed, possible parking spots, and which are their routes inside Oskarshamn. Gathering all this information together, hot spots for commonly owned CI can be located where stakeholders might be benefited from shared ownership, reducing their initial investment, making better use of the CI, and enhancing the feasibility of the project. The next figure shows the preferred areas for installing CI:

Figure 34. Areas preferred for installing the CI. Oskarshamn satellite view.

Area A is an industrial area with high truck traffic and where the two biggest stakeholders of this project have their facilities. Moreover, this area directly connects with the highway, which will allow not only the truck operators considered in the study but also external truck operators and private EV owners to benefit from the CI. Along their routes, EV owners could divert from the highway to charge their vehicles without spending much time. Area B is the harbor area which, as mentioned before, is where a lot of traffics take the ferry to Gotland. Those trucks usually wait around the harbor, and in the case of installing CI, they could use the waiting time to charge their BETs. Furthermore, many trucks operate loading and unloading goods since huge companies are located there, such as SAFT or Oskarshamn Energi. Additionally, some stakeholders selected this area as the desired charging area.

Once the Questionnaires have been received back from all the survey respondents, it is time to turn all the information into numerical data to be used in the Optimization Model developed.

4.3. Data adaptation

With the collaboration of the stakeholders described in section *4.1 Main Stakeholders*, it has been possible to collect data from four different truck operators. These four actors make up a total fleet of 94 trucks operating in Oskarshamn. However, at first, to show how the methodology is applied and which are the main applications of the Optimization Model (OM), only a part of the truck fleet will be taken. Nevertheless, the results obtained from the OM that considers the 25 flows, accounting for a total of 94 trucks, will be shown in section *5 Oskarshamn Case Study – Final proposal*, and at the end of this section, in Table 11, the main characteristics of the stakeholders are displayed.

Starting to handle the data for processing the information, *Excel* is used to turn qualitative data from the Questionnaires into quantitative inputs for the OM. First, the flows have been defined into four different categories according to their way of operating:

- *Internal (blue)*: Internal flows are those which operate with a high daily frequency and through short-medium distances. Moreover, these flows park their trucks in the municipality (therefore, they can be charged at night).

- *Internal_2 (red)*: Internal_2 flows are those which operate with a high daily frequency and through short-medium distances, but they do not park their trucks in the municipality (therefore, they cannot be charged at night).
- *External (blue)*: External flows are those which perform one trip per day and start their routes far from Oskarshamn, driving long distances to transport goods to Oskarshamn and staying in the municipality only for a short time. During this time, the BETs will need to completely recharge their battery to go back to their origin.
- *External_2 (red)*: External_2 flows are those which perform one trip per day and start their routes in Oskarshamn, driving long distances to transport goods from Oskarshamn. This kind of flow will require charging the battery also at its destination since the distances are too large to be covered with only one charge.

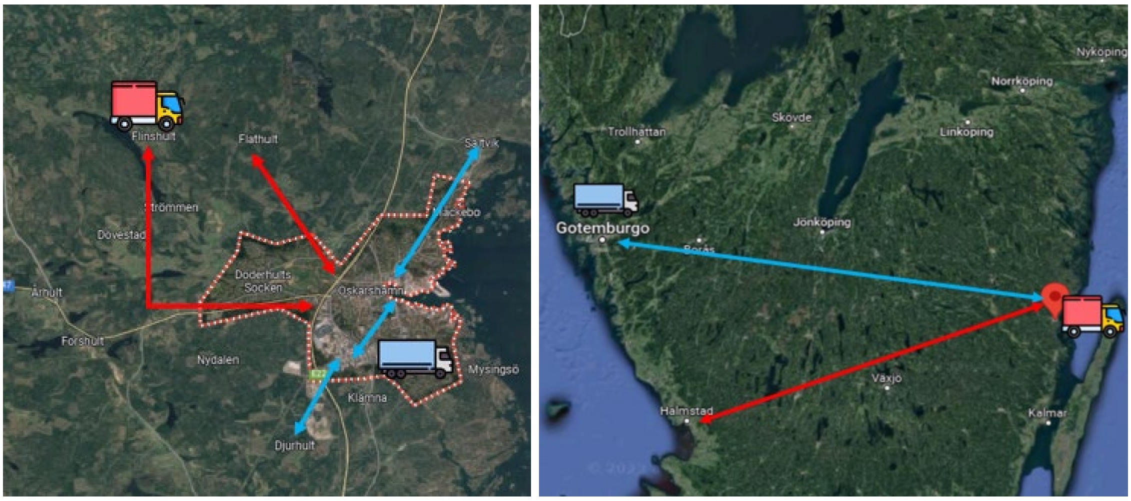

Figure 35. Internal (left) and external (right) flows.

Having received the information about the different flows, it is introduced in a table like Table 6 and then disaggregated in trucks like Table 7. As mentioned, these two tables only show some of the flows used for the study, and they are displayed to make it easier to visualize how data has been organized.

Flow number	Number of trucks	Daily frequency	Outbound Load (t)	Inbound Load (t)	Route one way (km)
Flow 1	3	17	15	3	2.5
Flow 2	3	17	20	3	6
Flow 3	3	10	28	5	6

Table 6. Flows table.

Flow number	Daily frequency	Outbound Load (t)	Inbound Load (t)	Route one way (km)	Total distance per truck (km)
Truck 1 F1	6	15	3	2.5	30
Truck 2 F1	6	15	3	2.5	30
Truck 3 F1	5	15	3	2.5	30

Table 7. Table of Trucks from Flow 1.

Using the values of energy consumed per kilometer (Table 2) and energy consumed per kilometer per kilogram of GTW obtained from the models studied literature review section, it is possible to estimate the energy consumed per flow. The following table shows the values just mentioned for all the truck models and the average:

	GTW (t)	Energy consumed per km (kWh/km)	Energy consumed (kWh/km/kg)
Scania Trailer Tractor	64	2.5	0.039
Scania Trailer Tractor	40	1.78	0.045
Volvo FM/FH Electric	44	1.8	0.041
Mercedes eAcros	27	1.12	0.041
Man eTGM	26	0.97	0.037
E-Force EF26	44	2.25	0.051
Average		1.737	0.042

Table 8. Energy consumption parameters of truck models studied.

With these average values, it is possible to get the approximate size of the battery necessary for powering the trucks if they were carrying their maximum payload, represented by *Energy for route with full payload (kWh)* in Table 9. This parameter does not represent the final battery size, and it is only used to obtain an approximation of the weight of the battery (using a battery energy density of 250 kWh/ton like most NMA and NMC batteries nowadays). In this sense, the battery weight is also considered in the GTW of the truck, that in the case of big batteries, must not be neglected. Finally, the *Energy needed per truck (kWh)* for every day and trip is obtained, which depends on the distance covered but also on their GTW. Table 9 shows this parameter and the final battery size considered in commercial values.

Flow number	Energy for route with full payload (kWh)	Battery weight (t)	GTW Outbound (t)	GTW Inbound (t)	Energy needed per truck (kWh)	Energy needed per trip (kWh)	Final battery size (kWh)
Truck 1 F1	52.10	0.21	26.21	14.21	25.70	4.28	40
Truck 2 F1	52.10	0.21	26.21	14.21	25.70	4.28	40
Truck 3 F1	43.42	0.17	26.17	14.17	21.38	4.28	30

Table 9. Energy consumption parameters of truck models studied.

The final battery size has been designed to be able to store at least 120% of the energy needed per truck. In this sense, the batteries will not only ensure that they can withstand one day without charging, but their capacity also takes into consideration the gradual degradation of the battery capacity. Based on the literature review, battery degradation has been estimated to be 2% per year, meaning that after ten years, the battery still has 80% of its initial capacity. In this sense, providing a battery with at least 120% of the energy needed will likely guarantee that after ten years, the truck will still be able to operate for the whole day without charging, not needing to replace its battery and reducing the TCO. It is also worth noticing that the losses during the charging process as well as in the energy conversion from the battery to the electrical engine have been considered to be neglectable (e.g., the final energy used by the truck is the same as the energy purchased from the grid and stored in the battery). This can be justified due to the high efficiency of the energy conversion processes, as has been seen in sections *3.3.2 Battery*, *3.3.3 Electric engine,* and *3.5 Charging stations for electric vehicles*.

Following, the operating times are defined according to the questionnaires. The operational hours of every flow are divided among its trucks since it is considered that trucks from the same flow will not follow the same schedule; therefore, they can be charged at different times. For example, Flow 1 operates for 16 hours, disaggregated into trucks Table 10 shows starting times and the time per trip of every truck from Flow 1, keeping them operating inside their flow timeframe of 16 hours (e.g., starting at 8:00 AM and finishing at 00:00 AM).

Flow number	Operational hours	Time per trip (min)	Starting time
Truck 1 F1	6	75	8
Truck 2 F1	6	75	13
Truck 3 F1	6	75	18

Table 10. Time schedules of trucks from Flow 1.

The time per trip refers to the maximum time that a truck can expend per trip (operational hours divided by daily frequency), which is longer than what they actually need to be. In this sense, every time per trip also considers the loading and unloading of goods. Furthermore, 15 minutes have been added to each of the trips. The reason why 15 minutes are added is that the CI is intended to be located in a nearby area and not inside the facilities where trucks operate. Hence, the 15 minutes account for the time that a truck will need to slightly deviate from its route to charge the battery. This deviation is also explained because most of the stakeholders are interested in common ownership of the CI, and installing them inside their private facilities will not allow them to share the ownership. For the case of *External_2* flows, instead of adding 15 minutes to their trip, 90 will be added. This is approximately the time that they would need to fully charge their battery at the destination.

At this point, and since it is an important aspect of how the OM is built, it has to be noted that all time data is defined in units that will correspond to time slots of 15 minutes or 0.25 hours (96 values per day). This will result in the creation of electric load profiles defined for timesteps of 15 minutes, where the power required is constant during the timestep.

Finally, the last step to turn all the necessary information from the Questionnaire into inputs for the model is to define the location where each truck will charge. This corresponds to the fourth and fifth part of the Questionnaire, which collects information regarding potential places for installing the CSs. The determination of charging areas is explained and shown in section *5 Oskarshamn Case Study – Final proposal*, as well as the final placement for installing the CI.

To consolidate all the gathered and processed information for utilization in the model, the following table presents the key characteristics of the four stakeholders engaged in the project:

	Truck Fleet Size	Energy Consumed per year (kWh)	Distance Recharged per year (km)
SH1	37	860,880	1,199,640
SH2	2	90,480	74,880
SH3	35	2,660,550	1,878,500
SH4	20	283,314	312,000

Table 11. Stakeholders' main characteristics.

4.4. Optimization Model

The Optimization Model (OM) developed has the main purpose of obtaining the power output and charging spots necessary to install in the Charging Infrastructure (CI) of Oskarshamn to be able to perform the transport operations by fully electric Battery Electric Trucks (BETs). It follows a node-based approach, which means that the charging demand occurs at the origin or at the destination of the trip (nodes). The two principal functions of the OM are:

- Minimize the peak power required for charging the BET fleet.
- Minimize the number of times that each truck needs to be connected.

The rationale behind performing these functions stems from the numerous positive outcomes they yield. Firstly, the system mitigates its impact on the local grid, thereby averting price hikes and energy supply shortages, while simultaneously enhancing the longevity of BET components, notably the battery. Secondly, it curtails the necessity for extensive logistics and planning by minimizing the frequency of truck charging and offering an optimized charging schedule.

The model is built using *PuLP*, a free, open-source software LP (Linear Programming) modeler written in *Python*. *PuLP* provides a high-level interface to model and solve linear programming problems. LP is a mathematical optimization technique used to find the best possible outcome in a mathematical model that is subject to linear constraints. Another important library used for programming the model is *Pandapower*. *Pandapower* is a stand-alone power systems analysis toolbox with an extensive power system model library, power flow solver, and many other power systems analysis functions. Basically, *Pandapower* provides a comprehensive set of tools for analyzing, simulating, and optimizing electrical power systems.

Once all the data has been introduced in *Excel*, it can be imported into the OM. The code will analyze all the flows obtained in the data collection, but in the same way as it has been done previously, and for the sake of procuring a clear explanation, the methodology will only be explained for a share of the flows studied.

First, the model reads the Excel file and creates the DataFrame where all previous information will be stored and can be easily accessed and represented. Figure 36 shows some of the trucks contained in the Dataframe. This Dataframe will be from where the inputs of the model will be extracted.

```
dfT = pd.read_excel(r"C:\Users/Truck_Data.xlsx", sheet_name="Trucks")
```

Flow number	Daily frequency	Outbound Load (t)	Inbound Load (t)	Route one way (km)	Total distance per truck (km)	Aprox energy per day (kWh)	Battery weight (t)	GTW Outbound (t)	GTW Inbound (t)	Energy needed per truck (kWh)	Energy needed per trip (kWh)	Final battery size (kWh)	Operational hours
Truck 1 F1	6	15	3	2.5	30	52.100000	0.208400	26.208400	14.208400	25.704795	4.284132	40	6
Truck 2 F1	6	15	3	2.5	30	52.100000	0.208400	26.208400	14.208400	25.704795	4.284132	40	6
Truck 3 F1	5	15	3	2.5	25	43.416667	0.173667	26.173667	14.173667	21.383845	4.276769	30	6
Truck 1 F2	6	20	3	6.0	72	125.040000	0.500160	31.500160	14.500160	70.214096	11.702349	90	6

Figure 36. Dataframe storing trucks and itineraries data.

The next step is to create a matrix that indicates the presence in the facility of each of the trucks for each timestep. Presence in the facility can be understood as availability to charge, so if the truck is present at the facility, that means that it will also be possible to charge it at the CS. This matrix will be stored in a Dataframe full of 0 and 1, and it will simply have a value of 1 when the truck is at the facility and 0 when it is transporting goods (consuming energy). For the case of *Internal_2* flows, the matrix can also have a value of 2. As described previously, *Internal_2* flows are those which frequently operate in Oskarshamn but park their trucks outside Oskarshamn. So, when they have a value of 2 means that the truck is not operating but cannot be charged because it is not close to an area where it can be charged.

As mentioned before, the time will be represented by time slots of 15 minutes. Therefore, since the operations have been defined for a 5-day week, this Dataframe will have 480 values for each truck (e.g., 4 time slots per hour multiplied by 24 hours a day for a 5-day week). So the dimensions of this Dataframe will be 480 rows, and as many columns as trucks will be assigned to charge in the CS corresponding to the Dataframe. Next, a fragment of the matrix of presence in the facility is shown:

Flow number	Truck 1 F1	Truck 2 F1	Truck 3 F1	Truck 1 F2	Truck 2 F2	Truck 3 F2	Truck 1 F3	Truck 2 F3	Truck 3 F3	Truck 1 F4	Truck 2 F4	Truck 3 F4
0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	1.0	1.0
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	1.0	1.0
2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	1.0	1.0
3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	1.0	1.0
4	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	1.0	1.0
6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	1.0	1.0

Figure 37. Fragment of the matrix of presence in the facility.

It is also possible to analyze more than five days. Nonetheless, the reason why only five days have been considered is that, even though some flows will operate during the weekend, the more restrictive requirements are found during weekdays, where traffic is more abundant and charging schedules are more limited. Following, Figure 38 represents the presence in the facility of Truck 1 from Flow 1 during the whole week. X-axis indicates the timesteps, and Y-axis is the value to indicate the availability to charge. Next to it, the values of the matrix of presence in the facility from timestep 31 to 41 are shown to clearly visualize the relation between the DataFrame and the graph, representing the operation of the truck. As said, when Y-values are 1, the truck can be charged, and when they are 0, it cannot.

31	1.0
32	0.0
33	0.0
34	0.0
35	0.0
36	1.0
37	0.0
38	0.0
39	0.0
40	0.0
41	1.0

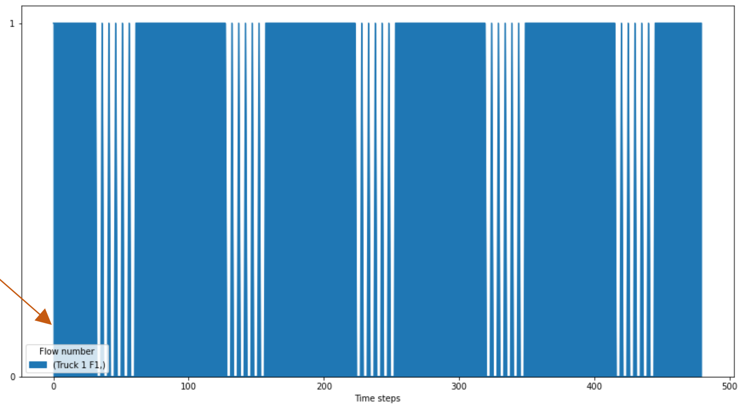

Figure 38. Presence in facility or availability to charge for Truck 1 Flow 1.

Now, if all trucks considered in this example are added up together, the profile along the week of the number of trucks in the facility at each moment can be obtained, as shown in Figure 39. This will be used by the OM in order to decide when the most optimal time is for a truck to charge in order to minimize the maximum power requirement while guaranteeing that the transport needs are still fulfilled.

Figure 39. Presence in facility or availability to charge for all trucks assigned to a CS.

Once the matrix of presence in the facility has been calculated, all the inputs provided by the Questionnaire are adapted for defining the linear programming problem and its decision variables. Now, it will also be necessary to introduce additional inputs that will act as a constraint and, varying their values, could test the performance and requirements of the model/system. The input parameters will define the constraints imposed on the model and are differently defined for each truck depending on their transport itinerary.

The following table summarizes all the inputs, which is their source, and which constraints bring into the OM:

Input	Source	Constraints
Battery Size	Questionnaire	Limits the maximum energy that a truck can store.
Energy per trip	Questionnaire	Establishes the minimum energy necessary for a truck before leaving the facility. In this way, it guarantees that no truck runs out of battery.
Presence in the facility	Questionnaire	Establishes when it is possible to charge a truck, when it will be consuming, and when it will be parked without charging.
Initial state of the battery	Decision	Decides which is the state of the battery at the beginning of the day. In this case, it only affects the first day since it is a continuous time model.
Minimum SOC	Decision	Establishes the minimum energy level in the battery. It will prevent the battery from discharging too much or going into deep discharging.
Battery oversize factor	Decision	Allows to change the energy capacity of the battery. In this sense, if bigger batteries are introduced, they might be charged less

		frequently, and the opposite for smaller batteries.
Maximum charging power	Decision	Allows to limitate the power output of certain CSs. In this way, trucks that can charge in different CSs might be redirected to others.

Table 12. Input parameters to the Optimization Model.

Once all the input parameters have been introduced, the OM can run the simulation to optimize the charging schedule and minimize the peak power of the system.

Finally, it is important to take into consideration another important aspect of the OM related to the *Maximum charging power* input parameter. Since the OM aims to minimize the peak power requirement, once the minimum peak power is defined, that implies that the CS will need to at least provide that power output. Hence, the CS will have a power output equal to or greater than the peak power, and, therefore, all the trucks could be charged at that power rate. In this sense, the OM will always prefer to charge a truck at the highest power level possible (which is the CS maximum power output) to minimize the charging time as well as the number of trucks connected at the same time. Doing this not only reduces the charging time but also requires fewer charging spots and reduces the traffic congestion in charging areas. However, this might bring a problem when the power output required to charge a specific truck is much higher than others since that will not allow the OM to further minimize its power value. This means that, given that the CS will need to at least provide a high power output, the model will prefer to charge trucks with lower power requirements at that high power to reduce charging time. That is why the *Maximum charging power* input parameter is necessary. The *Maximum charging power* will be applied to trucks with lower power requirements which can be charged slower to limit their charging power and reduce the impact on the grid. To determine the value of the *Maximum charging power,* it will be necessary to run the optimization without considering the trucks with higher power requirements, which will be identified by analyzing and understanding the itineraries, addressing presence in the facility and energy required per trip. By doing so, it is possible to limit the charging power of trucks with lower power requirements, making the power demanded by these trucks more constant while the model keeps optimizing the system for trucks with higher power requirements. This can be seen clearly in the next figure:

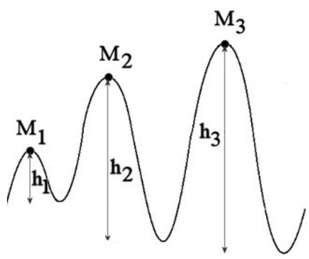

Figure 40. Peak power analysis.

If the system cannot reduce the power required in M_3 due to time schedule limitations, the OM will set the charging power at h_3 and will prefer to charge all trucks at h_3 to reduce charging time, although trucks 1 and 2 can charge at a lower power. In order to avoid this phenomenon, the OM would, instead, run the simulation without considering truck 3. Thanks to this, a new lower peak power will be defined (in Figure 40, it would correspond to M_2) after optimizing the system, and this will be the power to limit charging for trucks with lower power requirements. This can be done as many times as different *Maximum charging powers* want to be defined, though virtually, it makes sense to define one per CS that wants to be installed. Otherwise, if the power output of the CS is kept at M3, the charging profile result of the OM will be an intermittent high-power requirement, which will have detrimental effects on the local grid and will damage batteries that are not designed for such high-power requirements. By limiting the *Maximum charging power* for trucks with lower power requirements, the OM is forced to charge these smaller trucks at a lower power level, leveling the charging along the day rather than supplying high powers intermittently.

4.5. Applications of the Optimization Model

Now, before analyzing the whole system and going into the final results, the last subsection is dedicated to making visible the versatility that the model offers for treating a wide range of data, adapting new restrictions or constraints, and dealing with the uncertainty of data. In order to enhance the utility of the OM, several scenarios have been developed to show the user the multiple possibilities that the OM offers to adapt to the user's concerns, in this case, the stakeholders of the project.

Four different scenarios have been developed and can are thoroughly detailed in *Appendix V: Optimization model applications*. The scenarios are briefly detailed next:

- Example case: this scenario aims to reflect the behavior of a reduced truck fleet, allowing to select just a sample of trucks.
- Variation of truck itineraries: this scenario aims to reflect the repercussions in the electrical load (charging profile) due to variations in the operating times of trucks.
- Variation of battery sizes: this scenario aims to reflect the effect a variation in the battery sizes will have on the charging schedules. It allows stakeholders to analyze the relationship between the increase in initial investment and the comfortability of having bigger battery sizes.
- BAU vs. Optimization Model: this scenario aims to reflect the impact of a human charging strategy versus an optimized one.

Having shown all the alternatives that the model affords for analyzing the system from different perspectives, the OM will finally be applied to the case study of the whole truck fleet from Oskarshamn. In the next section, the information received from Oskarshamn's truck operators participating in the project will be processed to optimize the charging schedule of the complete truck fleet of 96 trucks and provide the CI necessary to cope with the electricity demand.

5. Oskarshamn Case Study – Final proposal

This section will be completely focused on the results obtained after the optimization of the whole truck fleet as a whole and disaggregated into charging areas and Charging Stations (CSs). Following the same methodology explained in these last sections, the Optimization Model (OM) will take the information processed from the 25 flows, made up of 94 trucks, to minimize the peak power required by the whole system providing the most efficient charging schedule.

5.1. Charging profile at a municipality level

First of all, the charging optimization is done for the system as a whole. By doing this, it is possible to understand which will be the impact that the whole truck fleet will have on a municipality level. This is important to allow the electrical grid operators to be able to book the energy capacity necessary at a global level to power the trucks, preventing shortages in the electricity supply or huge increases in electricity prices.

After optimizing the system with the most optimal charging schedule, the peak power is kept at 579.19 kW. The next figure shows the resulting power requirement of the whole truck fleet at a municipality level during the time studied (5 days). It has to be noticed that the deviation from the flat shape that occurs for the highest values of the x-axis is due to the fact that the analysis does not consider future operations, and the truck will not need to continue being charged. However, this can be omitted since, in a real scenario, the trucks will continue being charged, and the shape will continue to be flat.

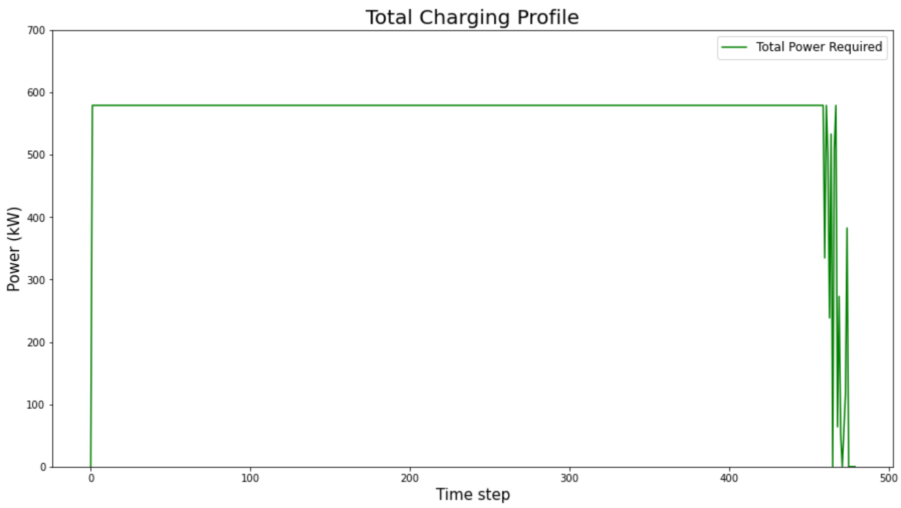

Figure 41. Power requirement on a municipality level without Maximum Charging Power limitation.

As explained before, the OM establishes the most beneficial charging schedule to minimize the peak power while keeping the lowest number of trucks connected at the same time. In this way, the system will avoid producing instabilities to the grid, preventing an increase in electricity prices and reducing traffic congestion in charging areas. However, the minimization of trucks connected simultaneously produces a non-desired output. The OM will charge the trucks as fast as possible without exceeding the maximum power, forcing some trucks to charge faster than necessary. For example, with the peak power minimized to 579.19 kW, it means that the Charging Infrastructure (CI) should be able to provide at least 579.19 kW and, to minimize the number of trucks connected at the same time, the OM will decide to charge some of them at that maximum power. This can be clearly seen in Figure 42, which shows the number of trucks connected every timestep. With the power kept constant at 579.19 kW, the number of trucks connected at the same time is very low, with only one truck connected 15.21% of the time, two trucks 29.17%, and three trucks 23.12%.

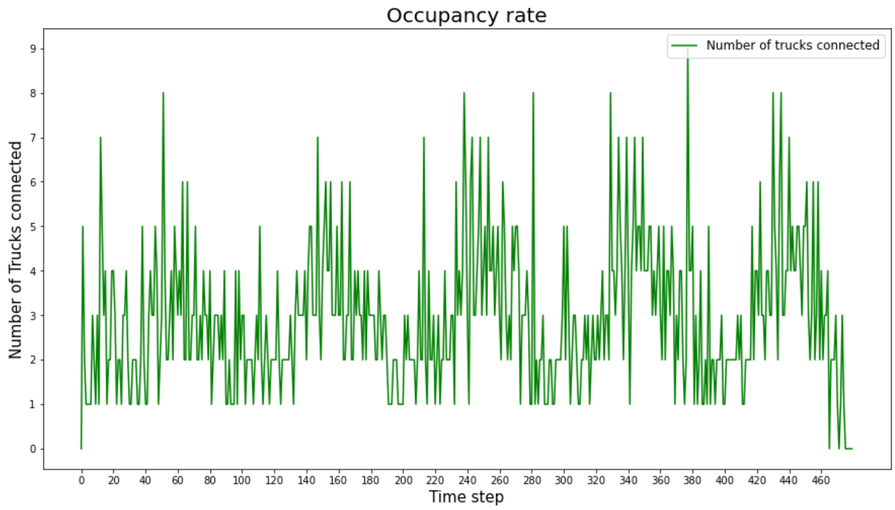

Figure 42. Occupancy rate without limitation on Maximum Charging Power.

This means that a single CS should be able to provide 579.19 kW. This charging power is really high, and it should be limited for two main reasons. First, Fast DC CSs currently provide powers of around 375 kW, they are the most expensive kind of CSs, and their maintenance is the most complex one. So even if it was technically feasible to install a CS of more than 579.19 kW, the Total Cost of Ownership (TCO) would be very high. Secondly, such a fast charging rate could damage and decrease the lifetime of some of the elements of BETs that have smaller energy requirements.

Hence, to limit the charging power, it is necessary to define the *Maximum charging power*. The *Maximum charging power* has been determined by specific analysis and iteration of the different flow requirements. *Pulp* allows optimizing the model setting specific limitations, and, through an iterative process, identifying if the limits established are possible to fulfill. In this way, limits to the *Maximum charging power* have been defined, always ensuring that the transport needs were fulfilled. After iterating with multiple values, two different *Maximum charging powers* have been designated, 50 kW and 150 kW. The lower limit will be used for trucks with lower energy requirements, identified by analyzing their *Energy needed per truck (kWh)* and *Energy needed per trip (kWh)* (Table 9), and the time that they spend in the facility.

Once these limits are established, after optimizing the system, the peak power registered at a municipality level is 581.5 kW, and it is kept constant throughout the five days, as seen in Figure 43, very similar to Figure 41.

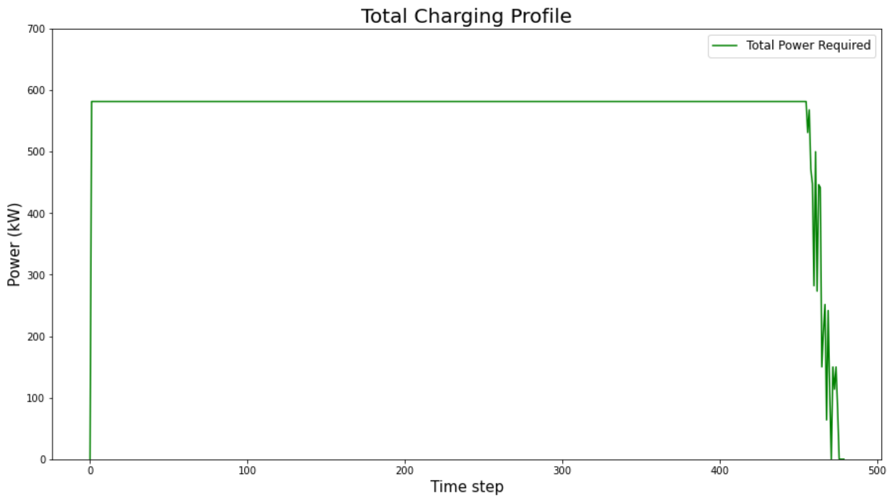

Figure 43. Power requirement on a municipality level with Maximum Charging Power limitation.

However, when looking at the occupancy rate in Figure 44, the number of trucks connected simultaneously has notably increased. Now, only 0.83% of the time there is one truck connected, and two and three are 0.62% and 0.42%, respectively. On the contrary, more than 80% of the time there are between 5 and 8 trucks connected.

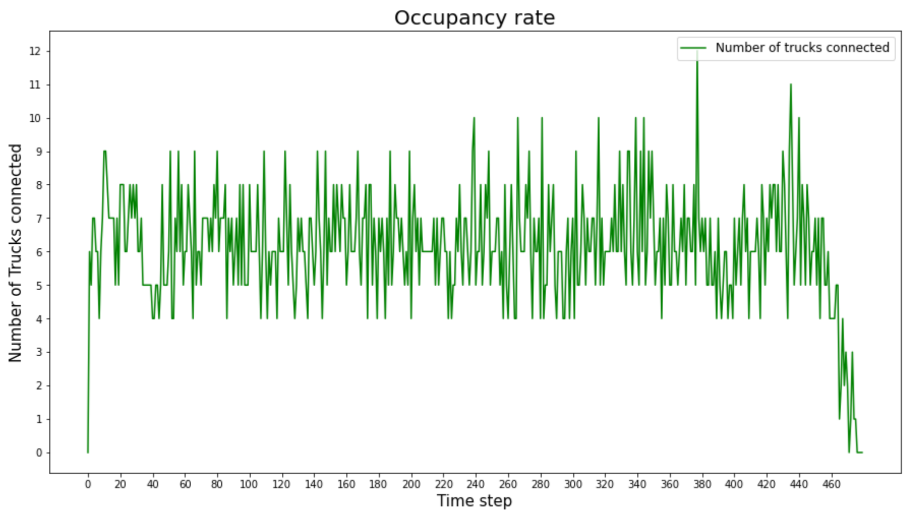

Figure 44. Occupancy rate with limitation on Maximum Charging Power.

Thanks to the limitation in *Maximum charging power,* it becomes possible to design a CI that diversifies the power needs among different CSs. This will allow to have CSs with lower power outputs, which will decrease their price and maintenance, and will ensure a longer life expectancy of the BET's components. Nevertheless, this is still a centralized power profile, which replicates the behavior of the charging profile of the trucks at a municipality level. Now, it is necessary to split the charging depending on where each truck will charge in order to obtain the power requirement at a district level. For identifying where each truck should charge, each actor has indicated in the Questionnaire their preferable location for installing CI. In the next section, the disaggregation of the power requirement will be done to obtain the charging profile of the truck fleet at a district level, which is divided into two districts.

5.2. Charging profile at a district level

In this section, the charging profile at a district level will be analyzed to determine where each truck should be charged. The OM will be in charge of allocating the trucks that can charge in more than one area to balance the energy utilization of the charging infrastructure. Previously, section *4.3 Data adaptation* has explained how the charging areas were defined, and they were shown in Figure 34. Each of those two previous areas corresponds to a district, and they are named District A and District B. Now, Figure 34 the charging area preferences of each stakeholder are depicted in Figure 45, illustrating their respective choices.

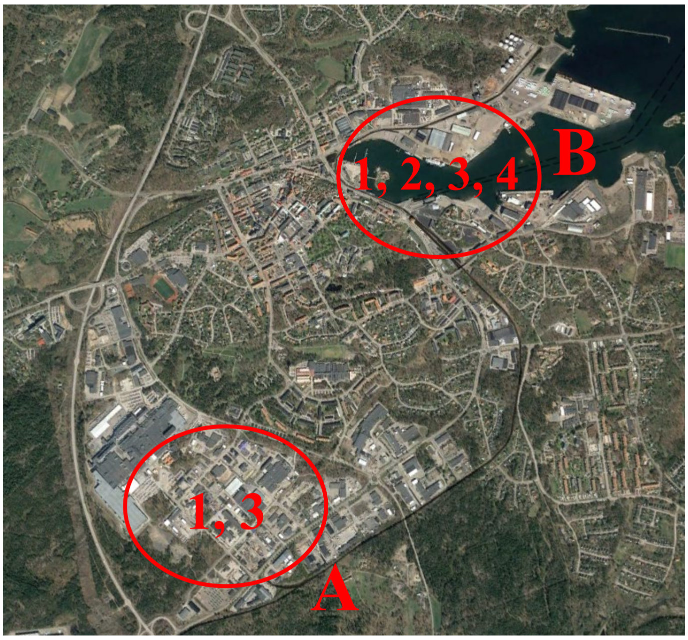

Figure 45. Preferred charging district for each stakeholder.

As can be seen, Stakeholders 2 and 4 have only indicated in the Questionnaires their preferred charging area as District B. On the other hand, Stakeholders 1 and 3 have some trucks that can charge in both Districts. In total, there are 54 trucks that only have the possibility to charge in one location. The other 40 trucks (from stakeholders 1 and 3) have the possibility to charge in both A and B. Usually, the trucks that have the possibility to charge in both districts are external flows or those which have a low frequency. These trucks have the possibility to charge in both districts since the time that they need to divert from District A to B barely affects the duration of their route. Thus, it is interesting to define which is the most appropriate location to charge at every time in order to avoid traffic congestion, provide enough space for parking while charging, and determine the most optimal power output and utilization for the CSs.

In order to allocate each truck to a CS and keep the same impact on the local grid, the charging profile of each truck obtained from the optimization at a municipality level will be used. In this way, the energy required at every time is already determined, and the OM will now need to allocate each of the trucks to a charging area to, as said, allow fluid traffic and provide optimal utilization of the CI. According to the power profile obtained in the OM to minimize the impact on the local grid, it is found that trucks that can only charge in A continue registering a peak power of 581.5 kW, while for those that can only charge in District B, it is 358.00 kW. This means that the necessary power output of these districts should be equal to or greater than these values. Now, the OM will be in charge of allocating each of the trucks to a charging area.

First, the power outputs for each district must be determined. It is important to notice that this power output does not represent the rated power that the CSs will have. Since the *Maximum charging power* has been limited to 150 kW, the total power of the district could be provided by various CSs of 150 kW. The final sizing and placement of CSs can be seen in section *5.3 Sizing of the Charging Stations*. The power output that the CI for District A will be able to provide has been set to 600 kW. This is due to the fact that it should provide at least the 581.5 kW registered in the area. For District B, the power output has been set to 450 kW. This power output is much larger than the peak power registered in the area for two main reasons. The first reason is that providing a higher power output will help to decongest District A by allowing more trucks to charge at District B. The second reason is owed to the fact that District B is located in Oskarshamn's Harbor area. This area is frequented by trucks, and where a lot of them wait before going on the ferry to Gotland. Therefore, it is an area of great potential for installing CI not only for the truck fleet studied in this project but also for other truck operators.

Secondly, once the maximum power outputs for each district have been defined, the OM will, for every timestep, allocate in one of the districts the trucks that have the possibility to charge in both of them. To do so, the OM will balance the energy consumed at each district to keep a reasonable degree of utilization in both of them. Once the system has been optimized, the energy provided during the 5-day period in both districts is exactly the same, 33,758.2 kWh in each of them. This results in a total energy consumption of approximately 3,510.85 MWh annually. It has to be noticed that the real 5- days period energy consumption will be slightly higher than the value obtained. This is due to the fact that the OM considers the end on the fifth day without considering future times. However, in reality, this system will be cyclical, meaning that on the fifth day, it will need to recharge the trucks for the next week rather than letting them completely discharged. This increase in energy consumption has no impact on the design of the CI since it is the number of trucks connected simultaneously, or the peak power will be kept at the same level. Nevertheless, for the economic analysis, the energy consumption which also considers the charging on the fifth day will be used.

Next, each of the districts will be analyzed to define the characteristics that describe the behavior of the truck fleet and the charging profile of each of them.

District A

During the period studied, District A CI will be in charge of providing 33,758.2 kWh and will have a combined power output of 600 kW. Next, Figure 46 and Figure 47 show the resulting power supply from the CI.

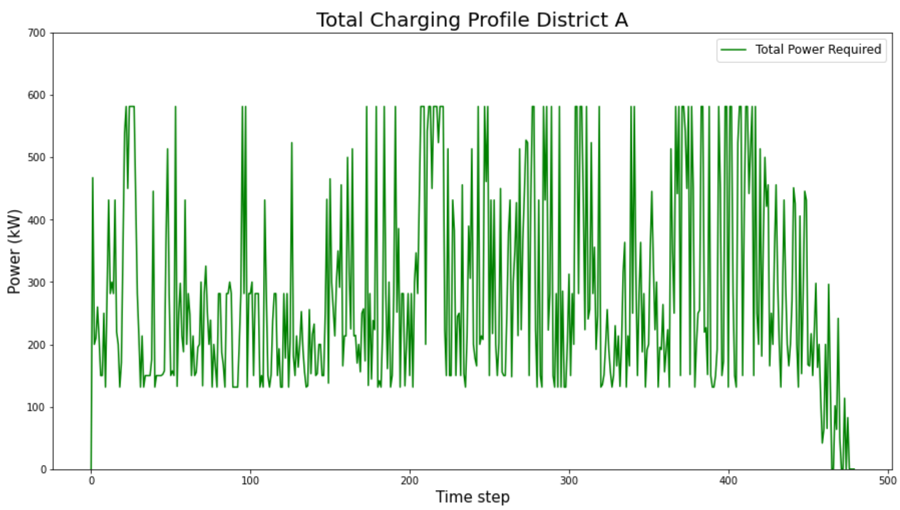

Figure 46. Weekly load profile in District A CI.

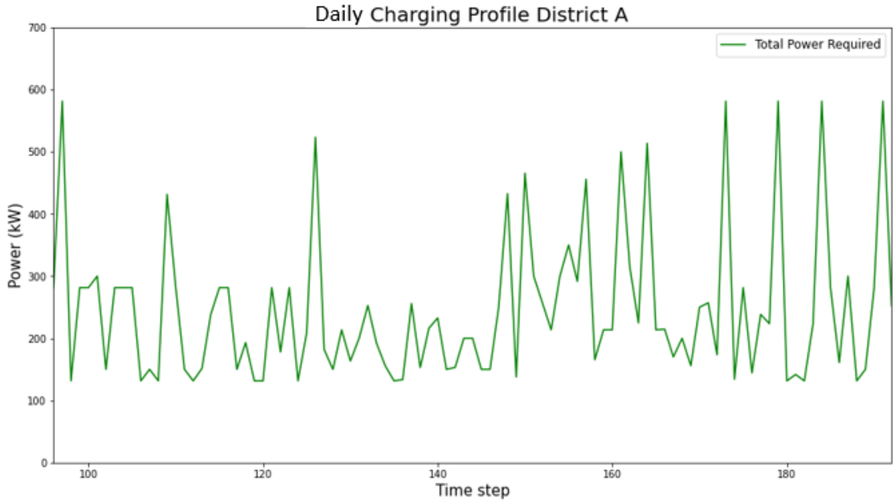

Figure 47. Daily load profile in District A CI.

In comparison with previous results where the load was kept at a constant level, now the variation in power requirement often has rough increases of up to 450 kW. However, thanks to the optimization of the system at a municipality level, if the power requirements from District A and District B are added together, the resulting power profile will again be completely flat. As mentioned before, this is a potential benefit for Oskarshamn grid operators since having an overall constant load makes it easier to predict which will be the power requirements for Oskarshamn, allowing them to easily determine the connection fee with Svenska kraftnät.

Going deeper into the analysis, in order to provide the appropriate number of charging spots and the most optimal power output that each CS should have, it is necessary to address how the connections are made at the most critical hours. First, Figure 48 displays the number of trucks connected every time step. It can be seen that since the charging has been divided into two areas, now the occupancy rate is lower. While if the charging was centralized, more than 80% of the time there would be between 5 and 8 trucks connected, now more than 85% of the time there are between 1 and 6. However, although it only happens once, the maximum number of trucks connected remains at 12.

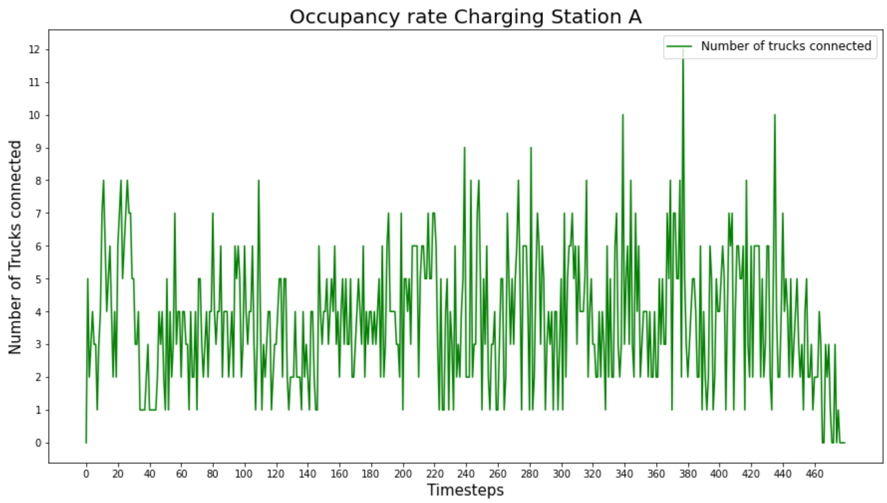

Figure 48. Occupancy rate Charging Infrastructure District A.

The number of trucks connected will be used to define the number of charging ports necessary to install, and although the number of times that nine or more trucks are connected only represents 1% of the time, it is necessary to provide the CI to allow them to charge. Furthermore, a higher number of charging spots will enable more flexibility in the charging schedules.

District B

During the period studied, District B CI will be in charge of providing the same amount of energy as District B CI, 33.758,2 kWh, and will have a combined power output of 450 kW. Next, Figure 49 and Figure 50 show the resulting power supply from the CI.

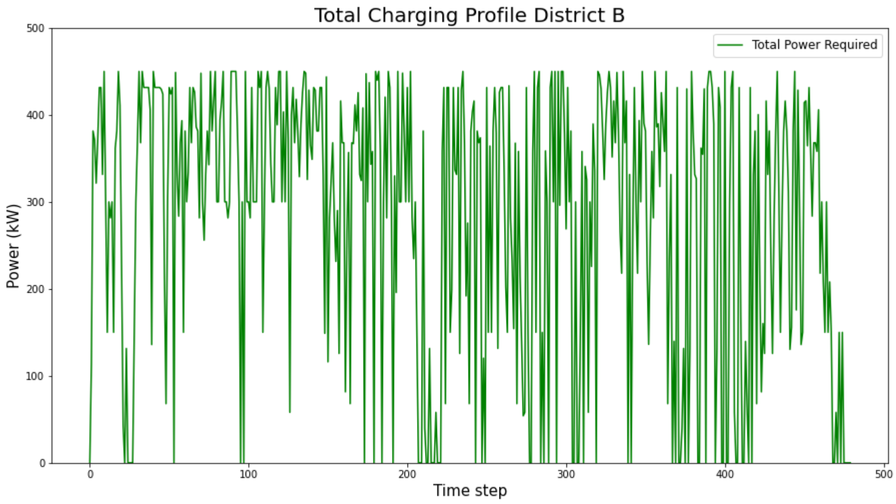

Figure 49. Weekly load profile in District B CI.

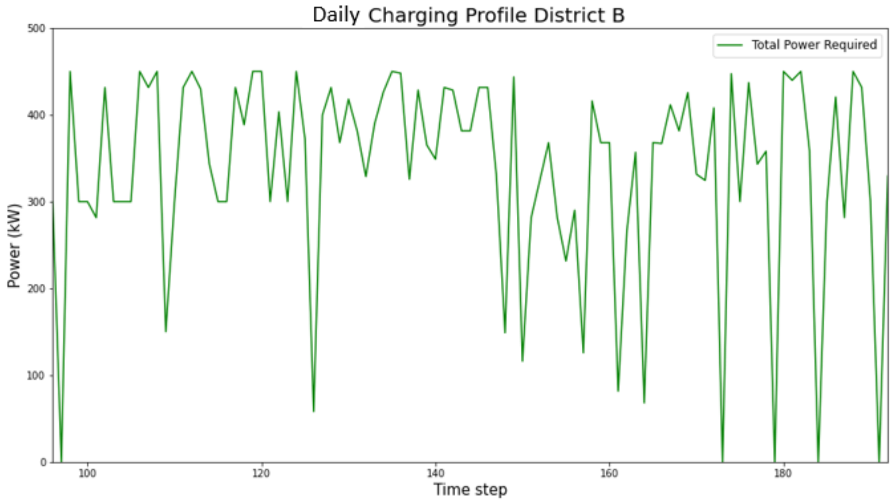

Figure 50. Daily load profile in District B CI.

Just in the same way as the District A charging profile, and given that they compensate each other, the variation in power output is often 450 kW, going from 0 to the maximum power required. Nevertheless, looking at the occupancy rate in Figure 51, it is clearly seen that the maximum number of trucks connected simultaneously is 6. Moreover, more than 80% of the time there are three or fewer trucks connected.

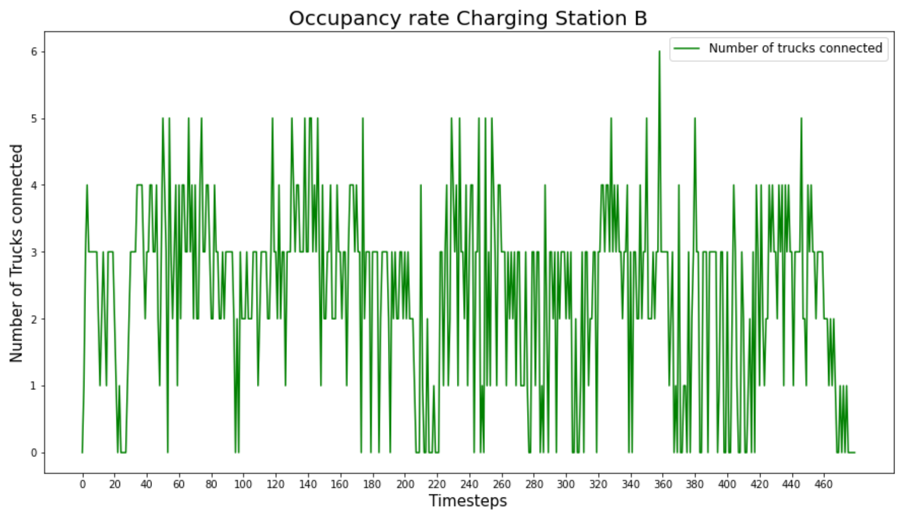

Figure 51. Occupancy rate Charging Infrastructure District B.

Individual Charging Profiles

Finally, some of the charging profiles of specific trucks daily and weekly are shown. First, Figure 52 shows on the two upper graphs the weekly charging profile, and in the two lower ones, the daily profile of Truck 1 Flow 3. In the same way, Figure 53 shows the same graphs for Truck 1 Flow 19. Analyzing Figure 52, up left thicker lines represent longer charging periods, while thinner represent shorter times. As can be noticed in both figures, charging occurs several times a day. This can become a problem since it might be time-consuming and overwhelming to constantly go to the charging areas for short times rather than going fewer times for longer periods. However, the charging schedules are based on the availability described by truck operators. If other restrictions want to be added, it could be possible to limit the times that trucks can charge according to the truck operator's preferences.

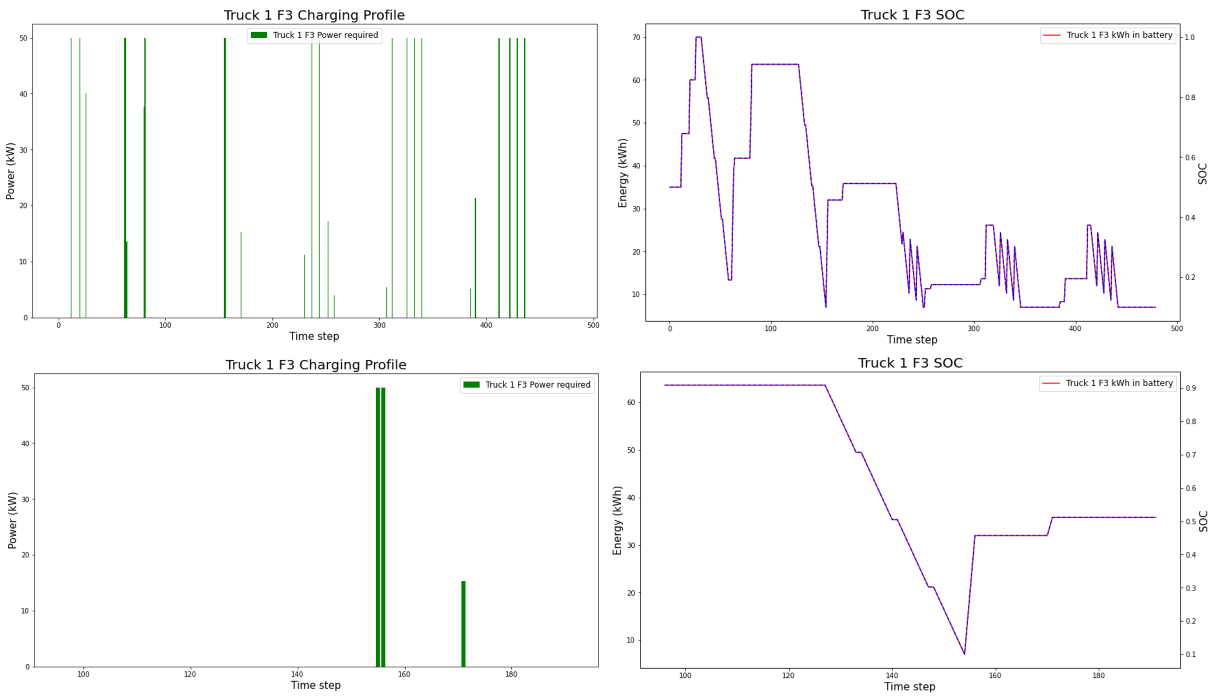

Figure 52. Daily and weekly charging profiles Truck 1 flow 3.

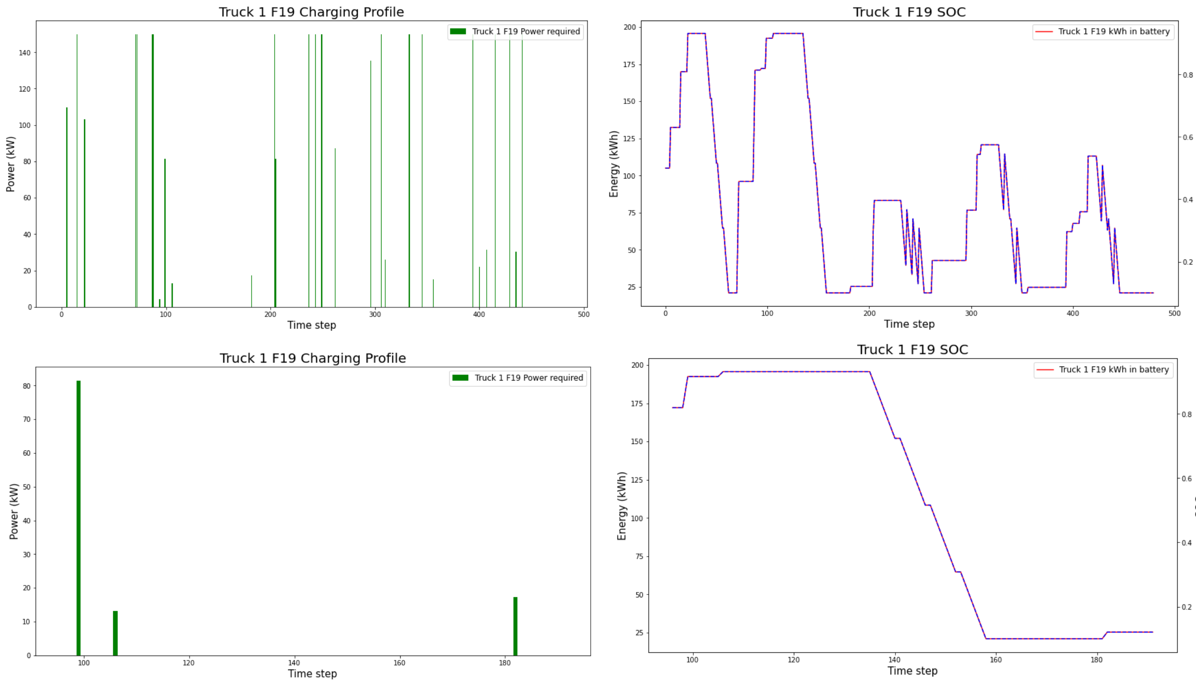

Figure 53. Daily and weekly charging profiles Truck 1 flow 19.

Finally, in the next subsection, the decision on the final configuration of the CI will be explained, including the number of connectors, CSs, and their power output.

5.3. Sizing of the Charging Stations

To conclude the final sizing of the CI, it is necessary to analyze deeper the most controversial connections to ensure that the proposed CI can fulfill all the energy requirements. The outputs and data extracted from the OM to perform the analysis, which justifies the decision, can be found in

Appendix II: Optimization model analysis results. Hence, this section will explain the final proposition of the power output and configuration of the CSs selected individually and at a district level.

District A

Addressing District A's dimensioning, the maximum number of simultaneous connections is twelve. However, the number of timesteps with nine or more trucks connected is only five, approximately 1% of the time. This means that even though twelve connectors might be needed, the charging can be slightly modified to avoid installing such a high number of connectors that will be underused. Since the connections are made for timesteps of 15 minutes, it would be possible to increase the charging power during these five timesteps, reducing the charging time and allowing more than one truck to be connected in the same connector during one timestep, which will reduce the number of connectors installed.

Secondly, it is important to look at the maximum number of trucks charging at the *Maximum charging rate* simultaneously and which is the occupation of the CSs while the maximum power is required (i.e., the maximum number of trucks charging at 150 kW simultaneously and how many trucks are connected in total when that happens). As explained, the *Maximum charging rate* was defined at 150 kW. Thus, it could be possible to install four CSs of 150 kW to cover the peak demand (581.5 kW), although installing CSs with only one connector would still be a problem. In order to solve this problem, thanks to the knowledge gained in the literature review, it is possible to address the problem with other alternatives. CSs can have more than one connector, dividing its power output into the number of trucks that are connected. This is the reason why it is important to understand the occupation of the CSs while the maximum power is required, given that in those cases, the CS could only charge one truck at a time, even if it has more than one connector.

With these two aspects in mind and having analyzed the most controversial timesteps of the charging profile shown in Appendix IIAppendix II: Optimization model analysis results, it is time to define the configuration of the CI for District A. First, it will be necessary to cover the peak power requirement (581.5 kW) to guarantee that the energy requirements can be fulfilled at all times. To do so, it has been decided to install four level-3 DC CSs of 150 kW. The datasheet and prices provided by Beny New Energy can be seen in *Appendix III: Charging Station Datasheet*. This charging pole has two DC plugs, which allows for splitting the power among the trucks connected, having a total of 8 connectors. However, when looking at the occupation while the maximum number of trucks are charging at the *Maximum charging rate* simultaneously (Appendix I), it can be found that the CSs will not be able to charge all the trucks. Since there are three trucks connected at 150 kW, three of the four CSs could only allocate one truck at a time, and only the fourth CS would be able to split its power into two. This allows connecting only five trucks simultaneously, which is not enough to charge all the trucks during those moments of *Maximum charging rate* when there are seven trucks connected. Therefore, it will be necessary to install a fifth charging post. The fifth charging post will have a power output of 60 kW, also from the models provided by Beny New Energy. With its additional power and its two plugs, it is possible to fulfill all the energy requirements at all times, even the most controversial cases which have been specifically analyzed. It is worth noting that there is one timestep where there are 12 trucks connected, and the installed number of connectors is 10. During this timestep, if trucks are charged at a faster rate, it is possible to fulfill the energy requirements with the proposed CI.

Therefore, district A will have five DC CSs installed, providing a total of 10 connectors. Four CSs with a rated power of 150 kW and two connectors each, and the fifth one with a rated power of 60 kW and two connectors. This will result in a total power installed of 670 kW. This CI will be able to supply enough power to cover the maximum power requirement expected (581.5 kW) and to provide enough connectors to fulfill the logistics of the optimized charging schedule.

District B

Addressing District B's dimensioning, as seen in Appendix II, the maximum number of simultaneous connections is six, though it only happens once. Furthermore, the maximum number of trucks charging at the *Maximum charging rate* at the same time is three, and when that happens, there are no more trucks charging. Finally, addressing the charging requirements with the moments of highest occupation has been possible to come up with the final configuration.

District B CI will have a different approach than District A CI. Given that District B CI is located in the harbor area, it is expected that the CI will most likely have higher occupancy if it is publicly available. The harbor area is usually frequented by trucks, not only the ones mapped in this study but many more that are operated by other truck operators in Oskarshamn and external ones that come to the harbor. Moreover, there is a high number of trucks that are often parked in the harbor area waiting for the ferry to Gotland, which, instead of waiting around the harbor, could be charging their BETs. Besides, as explained in the literature review, road goods transportation is increasing and expected to increase in the future, which would escalate the occupancy of the CSs. Therefore, District B CI will be designed to be future-proof, supporting today's and next-generation BETs, and with a modular system easy to scale up.

The proposed CI infrastructure will consist of three ABB HPC Power Cabinets, each with a power capacity of 175 kW, along with six ABB Terra HPC fast charging stations, two charging stations per cabinet. This system is widely regarded as the top choice in the market for high-power solutions due to its modular design, allowing for effortless scalability. It can provide an output from 175kW to 350kW due to a wide output voltage range of 150 – 920 VDC and a liquid-cooled charging cable capable of supplying up to 500 A. The characteristics of this CS can be found in *Appendix III: Charging Station Datasheet*.

Therefore, district B CI, with three ABB HPC Power Cabinet of 175 kW and six ABB Terra HPC fast CSs, will have a total power output of 525 kW and six connectors. This CI will be able to supply enough power to cover the maximum power requirement expected (450 kW) and to provide enough connectors to fulfill the logistics of the optimized charging schedule. Moreover, as can be seen in the connections possibilities in Appendix III, using ABB Dynamic DC the ABB HPC Power Cabinets can be connected together to deliver an output of 350 kW to one ABB Terra HPC fast CS or 175 kW to two of them. Besides, each ABB Terra HPC fast CS has two type of plugs, CCS (500 A liquid-cooled cables) and CHAdeMO (200 A). Thanks to the configuration of the ABB HPC Power Cabinets, trucks could also be charged at 350 kW. Additionally, this modular system would be easy to scale by installing more Power Cabinets if more power is needed or more fast CSs if more connectors are needed, being able to cope with the increasing demand for energy in the road transport sector.

The last aspect to address for any CI publicly available is to ensure that trucks assigned to this area will have availability to charge at their corresponding time. Since other BETs or EVs could access the charging area, it will be necessary to establish a booking system. This booking system will allow truck operators to book their timeslots to prevent the unexpected occupation of CSs.

Next, the final placement of the CSs will be addressed according to the desired location selected by truck operators.

5.4. Placement of the Charging Stations

The determination of the optimal location of the CSs is a challenging multi-objective problem. It requires considering the driving patterns, most frequented routes, geographically available sites, current existing electrical grid location and capacity, and financial factors, among others. Thanks to the Questionnaire, the location of the companies has been determined, as well as their preferred areas to install CI. Furthermore, thanks to the collaboration with Oskarshamn Energi, it has been possible to ensure that the locations selected have enough grid capacity to integrate the CI. Hence, in this section, the final proposition for the placement of the designed CI will be explained.

The locations selected for installing the CSs have been carefully chosen to ensure enough space capacity to accommodate the truck fleet as well as power capacity. However, these locations are not publicly available sites. Therefore, future steps of the project would require collaboration with Oskarshamn municipality and Oskarshamn Energi to identify public parking areas with power capacity. The next figures show the location where CSs will be implemented.

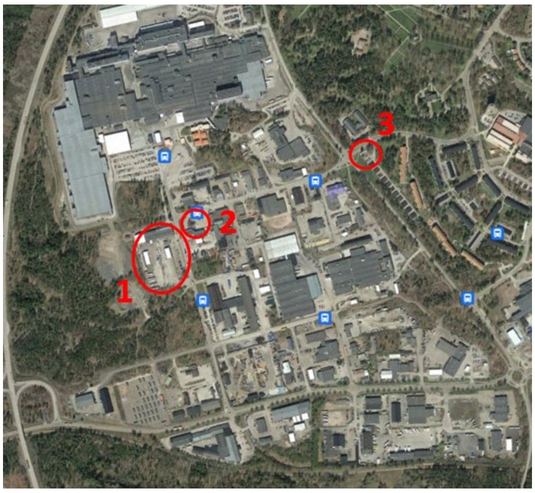

Figure 54. Selected locations for installing CI. District A.

Figure 55. Selected location for installing CI. District B.

Therefore, with the final locations already selected, the following table presents the configuration of the CI that has been described in the previous section and which will be the final solution designed for the project:

<table>
<tr><th>District</th><th>Zone</th><th>Model of CS</th><th>Units</th><th>Total Power (kW)</th></tr>
<tr><td rowspan="4">A</td><td>1</td><td>BDC-60
BDC-150</td><td>1
1</td><td>210</td></tr>
<tr><td>2</td><td>BDC-150</td><td>1</td><td>150</td></tr>
<tr><td>3</td><td>BDC-150</td><td>2</td><td>300</td></tr>
<tr><td colspan="2">Total</td><td>5</td><td>670</td></tr>
<tr><td>B</td><td>4</td><td>ABB HPC Power Cabinet
ABB Terra HPC</td><td>3
6</td><td>525</td></tr>
</table>

Table 13. Final configuration of the CI.

Finally, in the next section, the economic analysis at a stakeholder level will be performed to understand the financial implications of this project and its profitability.

6. Oskarshamn Case Study - Economic analysis

This section will focus on examining the profitability associated with replacing the stakeholders' current diesel truck fleet with an electric one. In order to finance the project, various operation models have been proposed to understand the range of alternatives that the stakeholders can apply.

6.1. Economic scenarios and main parameters

For the economic analysis, two scenarios are considered. The first one is called *BETs replacement.* In this scenario, it is assumed that each stakeholder possesses a functioning diesel truck fleet, which can be sold at 30% of its original cost. So the comparison will be between continue operating this diesel truck fleet or selling it and acquiring a new BET fleet, using the proceeds from the sale to partially offset the investment required for the new BET fleet.

The second scenario is called *BET vs. Diesel Truck.* In this case, the old truck fleet is deemed obsolete and cannot be sold. Consequently, the stakeholder evaluates the economic returns of investing in a new Diesel Truck fleet versus a BET fleet.

The economic assessment for this study utilizes main parameters that are categorized into four groups. The first category is the Charging Infrastructure (CI) costs, which can be further divided into material costs and labor costs. Material costs pertain to the equipment and hardware of the CI (see Appendix III), and these prices have been obtained by contacting technology suppliers and requesting their price lists for the respective solutions. On the other hand, labor costs have been sourced from the literature review (see section *3.5.1*). In the next table, these prices are displayed:

Item	Model	Cost per unit (€)
Charging Station	BDC - 60	5,860
Charging Station	BDC - 150	9,560
Power Cabinet	ABB HPC Power Cabinet	54,000
Charging Pole	ABB Terra HPC	24,500
Installation Labour CS	60 kW	4,675
Installation Labour CS	150 kW	7,475
Operation & Maintenance CS	60 kW	400
Operation & Maintenance CS	150 kW	500

Table 14. Charging Infrastructure costs.

The next category of costs includes those associated with the truck fleet. These prices have been gathered from the literature review. In the case of diesel trucks, they have a fixed price. However, for BETs, the cost comprises a base price plus the additional cost of the battery. The battery cost is contingent upon its capacity. Moreover, the operational costs of diesel trucks compared to BETs include more than just the difference in fuel prices. Diesel trucks require more frequent and intricate maintenance due to their more significant number of mechanical components and interdependencies. Consequently, the need for maintenance, control checks, and repairs is higher for conventional ICE trucks than for BETs. The following table collects these costs:

Item	Model	Cost per unit (€)
Diesel Truck	Standard	160,000
BET	Standard	300,000
Battery price per kWh	NMC	175
Old truck sale	Standard Diesel	48,000 (30% IC)
Extra Maintenance Cost Diesel Truck per km	Cost per km	0.096

Table 15. Truck costs.

In the third category, the costs related to fuel consumption are considered. All fuel prices are updated as of May 2023. The diesel price in Sweden has been obtained from Global Petrol Prices [124]. In the second place, the cost of electricity in Sweden for May 2023 has been sourced from the European Commission and Statistics Sweden [125], [126]. The price includes the three components: wholesale price of electricity in bidding area SE4 settled by Nordpool [127], Grid Fees to the energy company, and energy taxes and Levies paid to the government. The cost of electricity by the third party has been determined by comparison of multiple service providers like IONITY [128]–[130]. The table below shows all these costs:

Item	Cost unit	Cost
Diesel	€/liter	1.91
Electricity	€/kWh	0.16
Electricity from third-party	€/kWh	0.26

Table 16. Energy costs.

It is important to note that diesel consumption has been estimated according to the energy use per actor, a diesel energy density of 9.93 kWh/liter, and an ICE with 40% of efficiency.

Finally, the market evolution parameters. The discount rate of this project has been estimated at 3%. Inflation parameters have been obtained from official sources of experts on market analysis [131], [132]. Lastly, the project's lifespan has been determined to be 15 years based on the findings from the literature review. It is important to mention that the need for battery replacement is not taken into account due to the majority of trucks not accumulating enough mileage within the 15-year period to warrant replacement. Thus, considering the project's duration, the requirement for battery replacement is deemed unnecessary as the trucks typically do not reach the mileage threshold that necessitates such replacement within the specified timeframe.

Item	Value
Discount Rate	3%
Current Swedish General Inflation	10.5%
Diesel Inflation	5%
Electricity Inflation	2%

Lifetime	15 years

Table 17. Market evolution parameters.

6.2. Operational business model of the CSs

As mentioned before, different strategies will be defined to operate the CI to provide the stakeholders with other options and knowledge on the possibilities available. The strategy will be divided into the two districts and are explained following.

District A

Regarding District A, as discussed earlier, Stakeholders 1 and 3 are the exclusive users of the installed Charging Infrastructure (CI) in this area. Furthermore, upon reviewing Table 14, it becomes evident that the investment needed for this solution is significantly lower compared to the CI installation in District B. Consequently, Stakeholder 1 and Stakeholder 3 will jointly own the CI, with each party having a share proportionate to their utilization. This arrangement ensures a fair distribution of ownership based on the respective stakeholders' usage of the infrastructure.

District B

When considering District B, it becomes evident that having a shared ownership model with the four stakeholders might lead to chaos and potential disagreement among the parties involved. Furthermore, the higher initial investment required for this solution may not be justifiable for some stakeholders with low energy utilization. As a result, a more suitable business model for District B would be a Fully Funded Charging Point Operator (CPO) or Electric Vehicle Service Provider (EVSP) approach.

Under this business model, the CPO or EVSP would bear the costs associated with hardware, installation, and connection of the CI. This arrangement is expected to be appealing to the CPO or EVSP, given the high BET traffic density, proximity to highway and sailing networks, and other commercial factors, such as the presence of large companies in the harbor area, which will attract more BETs. Once the CI is installed, the CPO or EVSP would charge the stakeholders a higher electricity price for plugging in their BETs.

This business model offers several benefits. Stakeholders are relieved from the burden of making the initial investment, while the CPO or EVSP gains revenue by selling electricity at a higher price. By adopting this approach, both parties can capitalize on the advantages of the arrangement, making it a mutually beneficial solution for all stakeholders involved.

6.3. Economic analysis at a stakeholder level

The last part of the economic analysis will be addressed to evaluate the profitability of the proposed solution for each of the stakeholders as well as to understand and identify possible measures to improve profitability. First, District A stakeholders will be analyzed, followed by District B stakeholders, and finally, the third-party service provider, who owns the CI from District B. Then, a comparison of the profitability of all the actors will be provided, and a general evaluation will be provided explaining external factors that might affect the profitability of this project and how some actors could apply various strategies to enhance it. The economic analysis thoroughly detailed can be found in *Appendix IV: Economic Analysis Itemized.*

Stakeholder 1

In both scenarios considered, Stakeholder 1, who possesses a fleet of 37 trucks with an annual energy consumption of 860,880 kWh, primarily invests in the truck fleet. Additionally, Stakeholder 1, along with Stakeholder 3, owns the Charging Infrastructure (CI) in District A. Based on the results provided by the OM, Stakeholder 1's energy consumption at the CI in District A slightly exceeds 30%. As a result, Stakeholder 1 would bear 35% of the initial investment in the CI and 35% of the annual Operational and Maintenance (O&M) costs. The tables below present details regarding the initial investment for both scenarios, as well as the annual savings generated by operating a BET fleet instead of a diesel fleet. These details offer insights into the financial implications of adopting BETs in terms of cost savings and return on investment.

BETs replacement	Cost (€)	**BET vs. Diesel Truck**	Cost (€)
Charging Infrastructure	28,380	Charging Infrastructure	28,380
Truck Fleet	10,081,750	Extra BET Fleet Cost	5,937,750
Total	10,110,130	Total	5,966,130

Table 18. Initial investment costs Stakeholder 1.

Item	**Electricity**	**Diesel**
Annual Consumption Cost (€)	177,606	412,942
Annual O&M cost (€)	840	115,165
Annual Savings from Electrification (€)	349,660	

Table 19. Annual operational costs and savings Stakeholder 1.

Due to low annual savings in comparison with the high initial investment required, the profitability of this business for the *BETs replacement* scenario is relatively low, having the return of the investment after the 14th year. For the *BET vs. Diesel Truck,* the profitability is much higher, recovering the investment after the 10th year and with a considerably high Internal Rate of Return (IRR) and Net Present Value (NPV). The next table presents the NPVs and IRRs of both scenarios:

BETs replacement	Value	**BET vs. Diesel Truck**	Value
NPV (€)	279,246	NPV (€)	4,423,245
IRR (%)	0.3	IRR (%)	6.9

Table 20. NPVs and IRRs Stakeholder 1.

Hence, it is crucial for Stakeholder 1 to thoroughly evaluate the investment, as the significant risk associated with a large initial investment might be justifiable considering the potential long-term profitability of the business in the second scenario.

Stakeholder 3

The other stakeholder in District A, Stakeholder 3, possesses a fleet of 35 trucks with an annual energy consumption of 2,660,554 kWh, which is much higher than Stakeholder 1. Again, the investment is mostly directed to the truck fleet. As mentioned previously, Stakeholder 3 owns the Charging

Infrastructure (CI) in District A with Stakeholder 1. Based on the results provided by the OM, Stakeholder 1's energy consumption at the CI in District A slightly exceeds 60%. As a result, Stakeholder 3 would bear 65% of the initial investment in the CI and 65% of the annual O&M costs. The tables below present details regarding the initial investment for both scenarios, as well as the annual savings generated by operating a BET fleet instead of a diesel fleet.

BETs replacement	Cost (€)	**BET vs. Diesel Truck**	Cost (€)
Charging Infrastructure	52,700	Charging Infrastructure	52,700
Truck Fleet	10,990,000	Extra BET Fleet Cost	7,070,000
Total	11,042,700	Total	7,122,700

Table 21. Initial investment costs Stakeholder 3.

Item	**Electricity**	**Diesel**
Annual Consumption Cost (€)	544,474	1,276,197
Annual O&M cost (€)	1,560	180,336
Annual Savings from Electrification (€)	910,500	

Table 22. Annual operational costs and savings Stakeholder 3.

Presently, the substantially higher energy consumption relative to Stakeholder 1 results in significantly higher savings derived from utilizing a more cost-effective fuel source, electricity. Consequently, despite the continued high initial investment, the annual savings swiftly offset it, recuperating the investment in the 8th and 6th year for *BETs replacement* and *BET vs. Diesel Truck* scenarios, respectively. The next table presents the NPVs and IRRs of both scenarios:

BETs replacement	Value	**BET vs. Diesel Truck**	Value
NPV (€)	16,148,015	NPV (€)	20,068,015
IRR (%)	12.3	IRR (%)	21.0

Table 23. NPVs and IRRs Stakeholder 3.

Thus, it is highly advisable for Stakeholder 3 to invest due to its substantial energy utilization, which leads to an early recovery of the initial investment. Moreover, the project exhibits a high level of profitability, with IRRs surpassing the general inflation rate. This ensures attractive returns on the capital deployed and offers long-term financial stability.

Stakeholder 2

Moving to District B, Stakeholder 2 possesses a fleet of 2 trucks with an annual energy consumption of 90,480 kWh, which both are much smaller than stakeholders in District A. Since the business model applied would be a Fully Funded CPO, all the investment will go to the BET fleet. Therefore, thanks to this business model, the O&M will be covered by the CPO. However, it is important to note that O&M costs are affected by the slightly higher electricity price of 0.1 €/kWh. As a result, the operational costs of the BET fleet are relatively higher in comparison. This narrows the cost difference between operating with diesel and electricity, although electric operation remains significantly more economical. The tables below provide comprehensive information on the initial investment for both scenarios, as well as the annual savings derived from operating a BET fleet instead of a diesel fleet.

BETs replacement	Cost (€)	**BET vs. Diesel Truck**	Cost (€)
Charging Infrastructure	-	Charging Infrastructure	-
Truck Fleet	574,000	Extra BET Fleet Cost	350,000
Total	574,000	Total	350,000

Table 24. Initial investment costs Stakeholder 2.

Item	**Electricity**	**Diesel**
Annual Consumption Cost (€)	23,810	43,400
Annual O&M cost (€)	0	7,188
Annual Savings from Electrification (€)	26,780	

Table 25. Annual operational costs and savings Stakeholder 2.

This analysis reveals that both the annual savings and initial investment for Stakeholder 2 in District B are notably lower compared to stakeholders in District A. The next table presents the NPVs and IRRs of both scenarios for Stakeholder 2:

BETs replacement	Value	**BET vs. Diesel Truck**	Value
NPV (€)	82,102	NPV (€)	306,102
IRR (%)	1.6	IRR (%)	8.5

Table 26. NPVs and IRRs Stakeholder 2.

As can be seen, the project's profitability, while similar to that of Stakeholder 1, presents a lower initial risk and slightly higher overall profitability. Consequently, this alternative may appear more appealing to Stakeholder 3, considering the reduced risk exposure and the potential for favorable returns on investment.

Stakeholder 4

Stakeholder 4, another participant from District B, operates a sizable fleet of 20 trucks with an annual energy consumption of 283,314 kWh. Notably, the fleet size is significantly larger in comparison to its energy utilization, which adversely impacts the annual savings achieved through electrification. Similarly to Stakeholder 2, the business model employed in this district is a Fully Funded Charging Point Operator (CPO) approach, resulting in the entire investment being allocated towards the BET fleet. Consequently, there are no costs associated with the operation and maintenance (O&M) of the charging infrastructure. However, the O&M costs for the BET fleet are relatively higher compared to stakeholders in District A. The tables below provide comprehensive information on the initial investment for both scenarios, as well as the annual savings derived from operating a BET fleet instead of a diesel fleet.

BETs replacement	Cost (€)	BET vs. Diesel Truck	Cost (€)
Charging Infrastructure	-	Charging Infrastructure	-
Truck Fleet	5,320,000	Extra BET Fleet Cost	3,080,000
Total	5,320,000	Total	3,080,000

Table 27. Initial investment costs Stakeholder 4.

Item	Electricity	Diesel
Annual Consumption Cost (€)	74,555	135,900
Annual O&M cost (€)	0	29,952
Annual Savings from Electrification (€)	91,280	

Table 28. Annual operational costs and savings Stakeholder 4.

Upon comparing with other stakeholders, it becomes evident that the savings obtained from electrifying the truck fleet are considerably smaller in this case. The limited energy utilization is the underlying factor responsible for this outcome. As Stakeholder 4 has a relatively low energy consumption, the cost savings derived from operating the truck fleet with a more affordable energy source are minimal. Consequently, this has a detrimental effect on the project's financial viability, as the savings generated are insufficient to offset the initial investment within the studied timeframe. Next, the table below shows the economic performance of this last truck operator:

BETs replacement	Value	BET vs. Diesel Truck	Value
NPV (€)	-3,053,080	NPV (€)	-813,080
IRR (%)	-8.6	IRR (%)	-3.4

Table 29. NPVs and IRRs Stakeholder 4.

Third-party service provider

The third-party service provider, known as the Charging Point Operator (CPO) or Electric Vehicle Service Provider (EVSP), assumes the role of the sole owner of the CI in District B. By acquiring the CI and selling electricity at a higher price compared to direct grid purchases, this entity generates revenue streams that help recover the initial investment. The following table displays the initial investment alongside the annual benefits achieved through purchasing electricity at 0.16 €/kWh and selling it at 0.26 €/kWh. Additionally, it provides details of the annual O&M costs associated with CI ownership.

Item	**CI**
Initial investment (€)	359,470
Annual Electricity Sale (kWh)	1,911,730
Annual O&M cost (€)	2,700
Annual benefits from electricity sold (€)	194,510

Table 30. Initial investment and annual operational costs and savings CPO.

When looking at the NPV and IRR, it can be seen that this business model is a very attractive opportunity for CPOs. Thanks to the very high utilization of the CI, the amount of energy sold swiftly offsets the initial investment. The following chart shows the profitability of the business for the CPO.

Item	Value
NPV (€)	2,500,000
IRR (%)	116%

Table 31. NPV and IRR CPO.

Comparison and analysis

Initially, the subsequent table presents the outcomes obtained from both scenarios, offering a concise overview of the key parameters that shape the project's profitability for each stakeholder. Subsequently, an assessment of each stakeholder's profitability is conducted, accompanied by the exploration of potential strategies to enhance their financial performance.

Scenario	BETs replacement		BET vs. Diesel Truck	
Stakeholder	NPV	IRR	NPV	IRR
SH1	279,246	0.3	4,423,245	6.9
SH2	82,102	1.6	306,102	8.5
SH3	16,148,015	12.3	20,068,015	21.0
SH4	-3,0053,080	-8.6	-813,080	-3,4
CPO	2,500,000	116	2,500,000	116

Table 32. NPV and IRR of all stakeholders.

In the table, it can be noticed that *BET vs. Diesel Truck* scenario has always a much higher profitability. This is reasonable since for the *BETs replacement* scenario, the comparisson is done between acquiring a new truck fleet or continue operating with the existing one, while in the *BET vs. Diesel Truck* it is necessary to acquire a new one. Except for Stakeholder 4, all the other stakeholder register positive results from the electrification of the truck fleet. However, although the profitability for the stakeholders under the *BETs replacement* scenario is usually low, it is already pointed out that it is economically beneficial to replace an existing diesel truck fleet.

Furthermore, with the continuous expansion of the electric vehicle (EV) market and the increasing participation of companies in the electrification of the transportation sector, it is anticipated that prices will decrease over time. Consequently, the disparity between diesel trucks and battery electric trucks (BETs) will continue to decrease. The major cost drivers that contribute to the substantial initial investment gap between the two types of trucks, which are the battery and electric motor, have already been experiencing reductions and are projected to continue declining. This trend positions BETs to eventually reach a price point comparable to that of diesel trucks.

It can also be seen that the CPO business case stands out as the most lucrative, although this stakeholder is highly influenced by fluctuations in the electricity price. While other stakeholders will pay a fixed price for recharging their BETs in District B, the CPO can see its benefits affected by the variation in the electricity price. Similarly, Stakeholder 1 and Stakeholder 3 are also partially impacted by the electricity price, as some of their trucks charge in District A, where the charging price is not fixed. Since they are owners of the CI, they procure electricity from the grid at fluctuating prices, leading to potential adjustments in their costs.

Nevertheless, despite the volatility of electricity prices, the high energy utilization of the CI ensures the investment remains profitable. This provides two important considerations. First, the stakeholders that buy the electricity from the CPO can negotiate alternative contracts to redefine the payment terms. For example, Stakeholder 4, whose profitability is never positive, can negotiate a different electricity price by shifting its use of the CI to low occupancy hours or off-peak hours with lower electricity prices. Secondly, given the remarkable profitability of owning the CI, some stakeholders may opt for a more assertive approach by becoming CI owners themselves. For instance, Stakeholder 1 could decide to fully acquire the CI from District A, setting a fixed price for selling the electricity to Stakeholder 3. Through these strategies, stakeholders can potentially enhance the economic viability of the project.

7. Conclusion

This study shows that Sweden is already one of the leading countries towards transport electrification. Both governments and the private sector are already implementing severe changes in how people and goods move across the country. However, these solutions are still heavily directed toward light Electric Vehicles (EV) and slow Charging Infrastructure (CI). In order to replicate the refueling process of ICE vehicles and empower Heavy Duty Vehicles (HDV) to electrify, ongoing development plans and collaborations between public and private stakeholders are crucial. This study has played a pivotal role in bringing together these sectors to collaborate and benefit from a project planning that aligns private-sector electrification efforts with municipal plans for achieving climate neutrality. In this regard, Oskarshamn has taken a noteworthy step by initiating one of the first projects to evaluate the implementation of a shared CI owned by multiple private and public entities. By fostering such collaborative efforts, the study paves the way for future advancements in transport electrification and underscores the importance of aligning the interests of various stakeholders to achieve sustainable outcomes.

However, the electrification of HDV does not come guaranteed. The supply chain for lithium-ion batteries has experienced a substantial expansion, with the demand for such batteries soaring by more than 1,600% compared to 2020 levels. Moreover, China controls 80% of the total battery manufacturing industry, making countries highly dependent on China, which can lead to a supply shortage or a price increase in case of conflicts. Hence, although it is crucial to decarbonize the HDV sector, other alternatives to Battery Electric Trucks (BETs) should be considered, such as trucks powered with hydrogen or biofuels, to prevent strain on the global lithium supply. Furthermore, significant efforts are required to establish an effective scheme for the recovery and recycling of Li-ion batteries, to reduce this sector's environmental impact and alleviate material bottlenecks and their price effects.

Another potential obstacle to the electrification of Heavy Duty Vehicles (HDVs) is the current state of the electrical grid infrastructure. Despite the improved efficiency of Battery Electric Trucks (BETs) compared to diesel trucks due to a lower energy consumption per km, the increased electrical load resulting from electrification can have adverse effects if not adequately addressed. Some ongoing Fast Charging Station (CS) projects already operate at a power rate of 1 MW. In other cases, as seen in this project, the CI can deliver up to 350 kW in one single CS. Thus, if multiple Fast CS are implemented without proper planning or upgrading of the electrical grid, peak power requirements can create overloads in cables or transformers, leading to grid imbalances and complete blackouts in the worst case. Developing and upgrading the electrical grid in alignment with HDV electrification is essential to enable the energy transition. Although it may require significant investments of time and money, it is necessary for these two industries to collaborate and evolve together.

When considering their economic and technical aspects, BETs are already proving to be competitive alternatives to diesel trucks, while CSs match the functionality of diesel refueling stations. Although initial investment costs of BETs remain substantially higher, thanks to the economy of scale and the EV market's expansion, these prices are coming to parity. Notably, battery prices have witnessed a remarkable 83% decrease in the last decade. On the other hand, electric and electronic components, such as electric motors, inverters, and converters, are also becoming more cost-competitive thanks to the growth of the EV manufacturing industry. In terms of technical capabilities, BETs and the Charging Infrastructure (CI) are well-suited to meet the requirements of truck operators. BETs can offer long-range operations similar to their diesel counterparts, while Fast CSs provide charging times comparable to those of traditional diesel refueling stations.

Addressing the sustainability implications of this project, it becomes evident that as the adoption of electrification increases, there is a substantial reduction in Greenhouse Gas (GHG) emissions. This reduction is primarily due to the elimination of GHG tailpipe emissions associated with diesel trucks, which as seen previously, account for approximately 28% of Sweden's GHG emissions. Thanks to utilizing electricity stored in batteries, BETs power the wheels without emitting any exhaust gases. The only emissions linked to operating a BET fleet stem from the generation of electricity, which can vary significantly depending on the country or region. However, Sweden benefits from one of the cleanest energy generation systems, with an approximate emissions factor of 19 gCO2eq/kWh, whereas the European average in 2021 was 138 gCO2eq/kWh. Consequently, the emissions produced to generate the electricity required to power the BET fleet are not only low due to Sweden's energy production but also significantly lower than diesel tailpipe emissions. Moreover, as the energy system continues to transition towards more renewable generation systems, these emissions will continue to decrease.

Lastly, regarding the feasibility for stakeholders, it has been demonstrated that in 75% of cases, the business exhibits high profitability. As energy utilization grows, the disparity in operational costs widens compared to a diesel truck fleet, thereby enhancing the business's profitability for stakeholders with higher energy consumption. However, it has also been observed that the disparity in initial investment between BETs and diesel trucks remains a notable barrier for truck operators. To accelerate the process of electrification, it is essential to reduce this initial risk associated with the high upfront costs.

As the EV market continues to grow, the prices of EVs are approaching parity with traditional vehicles, which helps mitigate the risk associated with the initial investment. Additionally, to bring down this initial barrier, adopting a strategy of partial or progressive electrification can further reduce this risk. By prioritizing the electrification of routes with the highest energy utilization, truck operators can minimize the initial investment while still reaping the maximum benefits of operating BETs. This approach allows truck operators to minimize the perceived risk of the project while maximizing the Net Present Value (NPV) and Internal Rate of Return (IRR) of their business.

On the other hand, the profitability of the business for the Charging Point Operator (CPO) or Electric Vehicle Service Provider (EVSP) has highlighted this stakeholder as the best business model. This provides a clear insight into the various alternatives that the Stakeholders (SHs) can apply to maximize the profitability of their business. First, individual SHs could apply a more aggressive strategy of completely owning the CI. In this sense, the SH owner of the CI would become the CPO, benefiting from having electricity for its BETs at grid prices and selling electricity at higher costs to other SHs. Second, SHs with more flexibility in their charging schedules can shift their charging to hours with lower electricity prices or utilization rates. During these hours, it is possible to negotiate a different charging price with the CPO, reducing the operational costs of BETs and increasing the profitability of the SHs. And third, given that the SHs will be the most important users of the CI, they have the power to negotiate different electricity prices with the CPO to balance the profitability of all actors.

On the other hand, the profitability analysis has identified the Charging Point Operator (CPO) or Electric Vehicle Service Provider (EVSP) as the most favorable business model. This insight enlights the range of alternatives available to stakeholders (SHs) for maximizing their business profitability. Firstly, individual SHs can adopt an assertive strategy by fully owning the CI. By doing so, the SH who owns the CI becomes the CPO, benefiting from accessing electricity for their BETs at grid prices while selling electricity at higher rates to other SHs. Secondly, SHs with flexible charging schedules can optimize their charging activities during hours with lower electricity prices or utilization rates. By negotiating customized charging prices with the CPO during these off-peak hours, operational costs for BETs can be reduced, ultimately enhancing SHs' profitability. Lastly, as the primary users of the CI, SHs hold significant leverage to negotiate diverse electricity prices with the CPO, ensuring a balanced and profitable outcome for all stakeholders involved.

As a result, this project has provided valuable insights into the electric HDV sector. It comprehensively addresses all critical aspects, offering a holistic understanding of the electrification process and its implications. By examining the current state of HDV electrification in the Swedish context, exploring technology alternatives and their economic impact, and outlining various business models for operation, this project offers a comprehensive overview.

The findings demonstrate that the project yields both sustainable and economic advantages for stakeholders, highlighting the undeniable benefits and necessity of transitioning towards an electrified road transport system. Additionally, the project provides a thorough evaluation and offers practical recommendations for the involved SHs to facilitate their transition and capitalize on the numerous opportunities available to them.

Overall, this project serves as a valuable resource, equipping stakeholders with the knowledge and insights necessary to navigate the complexities of HDV electrification, fostering sustainable and profitable outcomes in the process.

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Appendix I: Questionnaire

These questionnaires have been created to obtain relevant information from Truck Operators in Oskarshamn, in order to study the potential of implementing a Charging Infrastructure to electrify the truck fleet and reduce the environmental impact caused by this kind of transport. The questionnaires take around 10 minutes to fill and they are mostly self-explanatories, but short clarifications and examples can be found in some of them to avoid doubt.

Thank you very much for your time and collaboration.

COMPANY INTRODUCTION

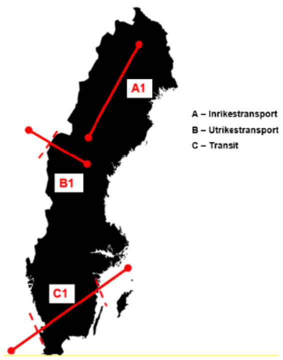
Please, fill the next questionnaire with all the information you know. If some information is unknown, it is possible to speculate or guess by marking it with a "#".

COMPANY INFORMATION	
Name of the company	
Business sector	
Annual revenues (optional)	
ADDRESS	
City	Oskarshamn
Postal Code	
Street	
Number	
SUSTAINABILITY COMMITMENT	
Do you have any measure to reduce environmental impact of your transport fleet? If yes, briefly name and explain them.	
Do you own Electric Trucks (ETs)? If yes, indicate number of ETs and percentage of the fleet.	
Do you own or rent Charging Stations (CSs)? If yes, indicate to whom, number of CSs and their power output.	

TRUCK FLEET QUESTIONNAIRE

Please, fill the next questionnaire with all the information you know regarding your truck fleet, considering all kinds of trucks owned. If some information is unknown, it is possible to speculate or guess by marking it with a "#".

TRUCK FLEET				
Number of drivers				
Number of trucks				
According to this image, indicate the amount of freight transport operations (truck trips) of each kind for your whole truck fleet.				
	A (<50km)	A (>50km)	B	C
Daily				
Weekly				
Monthly				



Please, fill the next table with all the information you know regarding your truck fleet distinguishing by group of trucks. **A group of trucks is considered as an aggregation of trucks having the same characteristics** (a group can also be formed by only one truck). If some information is unknown, it is possible to speculate or guess by marking it with a "#". <u>An example of how to do it is located under this table.</u>

	Number of trucks	Model	GTW[1] (tons)	Fuel (Diesel, gasoline, etc.)	Age	Tank Size (liters)	Range with full tank (km)
Group 1							
Group 2							
Group 3							
Group 4							
Group 5							
Group 6							

[1]: GTW stands for Gross Trailer Weight in tons.

EXAMPLE OF TRUCK FLEET: 4 trucks model Z from 2015 powered by diesel of 64 t, with 1,200 liters tank size and an autonomy with full tank of 1,000 km, and 2 trucks model Y from 2021 powered by diesel of 64 t, with 1,400 liters tank size and an autonomy with full tank of 1,600 km:

EXAMPLE OF TRUCK FLEET							
	Number of trucks	Model	GTW[1] (tons)	Fuel (Diesel, gasoline, etc.)	Age	Tank Size (liters)	Range with full tank (km)
Group 1	4	Z	64	Diesel	2015	1,200	1,000
Group 2	2	Y	64	Diesel	2021	1,400	1,600

LOGISTICS QUESTIONNAIRES SIMPLE

Please, **mark the boxes with a cross** that represent the most the **common daily operations** of your truck fleet. If some information is unknown, it is possible to speculate or guess by marking it with a "#". If none of the boxes represent your operations, you can always introduce your data in the column "Other". At the end of the document, a more complex *LOGISTICS QUESTIONNAIRE* can be found, feel free to use it if preferred.

DISTANCES	<5%	10 - 20%	20 - 50%	50 - 75%	75 - 90%	100%	Other
How many of your trucks operate daily?							
How many trucks drive distances greater than 50 km **without stopping**?							
How many trucks operate distances greater than 100 km **without stopping**?							
How many trucks operate distances greater than 200 km **without stopping**?							
How many trucks operate distances greater than 100 km **during the day**?							
How many trucks operate distances greater than 200 km **during the day**?							
How many trucks operate distances greater than 300 km **during the day**?							
How many trucks operate distances greater than 400 km **during the day**?							
How many trucks operate distances greater than 500 km **during the day**?							

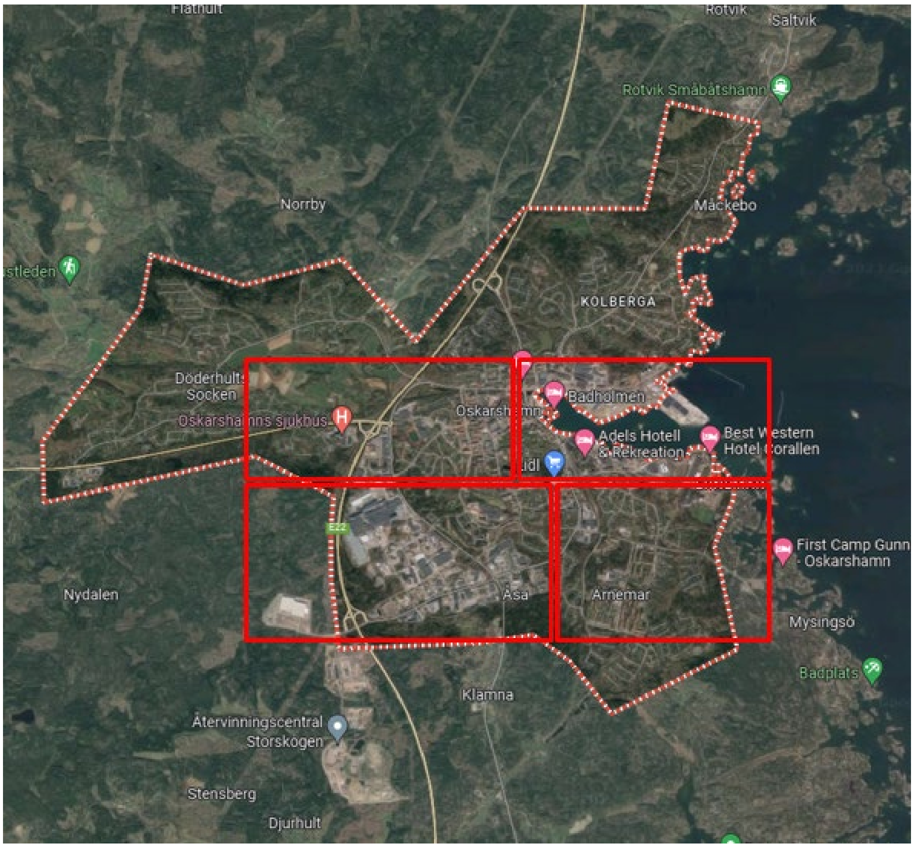
ROUTES	<5%	10 - 20%	20 - 50%	50 - 75%	75 - 90%	100%	Other
How many trucks come back to Oskarshamn to reload goods and continue their journey?							
How many trucks operate unload and load goods at least 2 times a day?							
How many trucks operate unload and load goods at least 3 times a day?							
How many trucks operate unload and load goods at least 4 times a day?							
How many trucks operate unload and load goods at least 5 times a day?							
How many trucks operate unload and load goods more than 5 times a day?							
If 100 % is 10 hours and 0% is 0 hours, how long do the 1st stop take?							
If 100 % is 10 hours and 0% is 0 hours, how long do the 2nd stop take?							
If 100 % is 10 hours and 0% is 0 hours, how long do the 3rd stop take?							
If 100 % is 10 hours and 0% is 0 hours, how long do the 4th stop take?							

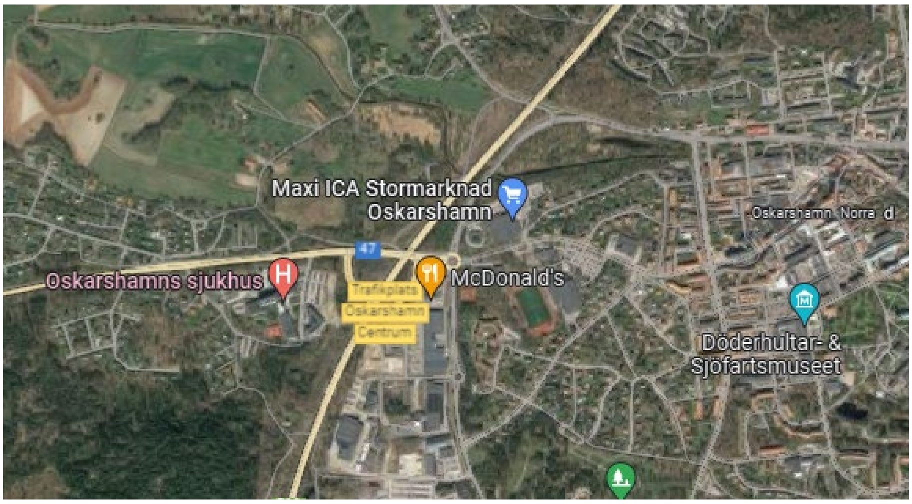
TIME SCHEDULES	<5%	10 - 20%	20 - 50%	50 - 75%	75 - 90%	100%	Other
How many trucks are parked in your facilities during night?							
How many trucks operate only half of the day?							
From 20:00 to 00:00 am, how many trucks are in operation?							
From 20:00 to 00:00 am, how many trucks **arrived in** your facilities?							
From 00:00 to 06:00 am, how many trucks are in operation?							
From 00:00 to 06:00 am, how many trucks **arrived in** your facilities?							
From 6:00 to 12:00 pm, how many trucks are in operation?							
From 06:00 to 12:00 pm, how many trucks **arrived in** your facilities?							
From 12:00 pm to 17:00, how many trucks are in operation?							
From 12:00 pm to 17:00, how many trucks **arrived in** your facilities?							
From 17:00 to 20:00, how many trucks are in operation?							
From 17:00 to 20:00, how many trucks **arrived in** your facilities?							

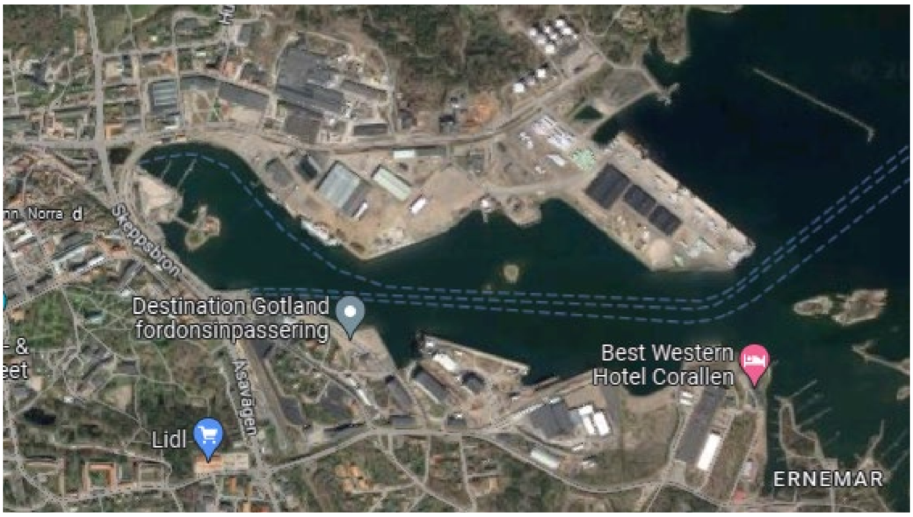
PARKING AVAILABILITY QUESTIONNAIRE

Please, mark in **blue** in the following Oskarshamn Maps where your trucks are parked. In case of implementation of Charging Stations (CSs), mark in **green** where would you like the CSs to be installed. If you know, indicate possible parking spaces available in **yellow**. If these locations are in one of the 4 squared areas, find closer images below.

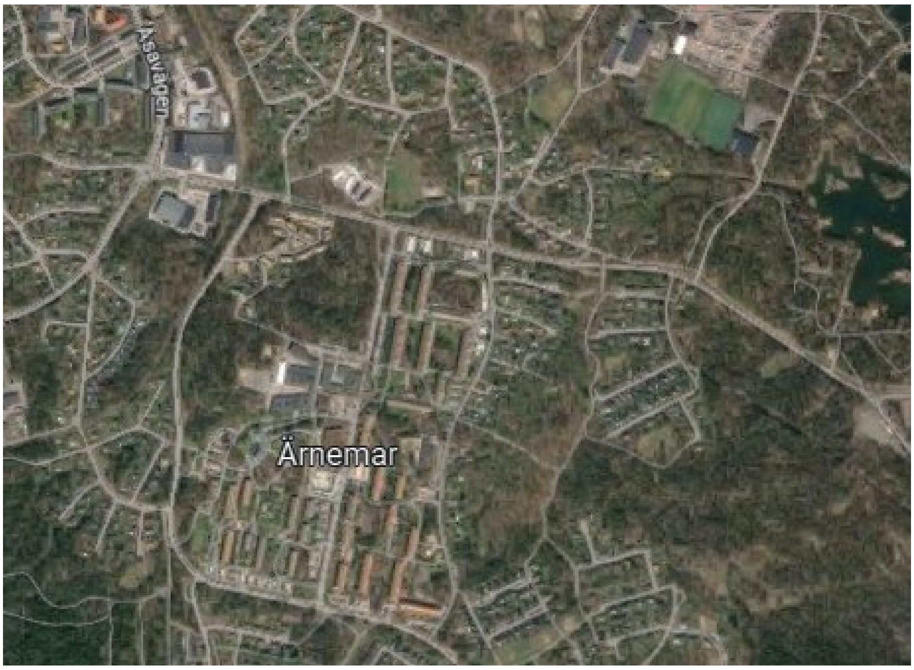
NAME OF THE COMPANY/INSTITUTION:





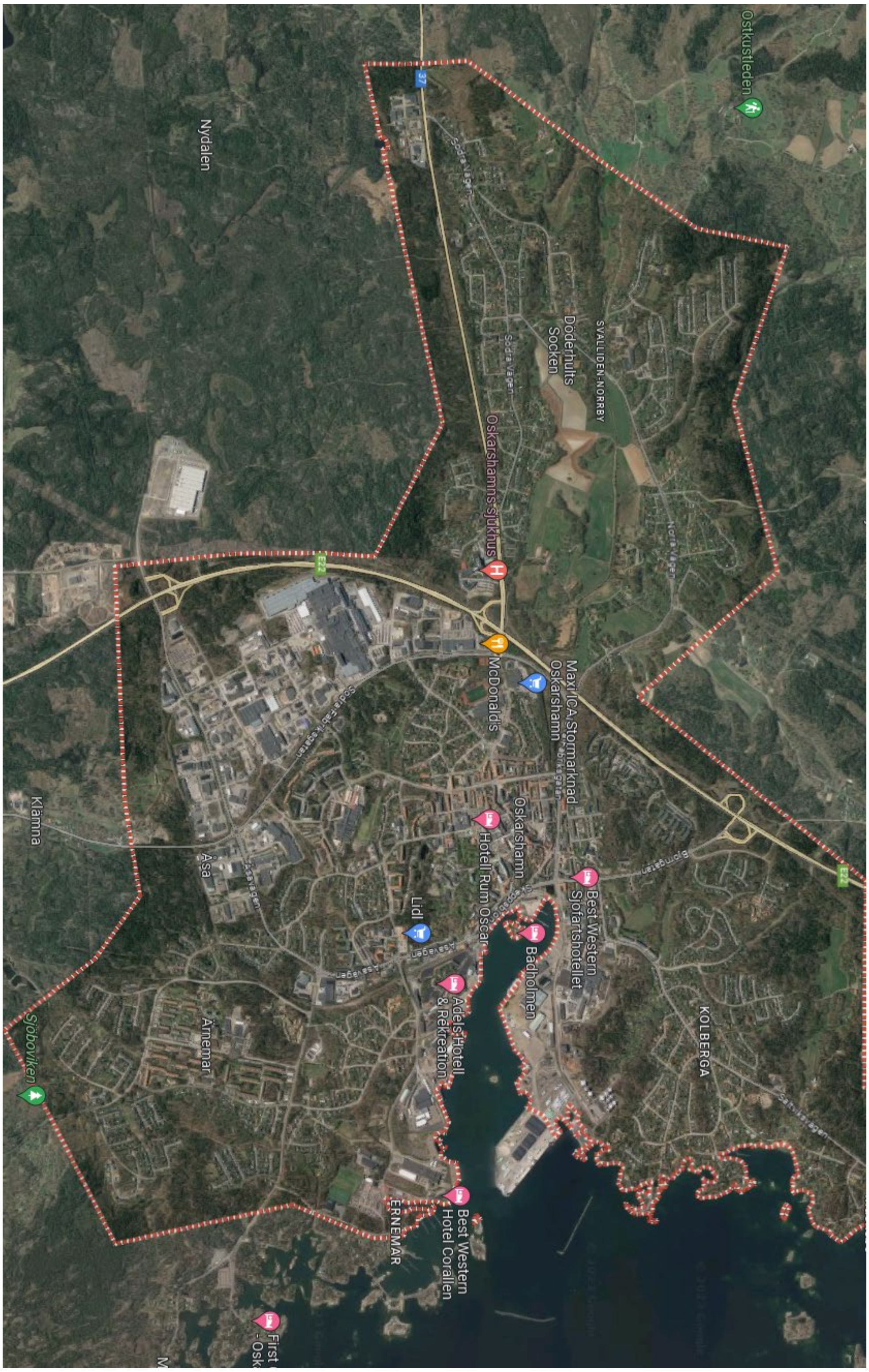

Skeppsbron
Destination Gotland
fordonsinpassering
Best Western
Hotel Corallen
Åsavägen
Lidl
ERNEMAR


E22
Västra Gravplatsen
Södra Fabriksgatan
Scania CV AB
SÖDERTORN
Åsavägen
Trafikplats
Oskarshamn
Södra
Materialmännen
Oskarshamn
Åsa
Applerumsvägen


Åsavägen
Ärnemar

ITINERARY DRAWING QUESTIONNAIRE

Please, mark in **red** in the following Oskarshamn Maps which are the routes that your follow. **This section is intended to identify common routes where shared Charging Stations (CSs) might be implemented**. The drawing does not to be completely exact, it is only necessary to identify the street or routes where most of trucks drive.



LOGISTICS QUESTIONNAIRE COMPLEX (OPTIONAL)

Please, fill the next table with all the information from your truck fleet itinerary. **Please notice that a truck can do 2 or more itineraries in the same day if it comes back to Oskarshamn to start another journey after having completed an itinerary. These itineraries should be differentiated in the table. When indicating the payload, if payloads are different indicate just the maximum payload of the complete itinerary.** If some information is unknown, it is possible to speculate or guess by marking it with a "#". An example of how to do it is located in the next page. In case more tables are needed they can be found at the end of this document.

	Day(s) (M, T, W, Tr, F, St, Sd)[2]	Group[3]	Number of Trucks	Payload per truck (tons)	Origin	End	Distance covered (km)	Number of stops
Itinerary 1								
Itinerary 2								
Itinerary 3								
Itinerary 4								
Itinerary 5								
Itinerary 6								
Itinerary 7								
Itinerary 8								
Itinerary 9								
Itinerary 10								
Itinerary 11								
Itinerary 12								
Does any itinerary finish its route at Oskarshamn to overnight? Please indicate itinerary's number								

[2]: Which days of the week do the trucks take the itinerary

[3]: Write the number of the group according to the table from before.

Now please indicate the time schedules of the previous itineraries:

	Start	End		Start	End
Itinerary 1			Itinerary 7		
Itinerary 2			Itinerary 8		
Itinerary 3			Itinerary 9		
Itinerary 4			Itinerary 10		
Itinerary 5			Itinerary 11		
Itinerary 6			Itinerary 12		

EXAMPLE OF TRUCK ITINERARY FOR A TRUCK FLEET:

On Monday (M) and Friday (F), 3 Group 1 trucks start the journey at 7:00 am from Oskarshamn, with 10 tons payload each, all the way to Linköping (160 km) where they are expected at 11:00 am, stopping in Gamleby. Then, at 12:30 pm they start the way back carrying 6 tons each and stopping in Åtvidaberg and Överum before arriving back to Oskarshamn at 5:00 pm. Then only on Mondays one of them (1 Group 1 truck) goes from Oskarshamn at 6:00 pm to Kristdala (27 km) in 45 minutes with 3 tons. At 7:15 pm starts the way to Oskarshamn with 2 tons.

On Tuesday 7:00 am, 2 truck of group 2 starts from Oskarshamn with 3 and 4 tons (4 tons will be the one to indicate since it is the maximum) driving 60 km to its first stop, other 60 km to the second stop and back to Oskarshamn 70 km where they will arrive at 12:00 pm. Finally the two of them go at 1:00 pm from Oskarshamn with 5 tons each driving 70 km in one hour to Mariannelund, and one comes back with 4 tons (irrelevant since its less than maximum) at 4:00 pm and the other stays ***(two different itineraries)****.*

	Day(s) (M, T, W, Tr, F, St, Sd)[2]	Group[3]	Number of Trucks	Payload per truck (tons)	Origin	End	Distance covered (km)	Number of stops
Itinerary 1	M, F	1	3	10	Oskarshamn	Linköping	160	1
Itinerary 2	M, F	1	3	6	Linköping	Oskarshamn	160	2
Itinerary 3	M	1	1	3	Oskarshamn	Kristdala	27	0
Itinerary 4	M	1	1	2	Kristdala	Oskarshamn	27	0
Itinerary 5	T	2	2	4	Oskarshamn	Oskarshamn	190	2
Itinerary 6	T	2	1	5	Oskarshamn	Oskarshamn	140	0
Itinerary 7	T	2	1	5	Oskarshamn	Mariannelund	70	0

Does any itinerary finish its route at Oskarshamn to overnight? Please indicate itinerary's number	1, 2, 3, 4, 5

	Start	End		Start	End
Itinerary 1	7:00 am	11:00 am	Itinerary 5	7:00 am	12:00 pm
Itinerary 2	12:30 pm	5:00 pm	Itinerary 6	1:00 pm	4:00 pm
Itinerary 3	6:00 pm	6:45 pm	Itinerary 7	1:00 pm	2:00 pm

	Day(s) (M, T, W, Tr, F, St, Sd)[2]	Group[3]	Number of Trucks	Payload per truck (tons)	Origin	End	Distance covered (km)	Number of stops
Itinerary 13								
Itinerary 14								
Itinerary 15								
Itinerary 16								
Itinerary 17								
Itinerary 18								
Itinerary 19								
Itinerary 20								
Itinerary 21								
Itinerary 22								
Itinerary 23								
Itinerary 24								
Itinerary 25								
Itinerary 26								
Itinerary 27								
Itinerary 28								
Itinerary 29								
Itinerary 30								
Does any itinerary finish its route at Oskarshamn to overnight? Please indicate itinerary's number								

	Start	End		Start	End
Itinerary 13			Itinerary 22		
Itinerary 14			Itinerary 23		
Itinerary 15			Itinerary 24		
Itinerary 16			Itinerary 25		
Itinerary 17			Itinerary 26		
Itinerary 18			Itinerary 27		
Itinerary 19			Itinerary 28		
Itinerary 20			Itinerary 29		
Itinerary 21			Itinerary 30		

Appendix II: Optimization model analysis results

Occupation rate districts A and B:

```
Occuaption of Charging Stations inside District A:

2.08 %   of the time there are 0 trucks connected, a total of 10 timesteps.
11.04 %  of the time there are 1 trucks connected, a total of 53 timesteps.
17.71 %  of the time there are 2 trucks connected, a total of 85 timesteps.
16.67 %  of the time there are 3 trucks connected, a total of 80 timesteps.
18.75 %  of the time there are 4 trucks connected, a total of 90 timesteps.
14.37 %  of the time there are 5 trucks connected, a total of 69 timesteps.
10.62 %  of the time there are 6 trucks connected, a total of 51 timesteps.
5.21 %   of the time there are 7 trucks connected, a total of 25 timesteps.
2.5 %    of the time there are 8 trucks connected, a total of 12 timesteps.
0.42 %   of the time there are 9 trucks connected, a total of 2 timesteps.
0.42 %   of the time there are 10 trucks connected, a total of 2 timesteps.
0.0 %    of the time there are 11 trucks connected, a total of 0 timesteps.
0.21 %   of the time there are 12 trucks connected, a total of 1 timesteps.


Occuaption of Charging Stations inside District B:

14.58 %  of the time there are 0 trucks connected, a total of 70 timesteps.
10.62 %  of the time there are 1 trucks connected, a total of 51 timesteps.
17.71 %  of the time there are 2 trucks connected, a total of 85 timesteps.
39.79 %  of the time there are 3 trucks connected, a total of 191 timesteps.
12.92 %  of the time there are 4 trucks connected, a total of 62 timesteps.
4.17 %   of the time there are 5 trucks connected, a total of 20 timesteps.
0.21 %   of the time there are 6 trucks connected, a total of 1 timesteps.
```

Maximum number of trucks connected simultaneously and Maximum number of trucks connected simultaneously at Maximum Charging Power (150kW):

```
Maximum number of trucks connected at the same time in District A: 12 .
Maximum number of trucks connected at the same time in District B: 6 .

Maximum number of trucks connected at the same time at the Maximum Charging Station A Power: 3 .
In this moment there are 7 trucks connected.

Maximum number of trucks connected at the same time at Maximum Charging Station B Power: 3 .
In this moment there are 3 trucks connected.
```

Power requirements in District A when nine or more trucks are connected:

```
Timestep: 239

Truck 1 F4 :    Power required 41.89 kW.
Truck 1 F9 :    Power required 150.0 kW.
Truck 1 F17 :   Power required 50.0 kW.
Truck 2 F17 :   Power required 50.0 kW.
Truck 3 F17 :   Power required 50.0 kW.
Truck 4 F17 :   Power required 50.0 kW.
Truck 2 F18 :   Power required 50.0 kW.
Truck 1 F20 :   Power required 49.5 kW.
Truck 1 F22 :   Power required 22.18 kW.

Timestep: 281

Truck 3 F1 :    Power required 17.11 kW.
Truck 1 F2 :    Power required 46.81 kW.
Truck 3 F2 :    Power required 46.64 kW.
Truck 4 F13 :   Power required 101.16 kW.
Truck 2 F17 :   Power required 50.0 kW.
Truck 3 F17 :   Power required 50.0 kW.
Truck 4 F17 :   Power required 50.0 kW.
Truck 1 F18 :   Power required 50.0 kW.
Truck 5 F18 :   Power required 19.79 kW.

Timestep: 339

Truck 1 F1 :    Power required 17.14 kW.
Truck 1 F2 :    Power required 46.81 kW.
Truck 2 F4 :    Power required 41.89 kW.
Truck 4 F5 :    Power required 1.6 kW.
Truck 2 F6 :    Power required 129.86 kW.
Truck 2 F17 :   Power required 44.22 kW.
Truck 4 F17 :   Power required 50.0 kW.
Truck 5 F17 :   Power required 50.0 kW.
Truck 3 F18 :   Power required 50.0 kW.
Truck 2 F19 :   Power required 150.0 kW.

Timestep: 377

Truck 1 F1 :    Power required 17.14 kW.
Truck 3 F1 :    Power required 17.11 kW.
Truck 3 F2 :    Power required 46.64 kW.
Truck 4 F13 :   Power required 82.66 kW.
Truck 2 F17 :   Power required 50.0 kW.
Truck 5 F17 :   Power required 50.0 kW.
Truck 4 F18 :   Power required 50.0 kW.
Truck 5 F18 :   Power required 14.4 kW.
Truck 4 F19 :   Power required 40.49 kW.
Truck 2 F20 :   Power required 13.07 kW.
Truck 5 F20 :   Power required 50.0 kW.
Truck 1 F21 :   Power required 150.0 kW.

Timestep: 435

Truck 1 F1 :    Power required 17.14 kW.
Truck 1 F2 :    Power required 46.81 kW.
Truck 2 F4 :    Power required 41.89 kW.
Truck 2 F6 :    Power required 45.36 kW.
Truck 2 F17 :   Power required 50.0 kW.
Truck 3 F17 :   Power required 50.0 kW.
Truck 4 F17 :   Power required 50.0 kW.
Truck 5 F17 :   Power required 50.0 kW.
Truck 3 F18 :   Power required 50.0 kW.
Truck 1 F19 :   Power required 30.31 kW.
```

Power requirements in District A when the maximum number of trucks requiring the Maximum charging power occurs:

```
Timestep: 25

Truck 2 F3 :    Power required 23.43 kW.
Truck 3 F3 :    Power required 23.43 kW.
Truck 1 F17 :   Power required 34.65 kW.
Truck 4 F18 :   Power required 50.0 kW.
Truck 2 F21 :   Power required 150.0 kW.
Truck 2 F22 :   Power required 150.0 kW.
Truck 5 F22 :   Power required 150.0 kW.

Timestep: 27

Truck 3 F2 :    Power required 27.92 kW.
Truck 1 F17 :   Power required 11.19 kW.
Truck 2 F18 :   Power required 42.4 kW.
Truck 5 F18 :   Power required 50.0 kW.
Truck 5 F19 :   Power required 150.0 kW.
Truck 3 F21 :   Power required 150.0 kW.
Truck 5 F21 :   Power required 150.0 kW.

Timestep: 220

Truck 1 F1 :    Power required 2.89 kW.
Truck 2 F4 :    Power required 28.61 kW.
Truck 5 F17 :   Power required 50.0 kW.
Truck 2 F19 :   Power required 150.0 kW.
Truck 2 F20 :   Power required 50.0 kW.
Truck 4 F23 :   Power required 150.0 kW.
Truck 5 F23 :   Power required 150.0 kW.

Timestep: 307

Truck 1 F3 :    Power required 5.37 kW.
Truck 1 F4 :    Power required 41.89 kW.
Truck 2 F5 :    Power required 150.0 kW.
Truck 2 F17 :   Power required 50.0 kW.
Truck 2 F22 :   Power required 34.24 kW.
Truck 5 F22 :   Power required 150.0 kW.
Truck 5 F23 :   Power required 150.0 kW.

Timestep: 371

Truck 5 F5 :    Power required 1.6 kW.
Truck 4 F20 :   Power required 50.0 kW.
Truck 5 F20 :   Power required 50.0 kW.
Truck 5 F21 :   Power required 150.0 kW.
Truck 1 F23 :   Power required 150.0 kW.
Truck 3 F23 :   Power required 29.91 kW.
Truck 4 F23 :   Power required 150.0 kW.

Timestep: 372

Truck 3 F1 :    Power required 17.11 kW.
Truck 3 F2 :    Power required 46.64 kW.
Truck 3 F17 :   Power required 41.76 kW.
Truck 2 F19 :   Power required 26.0 kW.
Truck 2 F22 :   Power required 150.0 kW.
Truck 3 F22 :   Power required 150.0 kW.
Truck 2 F23 :   Power required 150.0 kW.
```

Power requirements in District B when five or more trucks are connected:

```
Timestep: 50

Truck 4 F5 :     Power required 150.0 kW.
Truck 1 F16 :    Power required 58.0 kW.
Truck 2 F21 :    Power required 65.79 kW.
Truck 2 F22 :    Power required 150.0 kW.
Truck 10 F24 :   Power required 7.71 kW.

Timestep: 54

Truck 2 F7 :     Power required 150.0 kW.
Truck 1 F16 :    Power required 58.0 kW.
Truck 2 F16 :    Power required 12.02 kW.
Truck 2 F22 :    Power required 78.82 kW.
Truck 2 F23 :    Power required 150.0 kW.

Timestep: 66

Truck 3 F6 :     Power required 150.0 kW.
Truck 1 F12 :    Power required 105.92 kW.
Truck 1 F16 :    Power required 44.43 kW.
Truck 2 F16 :    Power required 58.0 kW.
Truck 6 F25 :    Power required 67.93 kW.

Timestep: 74

Truck 2 F16 :    Power required 58.0 kW.
Truck 3 F21 :    Power required 150.0 kW.
Truck 2 F23 :    Power required 12.7 kW.
Truck 9 F25 :    Power required 150.0 kW.
Truck 10 F25 :   Power required 10.8 kW.

Timestep: 118

Truck 1 F13 :    Power required 82.66 kW.
Truck 1 F16 :    Power required 58.0 kW.
Truck 1 F22 :    Power required 72.59 kW.
Truck 3 F23 :    Power required 150.0 kW.
Truck 5 F23 :    Power required 25.29 kW.

Timestep: 130

Truck 3 F5 :     Power required 4.52 kW.
Truck 1 F6 :     Power required 150.0 kW.
Truck 1 F16 :    Power required 58.0 kW.
Truck 2 F22 :    Power required 55.48 kW.
Truck 2 F24 :    Power required 150.0 kW.

Timestep: 138

Truck 1 F10 :    Power required 150.0 kW.
Truck 1 F16 :    Power required 58.0 kW.
Truck 2 F16 :    Power required 58.0 kW.
Truck 1 F21 :    Power required 12.51 kW.
Truck 2 F21 :    Power required 150.0 kW.

Timestep: 141

Truck 1 F9 :     Power required 133.54 kW.
Truck 2 F21 :    Power required 70.65 kW.
Truck 1 F22 :    Power required 150.0 kW.
Truck 6 F24 :    Power required 70.62 kW.
Truck 7 F24 :    Power required 6.69 kW.

Timestep: 142

Truck 1 F9 :     Power required 150.0 kW.
Truck 1 F16 :    Power required 58.0 kW.
Truck 2 F16 :    Power required 58.0 kW.
Truck 3 F22 :    Power required 150.0 kW.
Truck 7 F24 :    Power required 12.4 kW.

Timestep: 146

Truck 4 F5 :     Power required 15.5 kW.
Truck 1 F16 :    Power required 58.0 kW.
Truck 2 F16 :    Power required 58.0 kW.
Truck 2 F22 :    Power required 150.0 kW.
Truck 1 F23 :    Power required 150.0 kW.

Timestep: 174

Truck 1 F14 :    Power required 15.21 kW.
Truck 2 F16 :    Power required 58.0 kW.
Truck 3 F21 :    Power required 150.0 kW.
Truck 3 F22 :    Power required 150.0 kW.
Truck 2 F23 :    Power required 74.15 kW.

Timestep: 229

Truck 1 F6 :     Power required 150.0 kW.
Truck 1 F21 :    Power required 150.0 kW.
Truck 2 F21 :    Power required 73.1 kW.
Truck 1 F23 :    Power required 39.37 kW.
Truck 2 F24 :    Power required 19.04 kW.

Timestep: 234

Truck 1 F10 :    Power required 42.98 kW.
Truck 1 F16 :    Power required 58.0 kW.
Truck 2 F16 :    Power required 58.0 kW.
Truck 2 F21 :    Power required 150.0 kW.
Truck 5 F24 :    Power required 119.53 kW.

Timestep: 246

Truck 2 F7 :     Power required 75.06 kW.
Truck 2 F13 :    Power required 150.0 kW.
Truck 1 F16 :    Power required 58.0 kW.
Truck 2 F16 :    Power required 58.0 kW.
Truck 1 F21 :    Power required 32.63 kW.

Timestep: 250

Truck 1 F16 :    Power required 58.0 kW.
Truck 2 F16 :    Power required 58.0 kW.
Truck 4 F22 :    Power required 150.0 kW.
Truck 1 F25 :    Power required 97.56 kW.
Truck 2 F25 :    Power required 67.93 kW.

Timestep: 254

Truck 2 F9 :     Power required 133.54 kW.
Truck 1 F16 :    Power required 58.0 kW.
Truck 2 F16 :    Power required 58.0 kW.
Truck 2 F22 :    Power required 123.96 kW.
Truck 4 F25 :    Power required 8.0 kW.

Timestep: 328

Truck 1 F8 :     Power required 48.14 kW.
Truck 2 F21 :    Power required 28.26 kW.
Truck 4 F23 :    Power required 55.11 kW.
Truck 4 F24 :    Power required 150.0 kW.
Truck 5 F24 :    Power required 150.0 kW.

Timestep: 350

Truck 2 F9 :     Power required 47.56 kW.
Truck 1 F16 :    Power required 58.0 kW.
Truck 2 F16 :    Power required 58.0 kW.
Truck 3 F25 :    Power required 67.93 kW.
Truck 4 F25 :    Power required 150.0 kW.

Timestep: 358

Truck 3 F7 :     Power required 133.54 kW.
Truck 1 F16 :    Power required 58.0 kW.
Truck 2 F16 :    Power required 58.0 kW.
Truck 2 F23 :    Power required 21.92 kW.
Truck 7 F25 :    Power required 50.38 kW.
Truck 8 F25 :    Power required 67.93 kW.

Timestep: 380

Truck 2 F14 :    Power required 15.21 kW.
Truck 1 F22 :    Power required 150.0 kW.
Truck 4 F22 :    Power required 41.77 kW.
Truck 5 F22 :    Power required 24.53 kW.
Truck 2 F23 :    Power required 150.0 kW.
```

Power requirements in District B when the maximum number of trucks requiring the Maximum charging power occurs:

```
Timestep: 9

Truck 4 F21 :    Power required 150.0 kW.
Truck 4 F22 :    Power required 150.0 kW.
Truck 5 F22 :    Power required 150.0 kW.
```

Appendix III: Charging Station Datasheets

Zhejiang Benyi New Energy Co.,Ltd. Model BDC 60-240

Zhejiang Benyi New Energy Co.,Ltd.
Price List (DC Chargers)

CB CE

No.	Item No.	Specification	FOB Ningbo	Picture for Reference	Delivery time	Warranty	Structure Description
1	BDC-60~240	**Rated Power :** 60kW/90kW/120kW/150kW/180kW/240kW **Output Connector:** 2 PLUGS (DC*2) (CCS1: 0~250A 150VDC-1000V) or (CCS2: 0~250A 150VDC-1000V) or (CHADEMO 0~125A 150VDC-500V) **Communiction:** OCPP 1.6J **Network:** Ethernet/4G **Application:** Indoor/Outdoor **Working Temperature:** -30℃~+55℃ **Protection Level:** IP55 **Cooling:** Automatic forced-air cooling **Standards:** IEC61851-1, IEC61851-23	**1~5pcs:** 60kW/$6270 90kW/$7920 120kW/$9130 150kW/$10230 180kW/$11330 240kW/$12650		**1-5pcs:**30 days **>5pcs:**40 days	**Standard Warranty:** 1 Year; √ Tech Support √ Installation Support √ Failure Replacement **Extended Warranty:** 5% of the original price for the second year 10% of the original price for the third year	**Enclosure:** Carbon Steel **Dimension:** 800*800*1800mm(L*W*T) **Net Weight:** ≥300kG **Installation:** Floor-Stand * **9.1inch LCD TouchScreen** * **Emergency Stop Button** * **LED indicator** * **5m cable length** * **2 RFID Cards**
2	BADC-82~262	**Rated Power :** 82kW/112kW/142kW/172kW/202kW/262kW **Output Connector:** 3 PLUGS (DC*2, AC*1) **DC*2:** (CCS1: 0~250A 150VDC-1000V) or (CCS2: 0~250A 150VDC-1000V) or (CHADEMO 0~125A 150VDC-500V) **AC*1:** (Type 2 : 0-32A 0-380 Vac) **Communiction:** OCPP 1.6J **Network:** Ethernet/4G **Application:** Indoor/Outdoor **Working Temperature:** -30℃~+55℃ **Protection Level:** IP55 **Cooling:** Automatic forced-air cooling **Standards:** IEC61851-1, IEC61851-23	**1~5pcs:** 82kW/$8690 112kW/$10120 142kW/$11110 172kW/$12210 202kW/$13310 262kW/$14630		**1-5pcs:**30 days **>5pcs:**40 days	**Standard Warranty:** 1 Year; √ Tech Support √ Installation Support √ Failure Replacement **Extended Warranty:** 5% of the original price for the second year 10% of the original price for the third year	**Enclosure:** Carbon Steel **Dimension:** 800*800*1800mm(L*W*T) **Net Weight:** ≥300kG **Installation:** Floor-Stand * **9.1inch LCD TouchScreen** * **Emergency Stop Button** * **LED indicator** * **5m cable length** * **2 RFID Cards**

PRODUCT LEAFLET

Electric Vehicle Infrastructure
Terra HP high power charging UL

ABB's Terra HP is a modular 175-350 kW ultra-fast EV charging system supporting all 150-920 VDC compatible vehicles. The Terra HP is ideally suited for highway corridor and EV fleet operations.

Modular architecture
ABB's Terra HP system can be configured as:
- 175 kW: one charge post and one cabinet
- 350 kW: one charge post and two cabinets
- 175-350 kW: two charge posts and two cabinets

Scalable and future-proof
The Terra HP system is expandable over time by adding additional power cabinets and charge posts after initial site installation. This capability delivers site planning flexibility by offering a cost-efficient way to build expandable charge points that can grow with EV market demand.

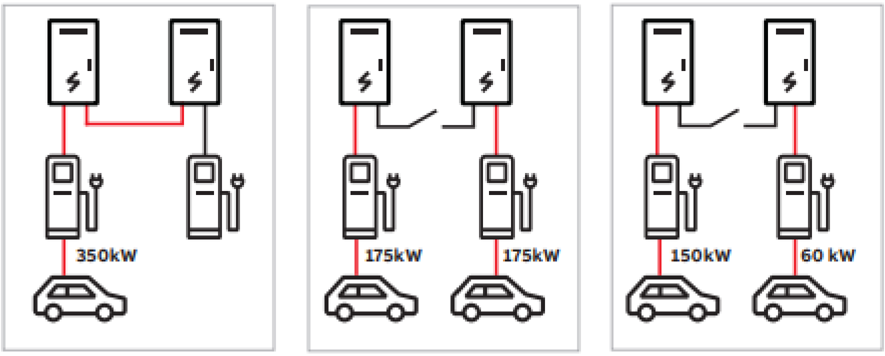
Dynamic DC capability
With ABB Dynamic DC power sharing technology, power cabinets can be connected to charge one vehicle at up to 350kW or two vehicles simultaneously at up to 175kW. This architecture enables higher utilization of charging assets.

Industry leading cable cooling technology
Every Terra HP charge post is equipped with an integrated chiller and environmentally-friendly cooled cables offering higher peak and continuous output power performance. This technology enables faster charging for vehicles where typical 200A rated systems cannot deliver above 80KW to 400V electric vehicles.

Dynamic DC illustrated

Dynamic DC utilization scenarios with varied vehicle demand profiles.

When one vehicle is fully charged, the power will be redistributed automatically.



Max charging dedicated to premium EV at up to 350kW on either charge post.

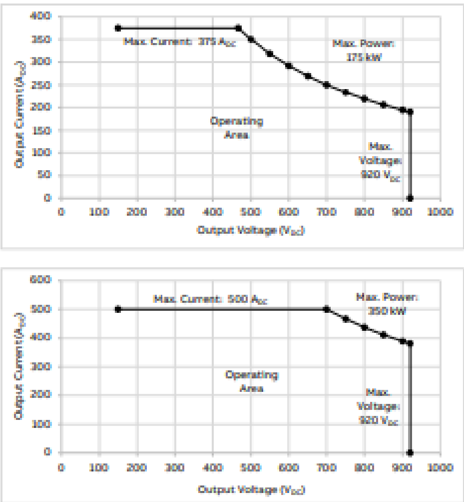
Shared power delivery for premium EV utilization at up to 175 kW to each vehicle.

Shared delivery tailored to varied EV model demands.

ABB Terra HP key features
- Non-refrigerant-based, cooled cable system
- Distance between power cabinet(s) and charge post(s) up to 60 m/200 ft
- Daylight readable, intuitive touchscreen display
- Integrated RGB LED strips with customizable color
- Energy management via OCPP Smart Charging Profile
- ADA compliant

ABB Terra HP optional features
- Dynamic DC functionality
- Customizable user interface
- Integrated payment terminal
- Buy America option available

Why charging operators prefer ABB
- ABB Ability Connected Services
  - Charger Connect: Easily connect chargers to OCPP back offices, over-the-air software updates
  - Charger Care: Remote diagnostics and resolution, manage service cases, notifications, data export
- ABB's decade of EV charging experience and close cooperation with EV OEMs, networks and fleets
- High volume, high OpEx production with a globally distributed manufacturing base
- Industry leading uptime with a global and local service presence



Terra HP 175 and Terra HP 350 output load and operational curves. De-rating characteristics apply.

Specifications	Terra HP 175	Terra HP 350
Electrical		
Max output power	175 kW peak 160 kW continuous	350 kW peak 320 kW continuous
AC input voltage range	UL: 3-phase, 480Y/277 V_{AC} +/- 10% (60 Hz) CSA: 3-phase, 600 V_{AC} +/-10% (60 Hz)	
AC input connection	L1, L2, L3, GND (no neutral)	
Nominal input current and input power rating	UL: 231 A, 192 kVA CSA: 185 A, 192 kVA	UL: 2x231 A, 384 kVA CSA: 370 A, 384 kVA
Recommended upstream circuit breaker(s)	UL: 1 x 300 A CSA: 1 x 250 A	UL: 2 x 300 A CSA: 2 x 250 A
Power Factor	≥ 0.97	
Current THD	IEEE 519 Compliant; <8%; option for 5%	
DC output voltage	150 – 920 VDC	
DC output current	375 A CCS-1 200 A CHAdeMO	500 A CCS-1 200 A CHAdeMO
Efficiency	95% at full load	
Interface and Control		
Charging protocols	CCS-1 and CHAdeMO	
User interface	7" high brightness full color touchscreen display Option for 15" display	
RFID system	ISO/IEC 14443A/B, ISO/IEC 15393, FeliCa™1, NFC, Mifare, Calypso (option: Legic)	
Network connection	GSM/3G/4G; 10/100 base-T Ethernet	
Communication	OCPP 1.5 and OCPP 1.6 enabled	
Support languages	English (others available on request)	
Environment		
Operating temperature	-35 °C to +55 °C (de-rating characteristics apply)	
Storage Temperature	-10 °C to +70 °C	
Protection	IP 54, outdoor use	
Humidity	5% to 95%	
Altitude	2000 m / 6560 ft	
General		
Charge cable	3.2 m (10 ft 6 in) CHAdeMO 3.2 m (10 ft 6 in) or 3.8 m (12 ft 6 in) for CCS-1	
Dimensions (H x W x D)	Power cabinet: 2030 x 1170 x 770 mm / 79.9 x 46.1 x 30.3 in Charge post: 2390 x 620 x 440 mm / 94 x 24.4 x 17.3 in	
Weight	Power cabinet: 1340 kg / 2954 lbs Charge post: 250 kg / 551 lbs	
Compliance and safety	UL/cUL UL 2202, NEC Article 625, EN 61851, EN 62196; CHAdeMO 1.2; DIN 70121, ISO 15118; IEC 61000-6-3 EMC Class B; BA Rule 49 CFR Part 661.5	

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4EVC700601-LFUS R5

Appendix IV: Economic Analysis Itemized

Stakeholder 1

- 35% Ownership of CI from District A
- 37 trucks
- 860,880 kWh recharged
- 1,199,640 km driven

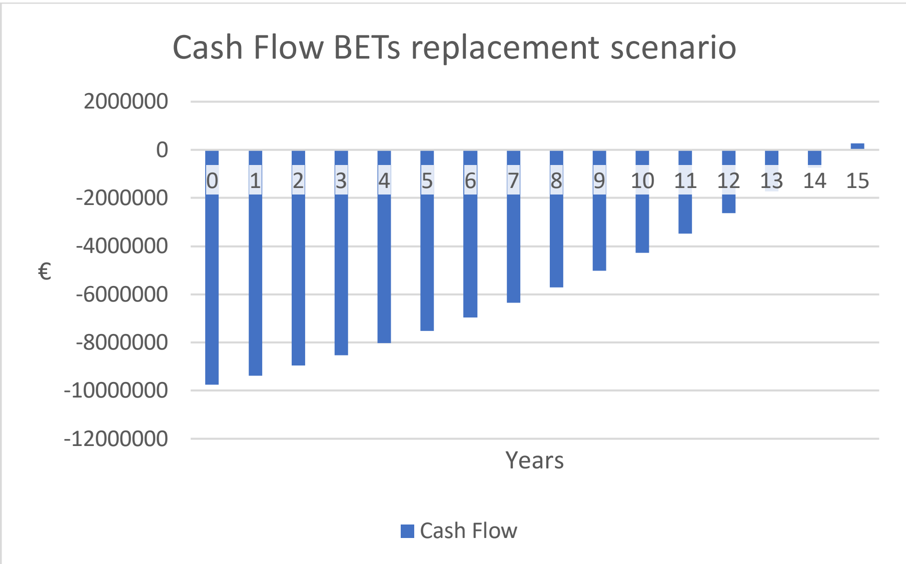
- Initial investment:

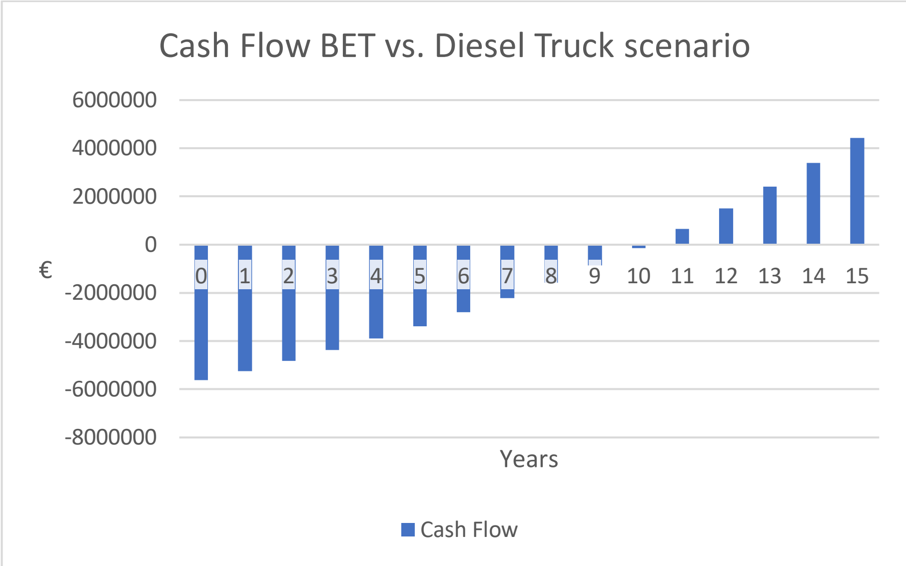
BETs replacement	Cost (€)	**BET vs. Diesel Truck**	Cost (€)
Charging Infrastructure	28,380	Charging Infrastructure	28,380
Truck Fleet	10,081,750	Extra BET Fleet Cost	5,937,750
Total	10,110,130	Total	5,966,130

- Operational costs and savings:

Item	**Electricity**	**Diesel**
Annual Consumption Cost (€)	177,606	412,942
Annual O&M cost (€)	840	115,165
Annual Savings from Electrification (€)	349,660	

- Cash flow evolution over the lifetime of the project:





- NPVs and IRRs in both scenarios:

BETs replacement	Value	**BET vs. Diesel Truck**	Value
NPV (€)	279,246	NPV (€)	4,423,245
IRR (%)	0.3	IRR (%)	6.9

Stakeholder 3

- 65% Ownership of CI from District A
- 35 trucks
- 2,660,554 kWh recharged
- 1,878,500 km driven

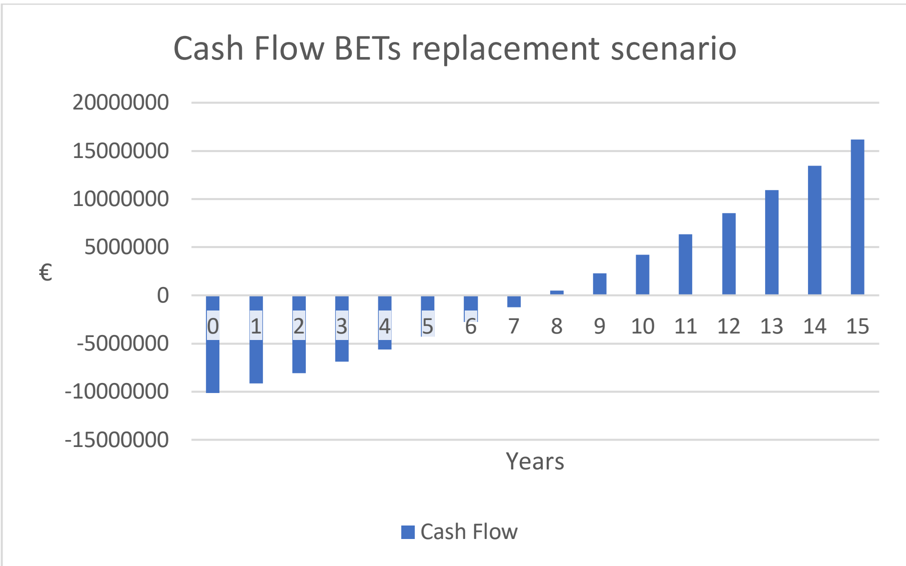
- Initial investment:

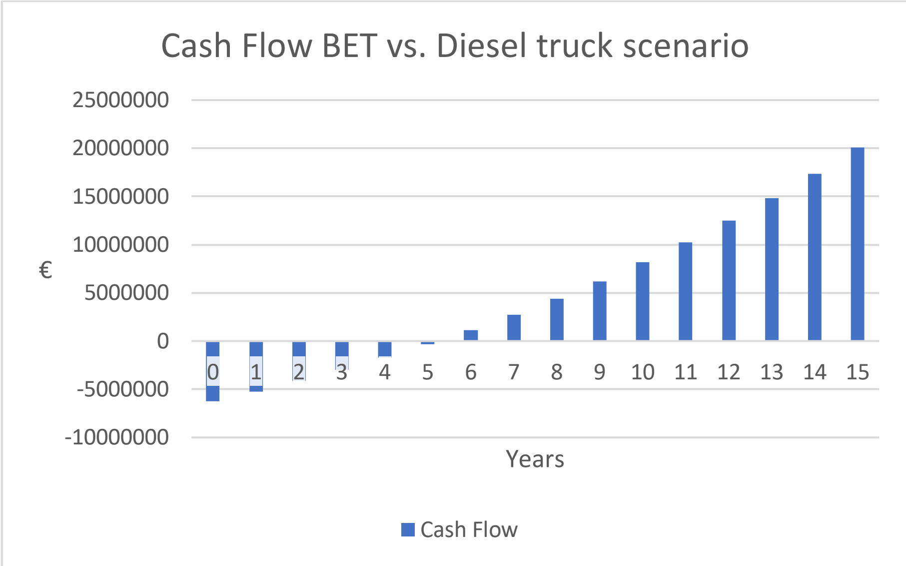
BETs replacement	Cost (€)	**BET vs. Diesel Truck**	Cost (€)
Charging Infrastructure	52,700	Charging Infrastructure	52,700
Truck Fleet	10,990,000	Extra BET Fleet Cost	7,070,000
Total	11,042,700	Total	7,122,700

- Operational costs and savings:

Item	**Electricity**	**Diesel**
Annual Consumption Cost (€)	544,474	1,276,197
Annual O&M cost (€)	1,560	180,336
Annual Savings from Electrification (€)	910,500	

- Cash flow evolution over the lifetime of the project:





- NPVs and IRRs in both scenarios:

BETs replacement	Value	**BET vs. Diesel Truck**	Value
NPV (€)	16,148,015	NPV (€)	20,068,015
IRR (%)	12.3	IRR (%)	21.0

Stakeholder 2

- 0% Ownership of CI from District B
- 2 trucks
- 90,480 kWh recharged
- 74,880 km driven

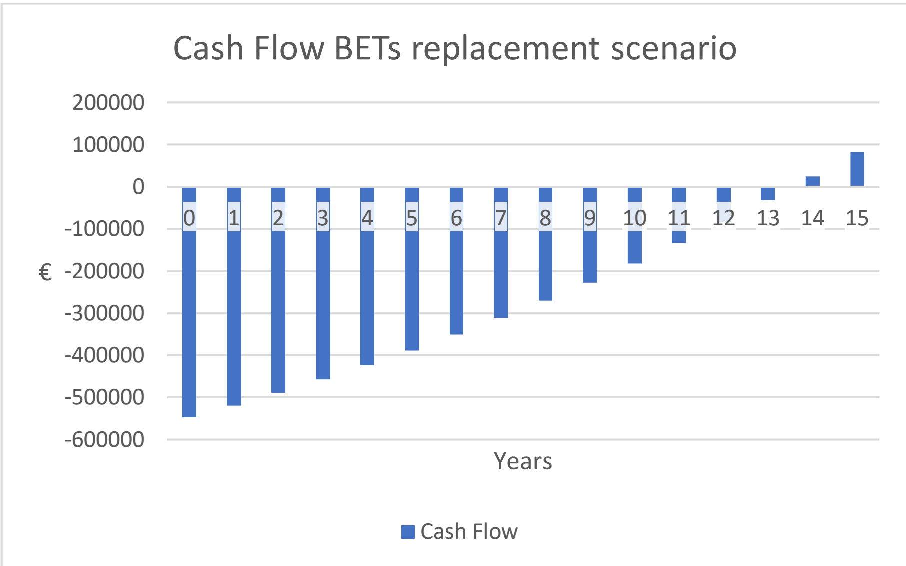
- Initial investment:

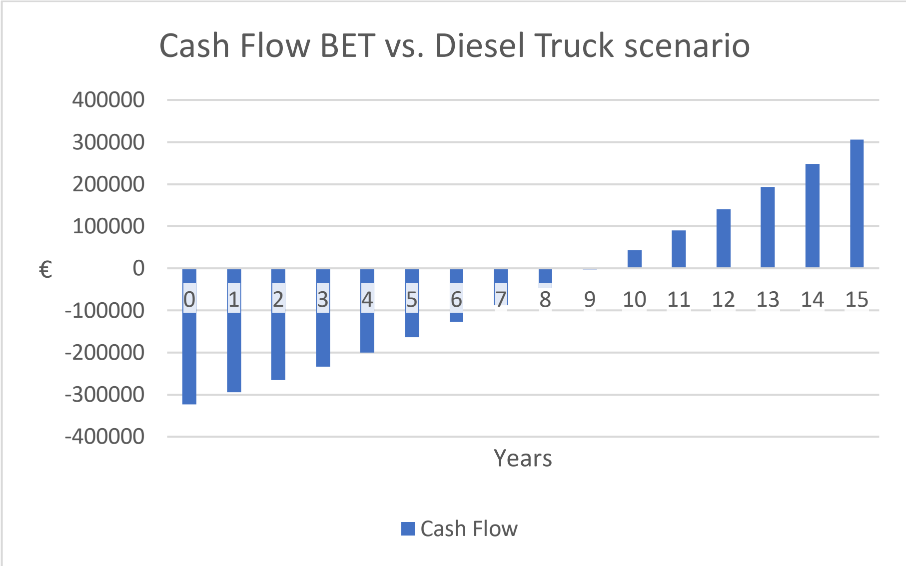
BETs replacement	Cost (€)	**BET vs. Diesel Truck**	Cost (€)
Charging Infrastructure	-	Charging Infrastructure	-
Truck Fleet	574,000	Extra BET Fleet Cost	350,000
Total	574,000	Total	350,000

- Operational costs and savings:

Item	**Electricity**	**Diesel**
Annual Consumption Cost (€)	23,810	43,400
Annual O&M cost (€)	0	7,188
Annual Savings from Electrification (€)	26,780	

- Cash flow evolution over the lifetime of the project:





- NPVs and IRRs in both scenarios:

BETs replacement	Value	**BET vs. Diesel Truck**	Value
NPV (€)	82,102	NPV (€)	306,102
IRR (%)	1.6	IRR (%)	8.5

Stakeholder 4

- 0% Ownership of CI from District B
- 20 trucks
- 283,314 kWh recharged
- 312,000 km driven

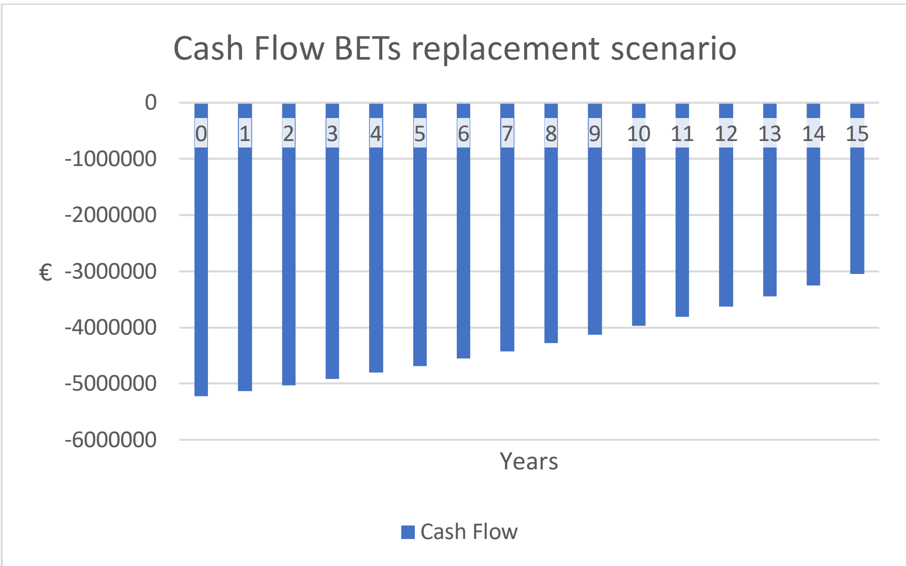
- Initial investment:

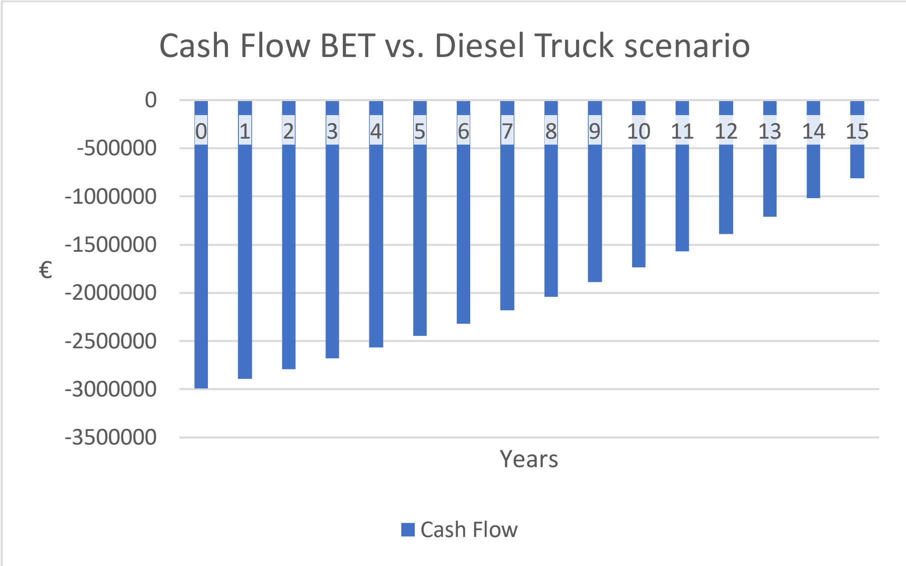
BETs replacement	Cost (€)	**BET vs. Diesel Truck**	Cost (€)
Charging Infrastructure	-	Charging Infrastructure	-
Truck Fleet	5,320,000	Extra BET Fleet Cost	3,080,000
Total	5,320,000	Total	3,080,000

- Operational costs and savings:

Item	**Electricity**	**Diesel**
Annual Consumption Cost (€)	74,555	135,900
Annual O&M cost (€)	0	29,952
Annual Savings from Electrification (€)	91,280	

- Cash flow evolution over the lifetime of the project:





- NPVs and IRRs in both scenarios:

BETs replacement	Value	**BET vs. Diesel Truck**	Value
NPV (€)	-3,053,080	NPV (€)	-813,080
IRR (%)	-8.6	IRR (%)	-3.4

Charging Point Operator (CPO)

- 100% Ownership of CI from District B
- 1,911,730 kWh sold

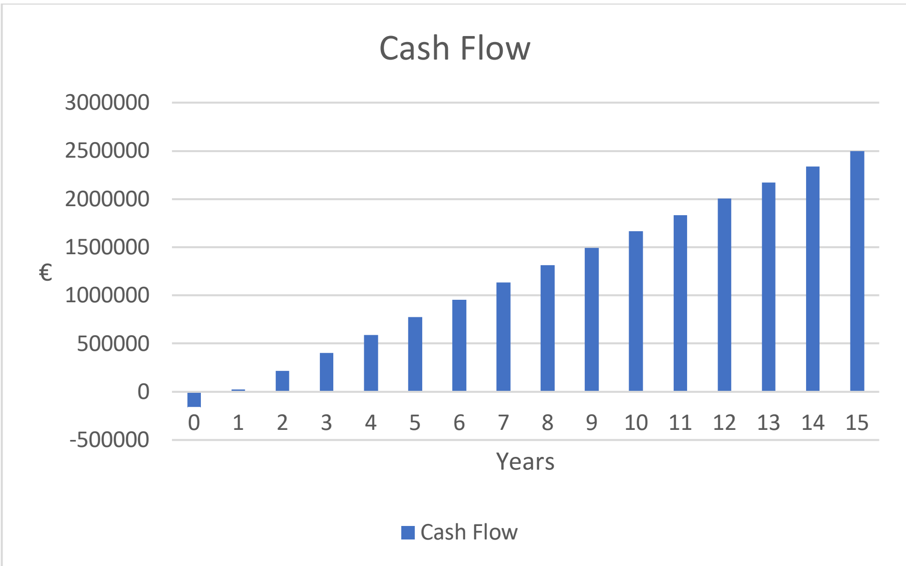
- Initial investment and operational costs and savings:

Item	**CI**
Initial investment (€)	359,470
Annual Electricity Sale (kWh)	1,911,730
Annual O&M cost (€)	2,700
Annual benefits from electricity sold (€)	194,510

- Cash flow evolution over the lifetime of the project:

Item	Value
NPV (€)	2,500,000
IRR (%)	116%

- NPV and IRR:



Appendix V: Optimization model applications

This appendix shows the different applications the OM can offer the user, in this case, the stakeholders of the project. This will allow them to modify the data and try to analyze different operational behaviors or technical characteristics of their truck fleet. Following, four types of applications are presented.

Variation of truck itineraries

The Questionnaire for truck operators has been designed to collect the data in the most accurate way while keeping it as simple as possible to fill out. However, the simplest version of it does not explicitly define the itineraries of trucks. Therefore, it has been decided to implement a section of the OM that randomly defines arrivals to the facilities (availability to charge) as well as the duration of the stay. In this sense, the model generates different itineraries, and it is possible to identify worse scenarios and design a CI capable of dealing with them.

The purpose of this subsection is to analyze the variation in power demand due to a variation of itineraries. So, in this case, the sample of trucks will also consider external flows and decision inputs are:

- *Number of trucks*: 37
- *Number of CS*: 1
- *Initial state of the battery*: 50%
- *Minimum SOC*: 10%
- *Battery oversize factor*: 1

The next figures show the charging profile of the different randomly generated itineraries. The maximum power requirements are 205.11 kW for Figure 56, 274.25 kW for Figure 57, and 223.24 kW for Figure 58.

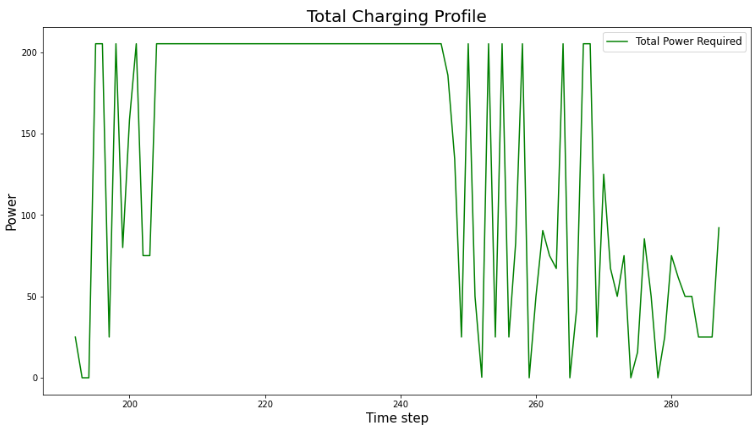


Figure 56. Charging profile of all trucks for one day. Random itineraries A.

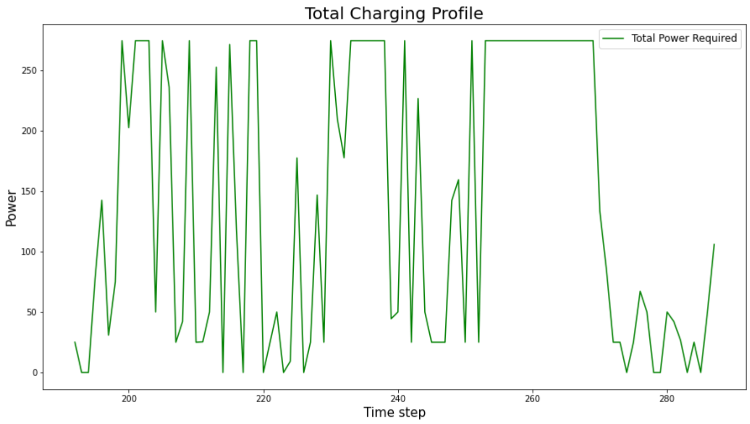


Figure 57. Charging profile of all trucks for one day. Random itineraries B.

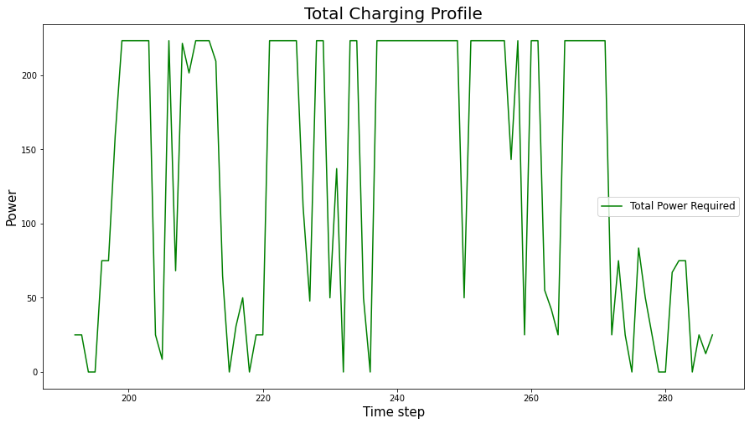


Figure 58. Charging profile of all trucks for one day. Random itineraries C.

As can clearly be seen, the peak powers, as well as the demand along the day, fluctuates differently. Peak power has seen an increase of 69.14 kW from case A to case B. This application of the OM shows the high relevance of a proper definition of truck itineraries. However, if that information could not be properly collected, the model still provides an alternative to analyzing the operation of the whole truck fleet under different itineraries, allowing to identify worst-case scenarios and to design a CI capable of supplying the energy needed even under these conditions.

Example case

In this section, the results from optimizing the charging schedule of a sample of trucks for a given day are shown. Once the system is optimized and the code has proven its feasibility, all the data is organized into two principal dataframes, which are used to display all the data. The first dataframe collects the charging power registered per truck every 15 minutes, and the second dataframe collects the energy level of each of the batteries of the trucks throughout the time studied.

Following with the example case, it is important to notice that this is just a mere example to make clearer which is the functioning of the OM. In this example case, the sample and decision inputs are:

- *Number of trucks*: 14
- *Number of CS*: 1
- *Initial state of the battery*: 50%
- *Minimum SOC*: 10%

- *Battery oversize factor*: 1
- *Maximum charging rate*: Optimized by the model.

Once the system has been optimized, the maximum power output requested by the CS is 37.47 kW, and it is kept constant throughout the day, as can be seen in Figure 59. Although this might seem too ideal, it has to be noticed that the model is just taking the constraints given by decisions, and it shows that if a smart charging strategy is used, it is possible to decrease the peak power down to 37.47 kW. However, as will be shown in section *5.2 Charging profile at a district level*, due to more time limitations, more trucks, and more CSs, the final charging schedule is far from constant, and the power outputs of the different CSs are above the maximum peak power to guarantee complete charging at all times.

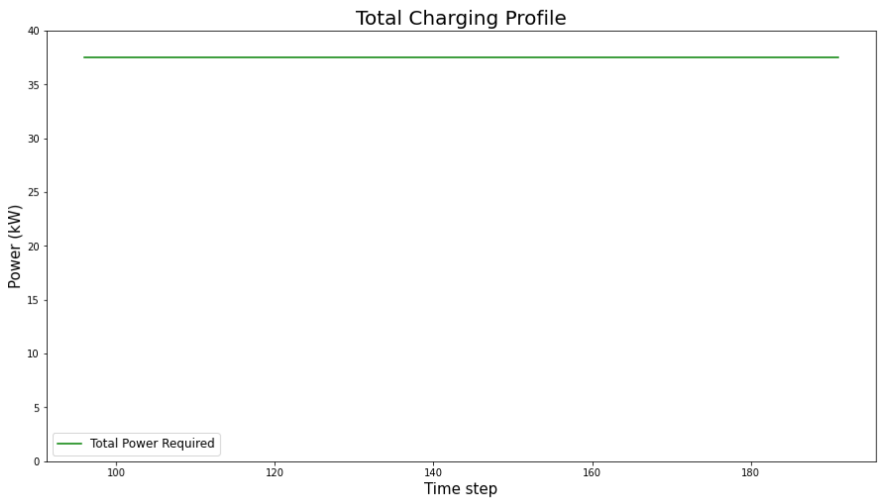


Figure 59. Charging profile of all trucks for one day. Example case.

As can be seen by its flat shape, although trucks are connected and disconnected throughout the day, they keep the same power requirement. This can be seen clearer in Figure 60, which shows the power required per truck during the middle hours of the day.

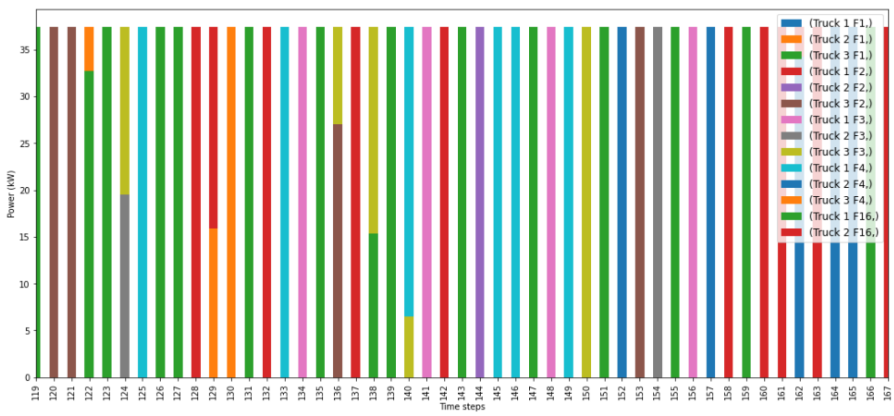


Figure 60. Power required per truck during the middle hours of the day. Example case.

As can be noticed, most of the timesteps show that only one truck is connected at a time, but there are other cases where more than one truck is connected, still keeping the power at a constant level. In fact, for this sample of trucks throughout the week, 82.5% of the time there is one truck connected, 13.3% two, 3.12% none, and 1.04% three. Next, Figure 61 shows the number of trucks connected at each timestep for the day studied.

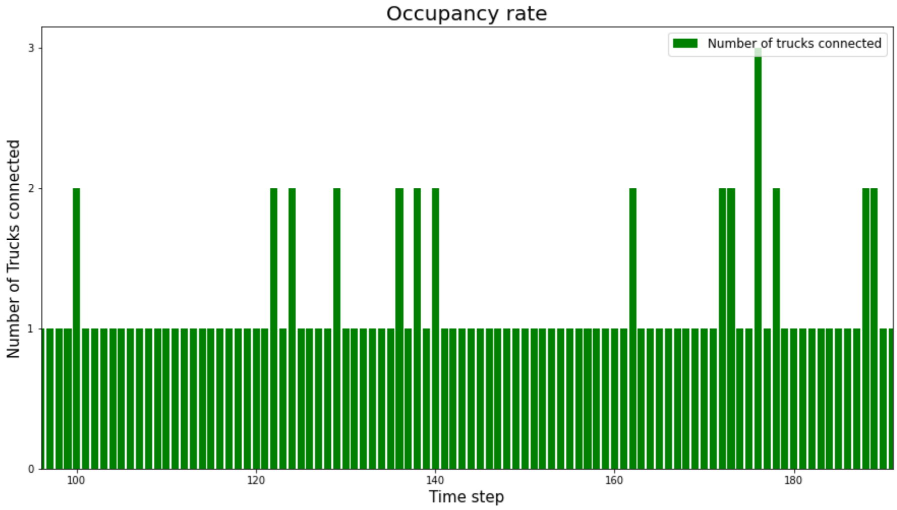


Figure 61. Occupancy rate of the trucks for one day. Example case.

Now, to get a more detailed view and to see clearly how each truck interacts with the CS, three charging profiles of trucks are shown in the next three graphs. The first graph shows the power required, the second graph shows the energy level of the battery, and the third graph shows the State of Charge (SOC).

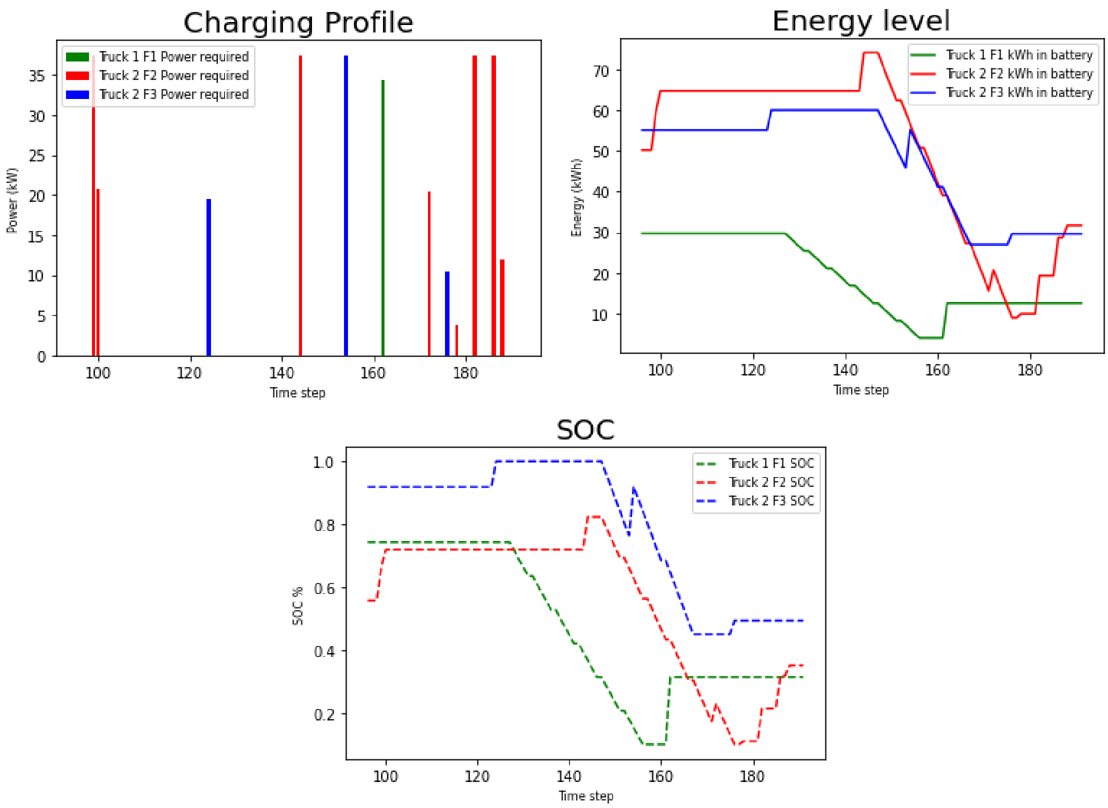


Figure 62. Graphs of charging profiles for individual trucks for one day. Example case.

Next, several case scenarios are going to be shown to understand the different applications of the OM.

Variation of battery sizes

In this subsection, the effect of varying battery sizes will be explained. Increasing battery sizes help the system to be able to scatter the charging over a wider time range, lowering the peak power required. On the other hand, smaller battery sizes will require more frequent charging. Since the battery cannot store as much energy as before, it should be charged to prevent it from deep discharging. This part of the OM allows to look at the balance between increasing battery size and reducing peak power. This is an important balance since, as has been explained previously, lower peak power requirements will usually mean lower electricity prices, thanks to not exceeding the power tariff or lower power tariffs. However, the price of increasing the battery capacity might be higher than the savings produced by reducing the peak power, which will negatively affect the feasibility of the project. Therefore, it is crucial to identify which is the most optimal balance between increasing battery size and reducing peak power.

Now, moving into the analysis with the same truck fleet and decision inputs as before, it is only necessary to change the *Battery oversize factor* for replicating two cases:

- *Battery oversize factor A*: 2
- *Battery oversize factor B*: 0.5

First, for *Battery oversize factor A*, which means that the trucks will have a battery able to store double the energy, the peak power registered is 33.24 kW. As expected, the increase in battery size has allowed for lower peak power in comparison with the Example case, which is 4.23 kW higher. Nevertheless, this case is likely to bring down the feasibility since the reduction in peak power is low in comparison to the increase in battery size. Therefore, the larger initial investment will be higher than the savings produced by the decrease in peak power.

As can be seen in Figure 64, the power demand throughout the day remains flat, although slightly lower. In Figure 64 and Figure 65, it can also be seen that even though the demand profile is identical to the Example case, now the number of trucks connected at the same time has slightly decreased.

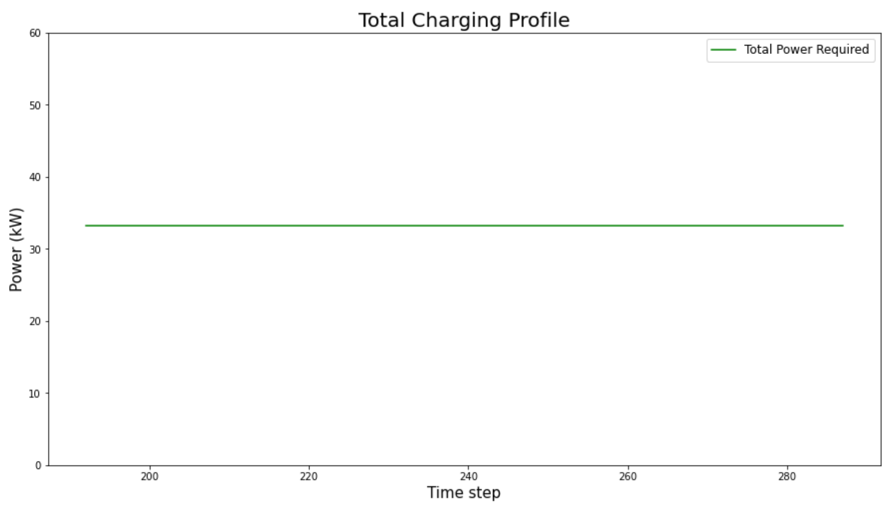


Figure 63. Charging profile of all trucks for one day. Battery oversize factor A.

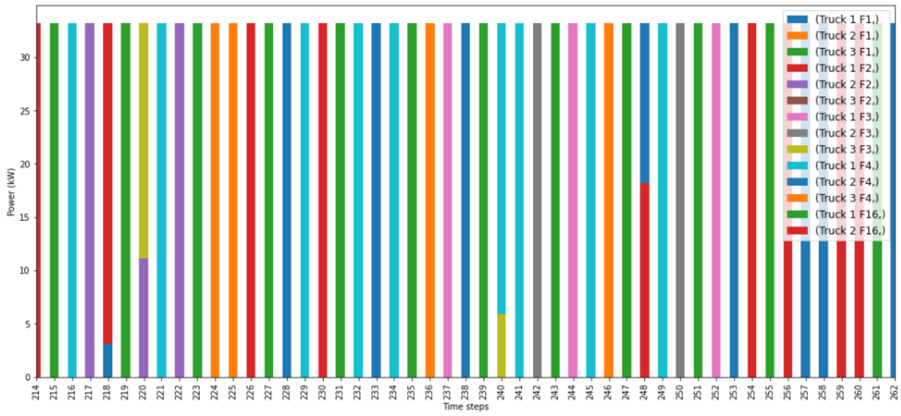


Figure 64. Power required per truck during the middle hours of the day. Battery oversize factor A.

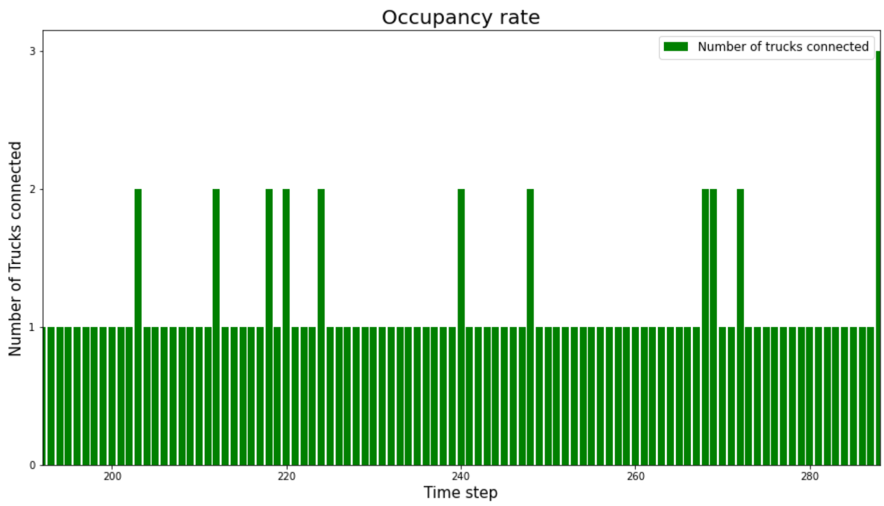


Figure 65. Occupancy rate of the trucks for one day. Battery oversize factor A.

Finally, when looking at individual power demands of trucks, it is possible to identify trucks that are not charged at any time during complete days.

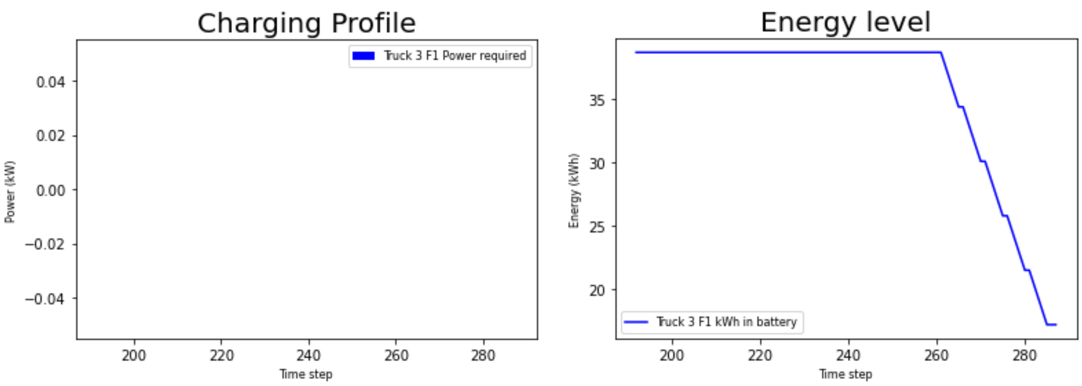


Figure 66. Graphs of charging profiles for a truck during one day. Battery oversize factor A.

For *Battery oversize factor B,* which means that the trucks will have a battery able to store half the energy, the peak power required by the truck fleet is 47.84 kW. This power is 14.6 kW higher than *Battery oversize factor B* and 10.37 kW higher than the Example case. Just in the same way as in the case of *Battery oversize factor B,* it will be necessary to determine if the reduction in initial investment of the battery compensates for the increase in electricity prices. Another aspect to bear in mind when reducing battery sizes is that it is highly likely that the charging strategy will become more complex since trucks will have to charge more often.

In Figure 67 and Figure 68, it can be seen that the charging profile is not flat anymore. Now, at some point, due to the smaller batteries, trucks have a higher power requirement (47.84 kW) which sets the minimum peak power possible. Since it is impossible to reduce that power requirement and with no *Maximum charging power* limit, the OM uses this peak power to charge all the trucks, creating intermittency in the energy supply.

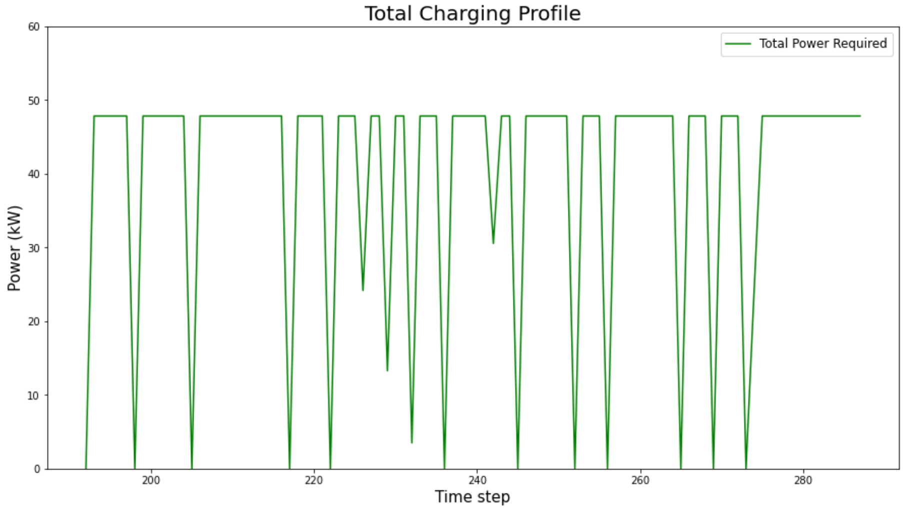


Figure 67. Charging profile of all trucks for one day. Battery oversize factor B.

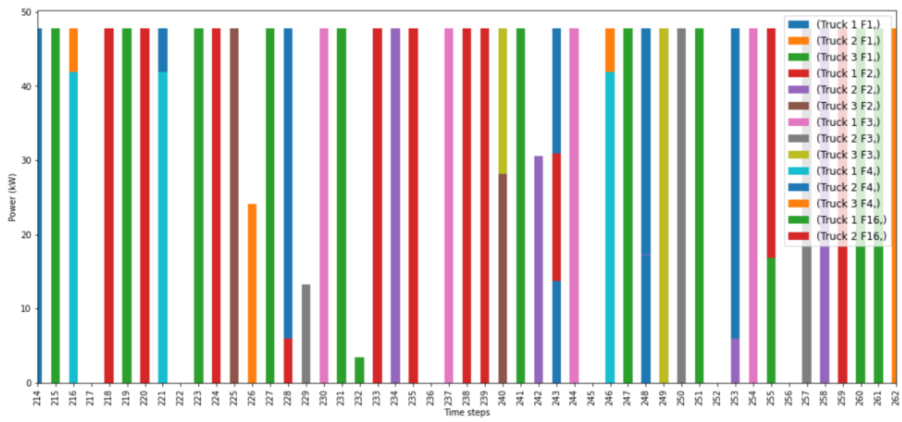


Figure 68. Power required per truck during the middle hours of the day. Battery oversize factor B.

When looking at the occupancy rate in Figure 69, the number of timesteps when only one truck was connected has been reduced (58.1% of the time) in comparison to the previous cases. This is due to lower battery sizes, which require charging more frequently, and due to a higher power output, which allows trucks to charge faster, leaving more timesteps with no trucks connected.

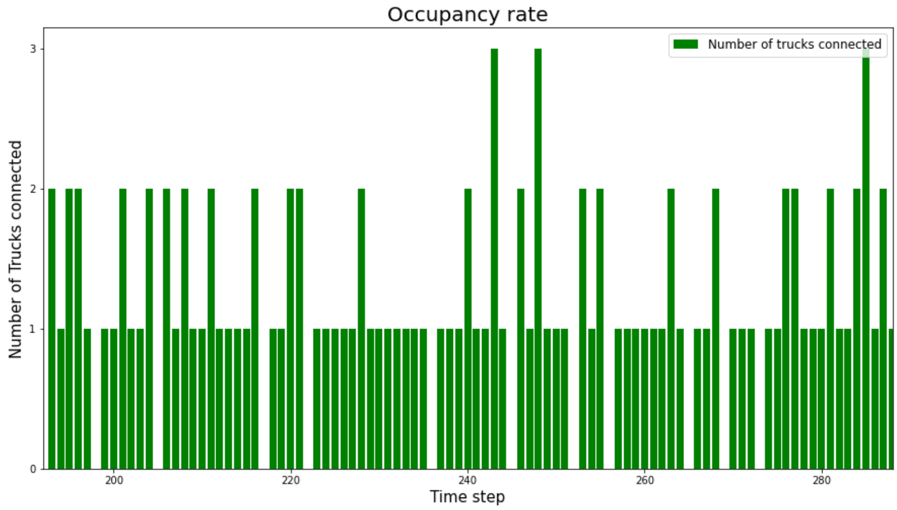


Figure 69. Occupancy rate of the trucks for one day. Battery oversize factor B.

Finally, looking again at the same power demand of the truck from Figure 66 it is clearly visible that, while in the case of doubling the energy stored in the battery there was no need for charging along the day, now, with a smaller battery size it is necessary to charge.

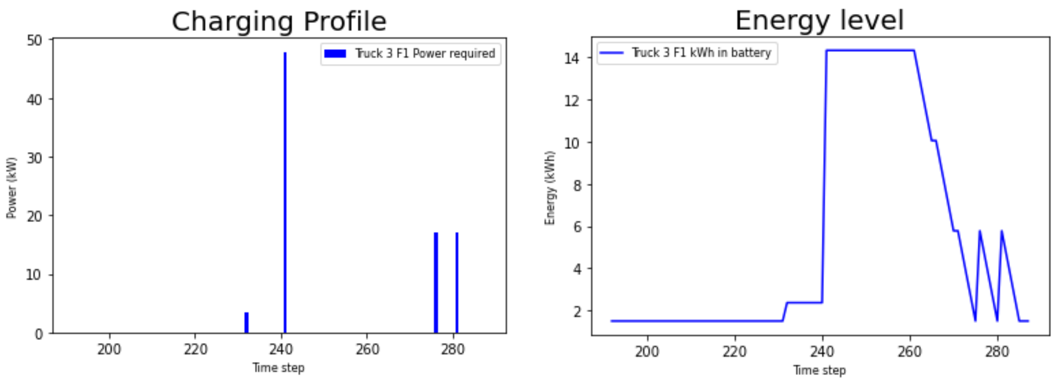


Figure 70. Graphs of charging profiles for a truck during one day. Battery oversize factor B.

So, using this tool of the OM, it is possible to study different alternatives for the truck fleet as well as for the CI. In this sense, it is interesting to analyze the relationship between the variation of initial investment (due to battery size) and the variation of operational costs (due to electricity prices).

Following in the next subsection, another example of the performance of the OM will be shown in order to understand its usefulness and the benefits that it offers with respect to uncontrolled charging. In this case, the results obtained from the previous section are going to be compared with a non-smart charging strategy.

BAU vs. Optimization Model

For this case example, the results from the *Example Case* are going to be compared with a charging method similar to conventional charging or Business As Usual (BAU). Nowadays, conventional charging is done by charging the battery whenever it goes to low energy levels. In this case, based on the results from the example case, it has been decided to provide several CSs of 40 kW for the same truck fleet as before. However, now truck drivers will only charge their batteries if their level is below

40% SOC and they have enough time to fully charge them, so they will charge the batteries to their full level.

The purpose is to compare both strategies in order to see which is the difference between charging profiles. So, the sample and decision inputs are:

- *Number of trucks*: 14
- *Number of CS*: 14
- *Initial state of the battery*: 50%
- *Minimum SOC*: 10%
- *Charging starts at*: SOC < 40%
- *Battery oversize factor*: 1
- *Maximum charging rate*: 40 kW per CS.

As seen in Figure 71, when the charging is not optimized, the overall peak power registered is much greater than before, reaching up to 200 kW, which is five times more than if the charging is optimized. On the other hand, even though more charging stations are available with higher global power output, the optimized charging strategy still designs a strategy to keep the power requirement at the same level as before.

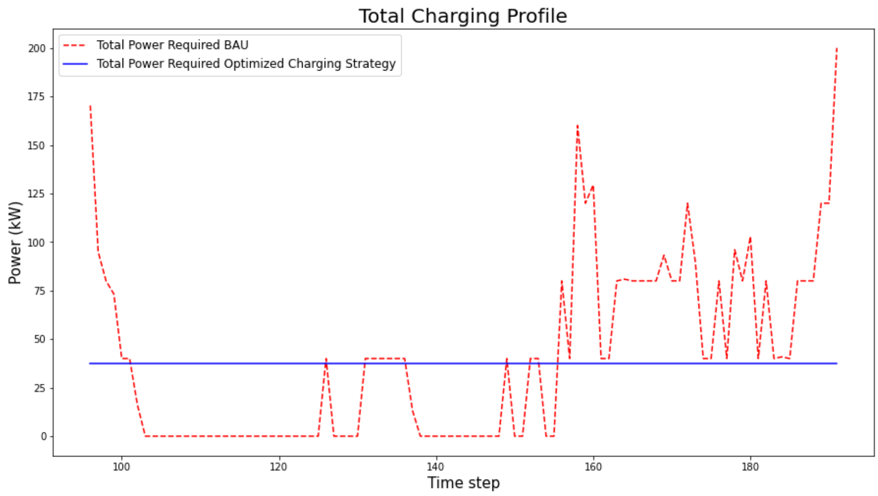


Figure 71. Charging Profiles with smart charging strategy and BAU.

Such high power peaks can be detrimental to the distribution lines. Besides, these power peaks can lead to an increase in the charging costs due to exceeding the power tariff. Additionally, it is important to note that only 14 trucks have been considered in this analysis, but this will be much worse when the whole truck fleet of Oskarshamn is considered, which can lead to cable lines overloading, exceeding transformer capacities, and, in the worst case, blackouts. The next two figures represent the power required per truck for one day and the occupancy rate of CSs for the whole week, both under the BAU charging schedule.

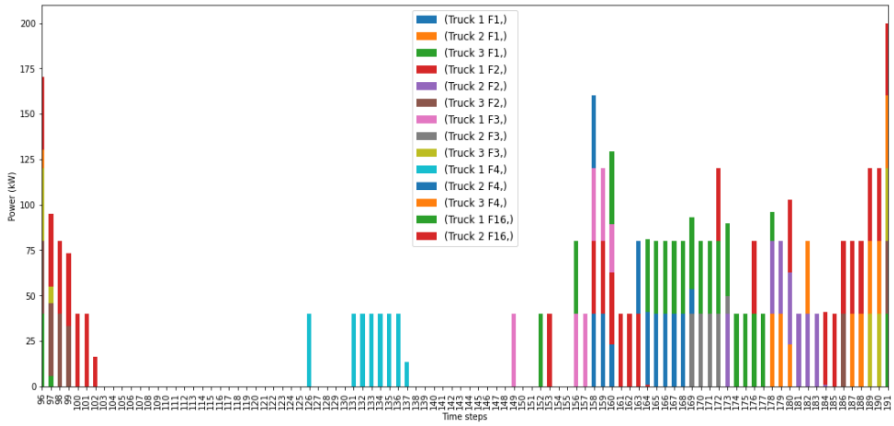


Figure 72. Power required per truck for one day. BAU scenario.

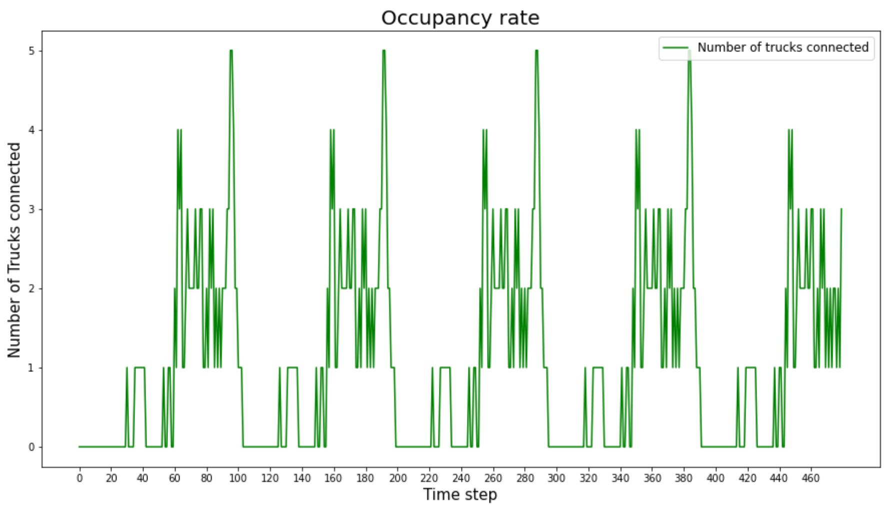


Figure 73. Occupancy rate throughout the week. BAU scenario.

Finally, in the same way as previously, the charging profiles of three trucks are shown in the next three graphs. As can be clearly seen in the first graph, the overlapping in charging schedules makes the peak power skyrocket.

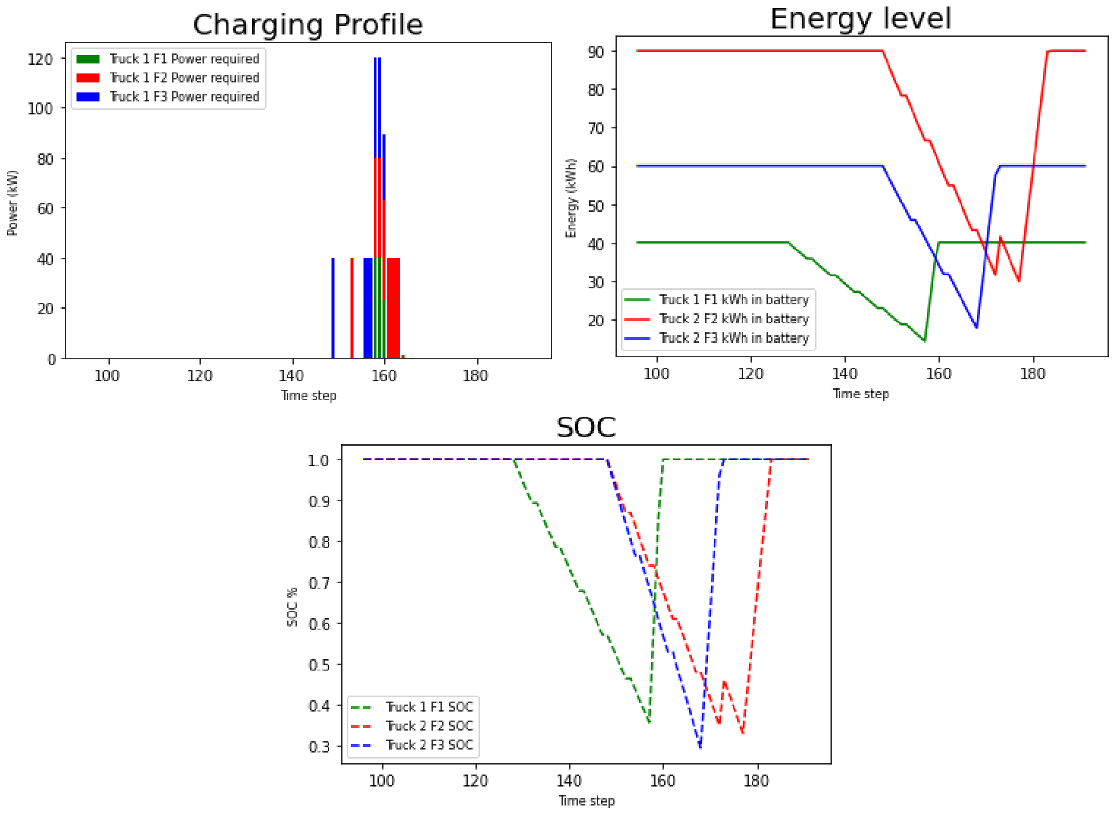


Figure 74. Graphs of BAU charging profiles for individual trucks for one day.

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