



**CHALMERS**  
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# **Electrifying Logstacker Operations**

A Site-Level Assessment of Charging Infrastructure Needs and Energy-System Impacts

Master's thesis in Sustainable Energy Systems

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**DEPARTMENT OF ELECTRICAL ENGINEERING**

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CHALMERS UNIVERSITY OF TECHNOLOGY

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MASTER'S THESIS 2026

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## **Abstract**

This thesis investigates the electrification potential of logstacker operations at a pulp mill, with a focus on charging infrastructure requirements and impacts on the local energy system. Using driving data from a plug-in hybrid logstacker, the study analyses daily energy demand, parking patterns, and charging opportunities to evaluate how different charging configurations can support increased electric operation. A simulation model was developed to assess charging performance under different charger configurations and charging strategies. The results show that installing a charger in a strategically selected location to allow for opportunity charging can substantially increase the share of electric operation and reduce diesel consumption. For a single logstacker, the share of electric operation increased from 54% to between 70% and 87% under the simplest charging strategy, depending on charger capacity. When multiple logstackers were included, charging contention reduced performance under simpler strategies, but cooperative fleet charging was able to mitigate these effects. The study also shows that charging demand creates short peak loads on the site's electrical system. Overall, the findings indicate that electrification of heavy material handling equipment offers strong potential for emission reductions, but successful implementation depends on suitable charging infrastructure, operational coordination, and integration with the site's energy system.

Keywords: electrification, logstacker, plug-in hybrid vehicle, material handling, charging infrastructure, energy system



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Edvin Rehult, Gothenburg, June 2026



# List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Alternating current
BEV	Battery electric vehicle
CFC	Cooperative fleet charging
CO <sub>2</sub>	Carbon dioxide
DC	Direct current
ECU	Engine control unit
FCFS	First come, first served
GHG	Greenhouse gas
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
LHV	Lower heating value
LSF	Lowest SOC first
NO <sub>x</sub>	Nitrous oxides
PHEV	Plug-in hybrid electric vehicle
REX	Range extender
SOC	State of charge



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# 1

## Introduction

As the need for decarbonisation has become more and more evident, many sectors have made and are making great efforts to reduce their emissions. One of these sectors is material handling which often relies on heavy machinery and equipment that emits large amounts of carbon dioxide and other greenhouse gases. One way in which emissions from material handling may be reduced is through electrification of the material handling fleet.

### 1.1 Background

Emissions from the transport sector has been growing substantially since 1990. From 1990 to 2019, greenhouse gas (GHG) emissions from the transport sector increased by 74% and in 2019 the transport sector accounted for 23% of the global energy-related CO<sub>2</sub> emissions and 15% of the total GHG emissions. If nothing is done, scenarios from both top-down and bottom-up models project that CO<sub>2</sub> emissions from transport may increase by up to 50% by 2050 due to increased demand for freight and passenger transport. Reducing carbon emissions is crucial to meeting temperature goals, and one pathway to reducing emissions is through electrification of transport, supported by low-carbon electricity. Battery electric vehicles and plug-in hybrid vehicles not only exhibit lower lifecycle GHG emissions than internal combustion engine vehicles; they may also be able to support grid operations and further reduce emissions through services such as vehicle-to-grid [3].

In the European Union, heavy-duty vehicles only comprise roughly 4% of the share of vehicles. However, despite the low number of vehicles they contribute approximately 26% and 40% of the total emissions of CO<sub>2</sub> and NO<sub>x</sub>, respectively, in the region. In addition to the environmental effects of the emissions, they also pose several negative local effects regarding public health [11]. The transport sector is a major contributor to environmental noise and particulate air pollution which increases the risk for cardiovascular and respiratory diseases, among other things [10].

While electrification of material handling is relevant across a wide range of industrial applications, its impact is particularly pronounced in environments where heavy machinery operates continuously in close proximity to industrial processes and personnel. In such settings, emissions and noise from diesel powered equipment contribute not only to global climate impacts but also to local air pollution and degraded working conditions. Electrification therefore offers the potential to improve the local environment by reducing exhaust emissions and noise levels.

### 1.2 Aim

The aim of this project is to investigate how an electrified material handling fleet may integrate with a site's energy system. This will be done by studying a plug-in hybrid logstacker at Östrand pulp mill in northern Sweden to understand how logstackers are utilised at an industrial site and how they can contribute to saving energy and lowering emissions. Furthermore, the study shall include an analysis of how plug-in hybrid logstackers affect the surrounding energy system. The project intends to answer questions such as:

- What is the daily energy demand from a plug-in hybrid logstacker and what impact does it impose on the site's energy system?
- What charging infrastructure may be installed to support different levels of electric operation and what impact does it impose on the site's energy system?
- How does the replacement of up to three conventional logstackers with plug-in hybrid logstackers affect the site's energy system, and what challenges and opportunities does this introduce?

### 1.3 Limitations

Limitations for this project include:

- Dimensioning of drivelines is not considered and no modifications to existing vehicles or driving patterns will be examined.
- Technical construction of components and equipment such as charging infrastructure and other utilities will not be evaluated.
- Only electrification of logstackers will be considered; no other vehicles within the site's material handling fleet will be considered in this project.
- Vehicle-data in this project will come from measurements from an EdiLog truck operating on the site in question. Up to three logstackers may operate simultaneously on the site but because they have similar driving cycles and operate in the same area conducting the same tasks, data from only one vehicle will be used to identify driving cycles that applies for the other logstackers also. In addition to the three logstackers operating on the site, a fourth logstacker is available as a backup if one logstacker has to be taken out of service.
- Only energy flows associated with the logstackers will be included in the site-level analysis.

### 1.4 Studied Vehicle

The vehicle studied in this project is a plug-in hybrid logstacker that has an internal combustion engine (ICE) operating on diesel that functions as a range extender (see section 2.1). The logstacker has an electrical traction motor that is solely used for traction, propelling the vehicle, and is supplied with energy from the battery. The battery has a capacity of 300 kWh and a C-rate of 0.5. The battery may be charged either through charging from the grid, charging from the generator being supplied by the ICE, or from regenerative braking. The logstacker uses an hydraulic log

grapple mounted on a telescopic boom and is capable of lifting around 30 tonnes in one grapple. The logstacker has a distribution gearbox that allows the logstacker's hydraulic pumps to be supplied both from the ICE or by using the generator as an electric motor. The logstacker weighs around 90 tonnes and has a top speed of 24 km/h.

## 1.5 Studied Site

The site relevant for this study is Östrand pulp mill in Timrå, Sweden. The pulp mill receives timber in three ways: by train, by road, and by sea, with the majority of timber arriving by train. Timber arriving with a train is unloaded by logstackers that move along the train and unload the carts. For timber arriving with trucks, the trucks park in a designated spot where a logstacker unloads them. Timber arriving by sea is not directly handled by a logstacker. Instead the timber is unloaded from the ships using cranes in the dock and loaded onto trailers pulled by wheel loaders. The trailers are then transported from the dock to the unloading area used for trucks, where they are unloaded by a logstacker. Note that logstackers do not operate directly at the dock, and whilst the cranes and wheel loaders are a part of the material handling fleet, they are excluded from this study.

The existing fleet of logstackers consists of three conventional diesel-powered logstackers and one plug-in hybrid logstacker. There may be up to three logstackers operating simultaneously on the site and an additional logstacker standing by if one has to be taken out of service. Currently, there is one 150 kW charger installed on the site that is fed by an 800 kVA transformer. Unloaded timber is either fed directly into the mill via two conveyor belts or placed in an intermediate storage area. This intermediate storage serves both as a buffer when the conveyor belts are full and as temporary storage during periods between deliveries. During normal operations, at least one logstacker must always be operating to make sure the pulp mill is continuously fed with timber.

Preliminary site observations indicate that charging behaviour is influenced by operational convenience and charger placement. In practice, operators do not always utilise the existing charger during shorter stops, as it is located some distance from commonly used areas such as the garage and break rooms. Instead, vehicles are often parked closer to these locations. Thus it is important to consider both infrastructure placement and operational patterns when evaluating electrification strategies.

Östrand pulp mill is currently self-sufficient in both electricity and heat, which are produced as by-products of the pulping process. The site generates approximately 1 TWh of electricity annually, and any surplus beyond the mill's own demand is exported to the grid. In addition, the mill supplies large amounts of district heating to the surrounding area. An overview of the site can be seen in figure 1.1 and a legend to highlighted areas can be seen in table 1.1.



Figure 1.1: Östrand Pulp mill. See legend in table 1.1.

Table 1.1: Table with explanations for figure 1.1.

Number	Explanation
1	Railroad
2	Intermediate storage
3	Unloading site for trucks
4	Conveyor belts
5	Existing charger
6	Garage/workshop
7	Docks

# 2

## Theory

This chapter explores different types of electrified vehicles and gives an overview of key differences between them. It then continues to explore charging technologies.

### 2.1 Hybrid Vehicles

In this section, relevant theory surrounding hybrid vehicles, plug-in hybrid vehicles, and battery electric vehicles with range extenders is presented.

#### 2.1.1 Hybrid Electric Vehicles

Hybrid electric vehicles (HEVs) run on both an ICE and one or more electric motors. The electric motors receive energy from a battery pack which is charged either by the ICE or from regenerative braking during which, the electric motor operates as a generator, converting the vehicle's kinetic energy into electrical energy that is stored in the battery. HEVs typically achieve better fuel economy and lower tailpipe emissions than non-hybrid vehicles, but are often more expensive [8].

#### 2.1.2 Plug-in Hybrid Vehicles

A plug-in hybrid electric vehicle (PHEV) functions similarly to a HEV. A PHEV typically has a larger battery pack than an HEV and may also charge its battery from an external electrical source, such as the power grid. This enables a higher degree of electric operation compared to conventional hybrids further reducing fuel consumption and local emissions. The combination of an electric drivetrain and an internal combustion engine also provides operational flexibility, as the vehicle can continue to operate using their ICE once the battery is depleted. At the same time, PHEVs introduce several challenges. The presence of both an electric powertrain and an internal combustion engine increases system complexity, vehicle weight, and manufacturing cost compared to conventional vehicles. To make use of the vehicles benefits it is key to consistently charge it to maximise the degree of electric operation [9].

### 2.1.3 Battery Electric Vehicles with Range Extenders

Another type of hybrid vehicle, which can be viewed as an enhanced PHEV, is battery electric vehicles (BEVs) with range extenders (REXs). A REX is an auxiliary power unit and is typically based on an ICE that is integrated into the BEV to generate electrical power and extend the vehicle's driving range. Unlike in HEVs and PHEVs, propulsion in a BEV with a REX is provided solely by the electric drivetrain while the ICE operates as a generator to supply electrical power when the battery state of charge (SOC) becomes low.

Compared to for example a PHEV, the ICE in a BEV with a REX is operated in a more restricted manner and typically only operates at one or a few steady operating points optimised for electricity generation. In comparison, the ICE in a PHEV operates over a wider range of loads and speeds due to varying driving conditions and acceleration and deceleration patterns. This difference allows the REX to be optimised for simplicity, low noise and compactness rather than for transient performance. Furthermore, by sizing the battery based on the typical daily driving demand and letting the REX cover any additional power demands, the battery capacity can be reduced, lowering the system cost and vehicle weight. However, since BEVs with REXs rely on fossil fuels during extended operation their environmental benefits are also tied to how frequently the vehicle is able to operate in a battery-only mode and be charged from the grid [2].

## 2.2 Charging Technologies

There exists a variety of charging technologies and ways to charge plug-in hybrid and electric vehicles. The two main ways that EV batteries are charged is through conductive charging, and wireless power transfer (wireless charging). Conductive charging transfers energy via a physical connection between the vehicle and the charger, for example via a cable, while wireless charging transfers energy without direct contact, for example through inductive power transfer.

### 2.2.1 Conductive Charging

Conductive charging can be divided into two categories: AC (alternating current) and DC (direct current) charging. During AC charging, power is supplied from the grid and converted to DC by using an on-board charger in the vehicle. For DC charging no on-board charger is required because AC-DC conversion is performed off-board in the charging station, allowing DC power to be supplied to the battery. This enables higher charging capacities and consequently faster charging times than for AC charging [7].

## Pantograph Charging

One conductive charging technology used primarily for electric buses and heavy duty vehicles in industrial transport fleets is pantograph charging. Pantograph charging relies on an automated overhead arm that lowers and connects to roof mounted contact rails on the vehicle to deliver high voltage DC to the battery. Because the charging process is automated, it is well suited for applications with frequent and predictable stopping points, such as route-stops, terminals, and depots where rapid charging during short dwell times is required. Pantograph chargers typically operate at high power levels, often between 150 kW and 600 kW, with some advanced systems approaching 1000 kW. This makes pantograph chargers especially suitable for vehicles with high energy demands and limited opportunities for long charging sessions. However, these advantages come at the cost of increased installation complexity and expenses. The high power levels involved also place significant demands on the local electrical grid and may require grid reinforcements or on-site energy management solutions [6].

### 2.2.2 Wireless Charging

Unlike conductive charging, wireless charging does not require a physical connection between the charger and the vehicle. There exists numerous wireless charging technologies but for electric vehicles, inductive power transfer is today the most mature and widely studied wireless charging technology. Inductive charging transfers electrical energy through electromagnetic induction, where a transmitter coil embedded in a charging pad generates a magnetic field, inducing a high-frequency alternating current in a receiver coil mounted on the vehicle. The received AC power is converted to DC on board before being supplied to the battery. Inductive charging is possible both when the vehicle is parked (static inductive charging) and when it is moving (dynamic inductive charging) [1, 4, 7].

#### Static Inductive Charging

In static inductive charging, the vehicle remains parked above the charging pad during charging. Thus, static inductive charging is intended for places where vehicles remain stationary for an extended period, for example, at public parking spaces, at traffic lights, and in garages. Static inductive charging offers several practical benefits. Since the vehicle simply needs to be parked above the charging pad, the charging process becomes highly convenient and fully automated, removing the need for drivers to handle cables and connectors. The absence of electrical contacts also improves safety by reducing the risk of electrical shocks, sparks, and fires. Inductive charging systems have few moving parts and are completely sealed against dust, weather, and mechanical wear, which reduces the need for maintenance and increases reliability [1, 4, 7].

Static inductive charging also presents several technical challenges. The charging system is sensitive to alignment between the vehicle's receiver coil and the charging pad's transmitter coil. Misalignment of the coils may impose lower power transfer

efficiency and may in some cases interrupt charging altogether. Efficiency is further constrained by the air gap between the coils caused by the vehicle's ground clearance. A larger air gap weakens the magnetic coupling between the coils and reduces how much power can be transferred. While static inductive charging solutions are close to early commercialisation there still exist some challenges for making the solution cost-efficient [1, 4].

### **Dynamic Inductive Charging**

Dynamic inductive charging operates on the same electromagnetic principle as static inductive charging but enables the vehicle to charge while moving because of transmitter coils embedded in the road. The transmitter coils may be implemented either as long continuous coils capable of charging multiple vehicles simultaneously, or as segmented coils connected in series or parallel that are activated when a vehicle is directly above them. Dynamic inductive charging can extend driving ranges and reduce the required battery size but it also introduces several challenges. The installation of the charging system is costly and complex, and requires extensive civil work. Pilot projects have demonstrated dynamic inductive charging at power levels up to a few hundred kilowatts for heavy vehicles. However, dynamic inductive charging remains in an early pilot stage and is not close to commercialisation as of today [1, 5].

## **2.3 Comparison of Charging Technologies**

Conductive charging is currently the most mature and widely deployed charging technology for electric vehicles. Its main advantages are high efficiency, relatively low system complexity, and broad compatibility with existing electrical infrastructure. AC conductive charging offers low installation cost but limited charging power, making it suitable for long dwell times, while DC conductive charging enables faster charging at the expense of higher infrastructure cost and increased grid impact. For heavy-duty vehicles such as buses, trucks, and industrial transport equipment, charging technologies must support high energy demand, predictable operating patterns, and limited downtime. Conventional DC conductive charging offers high efficiency and relatively straightforward integration, but charging times can still be long for vehicles with large batteries and pantograph charging may be a suitable alternative. It is particularly well suited for heavy-duty applications with fixed routes or schedules and is capable of delivering higher charging power during short dwell times, typically in the range of 5-20 minutes. This enables smaller battery capacities and increased electric operation but comes at the cost of complex infrastructure, high installation expenses, and increased grid requirements.

Wireless charging offers potential advantages in heavy-duty environments where automation, robustness, and reduced mechanical wear are important. Static inductive charging can improve safety and operational reliability by eliminating exposed connectors and moving parts, making it attractive for depots, terminals, and loading areas where vehicles frequently stop. However, compared to conductive charging

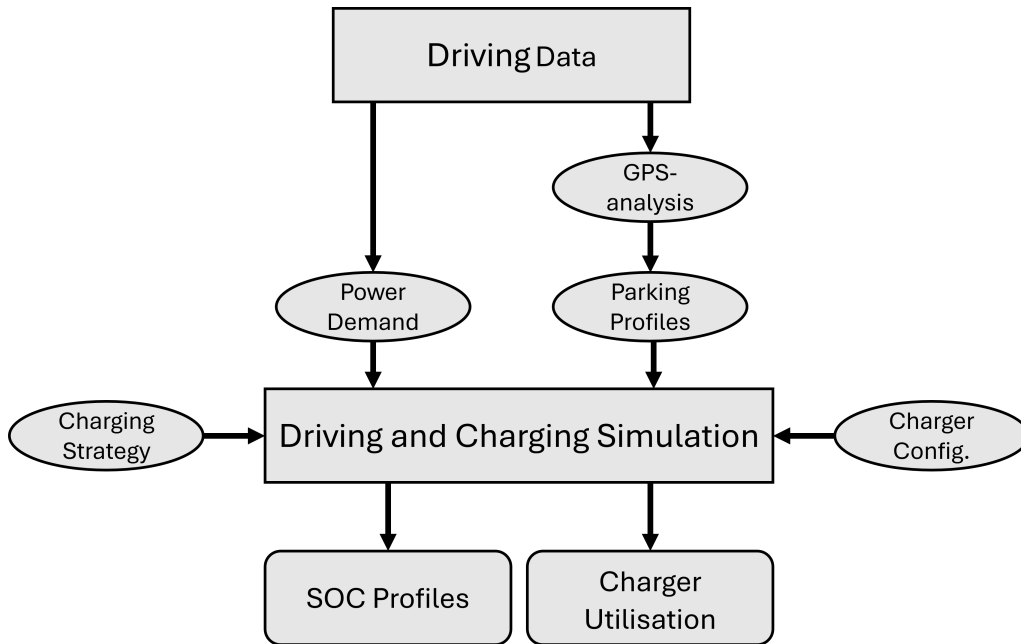
alternatives they suffer from lower efficiencies, sensitivity to alignment, and higher system costs. Dynamic inductive charging enables charging while driving, which could significantly reduce required battery capacity and increase operational flexibility for heavy vehicles. However, these systems face large technical and economic challenges, including high infrastructure cost, extensive civil works, and limited technological maturity, and are therefore still restricted to pilot projects.



# 3

## Methods

This chapter describes the methodology used in this thesis. Based on measured driving data from a logstacker, the vehicle's power demand and parking behaviour were investigated. The observed operational behaviour was then used to identify a suitable area for installing a new charger and to construct parking profiles. A simulation model was then developed to analyse how the state of charge of the logstacker(s) and the utilisation of charging infrastructure vary during operation under different charger configurations, fleet configurations, and charging strategies. In particular, three charging strategies were considered to analyse their impact on multi-vehicle operation. An overview of the methodology can be seen in figure 3.1.



**Figure 3.1:** Overview of the methodology used in this thesis.

### 3.1 Data Selection

For this project, driving data for a logstacker operating at Östrand pulp mill was provided by the logstacker manufacturer. Driving data for a 12-month period from February 2025 to January 2026 was analysed using CAN analysis software. The software was used to visualise time series to understand how the logstacker was operated. This was done by looking more closely at signals that described motion

and powertrain behaviour. During the 12-month period there existed logs from 263 days. Logs for some of the days were omitted from further analysis because the logstacker was out of service on those days or operated for an abnormally short period of time. Such days do not represent normal operating behaviour and would therefore bias the analysis of typical driving cycles and energy demand. Only days with complete and representative operation were retained for further processing. After analysis of the data, 92 of the days were omitted and 171 days from March 2025 to January 2026 were kept for further analysis.

## 3.2 Vehicle Energy Demand

From extracted driving cycles, the energy demand of a logstacker was determined. This was done by summing the net electrical energy exchanged with the battery, accounting for energy used by the traction motor and generator, and the energy supplied by the REX. This was obtained using an assumed lower heating value and an assumed ICE efficiency.

### 3.2.1 Energy from Battery

The net electrical energy exchanged with the battery was computed by summing the net electrical energy consumed by the traction motor and generator, see equations 3.1 and 3.2. The raw CAN data used for calculations was sampled at 1 Hz. Therefore the time horizon was discretised into one-second intervals, defined as  $t=0,1,2,\dots,T$ , where  $T$  denotes the final time step of the measured data. Under this discretisation, the continuous-time energy integrals are evaluated as discrete sums:

$$E_{trac,net} = \sum_{t=0}^T U_{trac}(t)I_{trac}(t)\Delta t \quad (3.1)$$

$$E_{gen,net} = \sum_{t=0}^T U_{gen}(t)I_{gen}(t)\Delta t \quad (3.2)$$

where  $U$  is measured voltage,  $I$  is measured current, and  $\Delta t = 1s$ .

The total net electrical energy exchanged with the battery was calculated according to equation 3.3.

$$E_{batt,net} = E_{trac,net} + E_{gen,net} \quad (3.3)$$

### 3.2.2 Energy from REX

Energy supplied from the REX was calculated based on the amount of consumed fuel. The consumed amount of fuel was calculated according to equation 3.4

$$V_{fuel} = \sum_0^T \dot{v}(t)\Delta t \quad (3.4)$$

where  $\dot{v}$  is the fuel rate. The chemical energy in the combusted fuel was calculated according to equation 3.5

$$E_{fuel} = V_{fuel} \cdot LHV \quad (3.5)$$

where LHV is the lower heating value of the fuel, assumed to be 36 MJ/l, equivalent to 10 kWh/l, for diesel. The electrical energy equivalent supplied from the combusted fuel was calculated as

$$E_{REX} = E_{fuel} \cdot \eta_{ICE} \quad (3.6)$$

where  $\eta_{ICE} = 0.4$  was assumed.

### 3.2.3 Total Energy Consumption

The logstackers' total energy demand was calculated according to equation 3.7.

$$E_{tot} = E_{batt,net} + E_{REX} \quad (3.7)$$

Based on the logstacker's energy consumption a power demand profile was generated with 1 s time step resolution. By comparing the total energy demand for each of the 171 days analysed, 15 days were selected for further analysis. The days selected for further analysis with the model were all within 20 percent of the average energy demand.

## 3.3 New Charger Area

Determining where a new charger could be suitable to install was done by examining where on the site the vehicle operates. This was assessed during a site visit and by analysing GPS data from the logstacker for the selected driving cycles. The site visit to Östrand pulp mill provided valuable contextual understanding of daily operations which complemented and facilitated the analysis of GPS data from the logstacker. The GPS data was analysed by plotting the logstacker's latitude and longitude over time and clustering the data points which allowed areas where the logstacker commonly dwells to be identified. These combined insights informed the evaluation of potential charger areas on site.

## 3.4 Parking Profiles

Having identified a suitable new charging area, binary parking profiles for each respective driving cycle were constructed. This was done by setting up a circular geofence around selected coordinates in the area. This was achieved using Haversine's formula (see equation 3.8) for computing the distance between the selected coordinates and the logged coordinates. It was assumed that during logstacker operations, if the logstacker is located within the geofence and has a speed of less than 0.5 km/h, it may be considered parked and able to charge.

The vehicle speed can be logged both from its engine control unit (ECU) or with a GPS logger. The two options were examined by comparing the absolute ECU-speed with the GPS-speed and it was found that they produced largely similar measurements but with some differences, especially at lower speeds where the ECU-speed was less stable than the GPS-speed. Due to this, the GPS speed was used as a reference when generating the parking profiles. To compensate for inaccuracies of the logged speed of the logstacker, a tolerance of 0.5 km/h was used. Parking profiles for the existing charger were also generated in a similar manner; the existing charger location can be seen in figure 1.1.

$$d = 2R \cdot \arcsin \left( \sqrt{\sin^2 \left( \frac{\phi_2 - \phi_1}{2} \right) + \cos \phi_1 \cos \phi_2 \sin^2 \left( \frac{\lambda_2 - \lambda_1}{2} \right)} \right) \quad (3.8)$$

where:

$\phi$  = latitudinal coordinates

$\lambda$  = longitudinal coordinates

$R$  = earth's radius in m

$d$  = distance between coordinates in m

The parking profiles were then examined to see how much time logstackers on average may be eligible for charging at each respective charger. By analysing the length and distribution of parking sessions, the suitability of different charging technologies for installation were assessed.

## 3.5 Simulation Model

A simulation model was set up in Python to investigate different charger options and charging strategies. The model was used to simulate how the battery SOC evolves over time under different charging configurations. By varying power levels, activation times, and charging strategies, the model was used to evaluate the battery and charger utilisation under different charging solutions.

### 3.5.1 Input Parameters and Constraints

The model takes binary parking profiles and corresponding energy demand profiles based on logged data as input. An initial SOC of 50% was assumed for each driving cycle and; additionally, the model operates under these constraints:

- Simultaneous charging is constrained by the number of available charging slots at each charger for every time step.

$$\sum_v x_{v,c,t} \leq S_c, \quad \forall c, \forall t \quad (3.9)$$

where  $x_{v,c,t} \in \{0, 1\}$  is a binary variable indicating whether vehicle  $v$  is charging at charger  $c$  at time step  $t$ , and  $S_c$  denotes the number of available charging

slots at charger  $c$ .

- Maximum power that may be delivered at each time step is limited by the transformer capacity.

$$\sum_c \sum_v p_{v,c,t} \leq P_{tr}^{max}, \quad \forall t \quad (3.10)$$

where  $p_{v,c,t}$  denotes the charging power delivered to vehicle  $v$  at charger  $c$  during time step  $t$ , and  $P_{tr}^{max}$  represents the rated power capacity of the transformer supplying the charging infrastructure.

- The SOC at each timestep is limited to vary within 30% to 90% of the maximum storage level for each vehicle.

$$0.3 \cdot SOC_{max} \leq SOC_{v,t} \leq 0.9 \cdot SOC_{max} \quad (3.11)$$

- SOC for the following second is calculated as a function of the SOC, charging, and vehicle energy demand for the present second.

$$SOC(t+1) = SOC(t) + Charging(t) \cdot \eta_{charge} - EV\ demand(t) \quad (3.12)$$

where  $\eta_{charge}$  is the efficiency of the charging process.

- Only parking events longer than 15 minutes at the existing charger, hereafter also referred to as charger 1, are considered eligible charging opportunities.

## 3.6 Charging Strategies

In this project, three charging strategies were investigated using the simulation model: First Come, First Served (FCFS), Lowest SOC First (LSF), and Cooperative Fleet Charging (CFC).

### 3.6.1 FCFS

FCFS entails that only the vehicle that first arrives at the charger will be able to charge. This was modelled by simulating charging at full charger capacity for the duration the logstacker was parked at the charger. This was done using the binary parking profile and assigning charging to the vehicles based on the order they arrive at the charger.

### 3.6.2 LSF

LSF entails that vehicles queueing for charging are prioritised based on which vehicle has the lowest SOC, such that the vehicle with the lowest SOC is assigned charging when multiple vehicles are eligible at the same charger. In the model, charging reassignment between vehicles was assumed to require a charger reconnection, incurring a time penalty equivalent to the charger activation delay. To avoid

excessive charger switching due to marginal SOC differences, a SOC margin was applied independently to both chargers. Reallocation was therefore only permitted when the SOC advantage exceeded the defined threshold, ensuring stable charger utilisation and avoiding frequent reassignment.

#### **3.6.3 CFC**

A cooperative fleet charging strategy was also evaluated, in which vehicles were assumed to share information about their SOC. The new charging station was treated as a shared fleet resource, where physical presence at the charger determined availability of charging power and allocation of it was determined at a fleet level.

The new charger was considered active if a vehicle was present at it but the charging power was assigned to the vehicle with the lowest SOC, provided that the vehicle was not simultaneously charging from another source, irrespective of whether the vehicle was parked at the charger or not. The strategy assumes that vehicles are functionally interchangeable and that work tasks can be reassigned between vehicles. The model assumes no handover time of tasks or relocation of vehicles. The charging strategy and charging allocation represents an idealised control system rather than a realistic implementation. Charger 1 was still utilised as an FCFS-resource.

# 4

## Results

This chapter presents the results of the study and summarises the main findings from the analysis of logstacker energy demand, parking behaviour, and charging performance. First, the measured driving data is used to characterise the vehicle's operational patterns and identify a suitable area for a new charger. The results then show how different charger configurations and charging strategies affect the achievable level of electric operation for one, two, and three logstackers. Finally, the impact of the investigated charging strategies on charger utilisation and local power demand is evaluated.

### 4.1 Logstacker Energy Demand

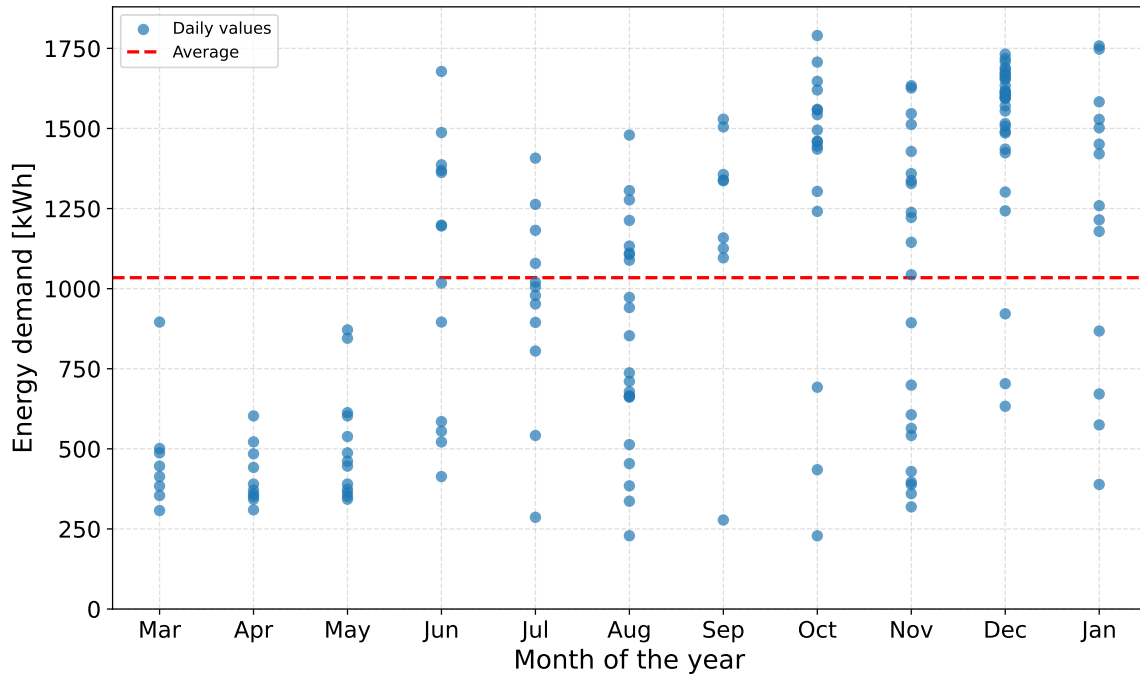
The logstacker's energy demand was calculated in terms of useful energy required according to equation 3.7, and the fuel consumption was calculated according to equation 3.4. See the energy demand and fuel consumption plotted for each day of the investigated period in figures 4.1 and 4.2, respectively. Max, Min, and average values for the daily energy demand and fuel consumption can be viewed in table 4.1.

**Table 4.1:** Energy demand and fuel consumption of the logstacker.

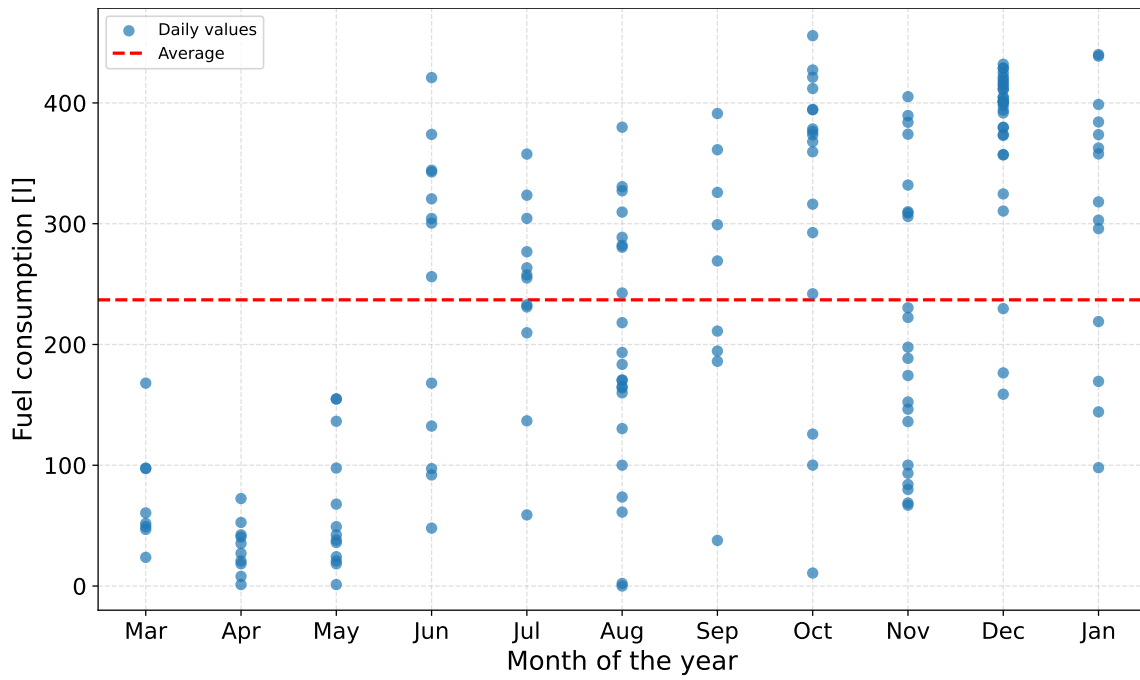
	<b>Energy demand [kWh]</b>	<b>Fuel consumption [l]</b>
Max	1790	456
Min	229	0
Average	1034	237

It may be noted that the energy demand and fuel consumption is generally lower during March, April, and May, relative to the rest of the investigated months. There also exists a few days where the REX is not used and the energy demand is met using only the battery.

## 4. Results



**Figure 4.1:** Energy demand of the logstacker.



**Figure 4.2:** Fuel consumption of the logstacker.

## 4.2 New Charger Area

From analysis of the logstacker's GPS data and from discussions with site personnel, a suitable new charger area was identified. The charger should be located in the area next to where the trucks are unloaded and next to the conveyor belts that feed the mill, see figure 4.3 and figure 1.1 for further reference. The logstacker's commonly dwell and stop in that area between tasks, and do not interfere much with operations of other logstackers if they are parked there, making it suitable for charging-stops.



**Figure 4.3:** New charger area highlighted in yellow.

### 4.2.1 Parking Profiles

Parking profiles for logstackers were generated for both the existing charger, charger 1, and the new charger, charger 2, by using circular geofences around the coordinates for each respective charger. From the 15 analysed driving cycles it was found that they on average spent 7.2 hours per day parked at the existing charger, and 2.9 hours per day parked within the area of the new charger. Assuming the existing charger takes 90 seconds to activate and stops shorter than 15 minutes are not eligible for charging, the logstacker is able to charge 5 times per day and is eligible for charging for 6.1 hours per day, on average.

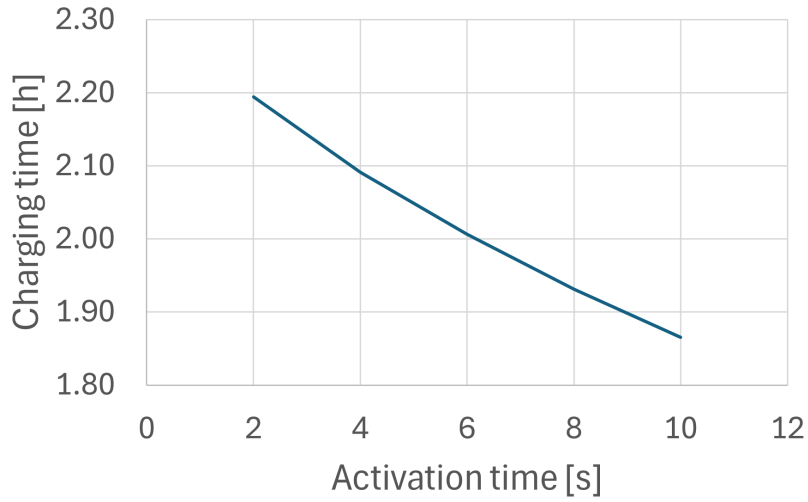
For the new charger location, the length of parking sessions were first investigated to assess what type charging technology could be suitable to install. It was found that the logstackers on average park for a minimum of five consecutive minutes only 6.5 times per day and would be eligible for charging for 0.97 hours in total. Due to the limited number of longer parking sessions in the area, conductive charging methods were disregarded from further consideration and instead static inductive charging methods were considered a suitable technology to implement in the model.

As inductive charging technologies have very short activation times, charger activation times ranging from 2 seconds to 10 seconds were tested, and it was found that under these assumptions a logstacker would be able to charge on 257 occasions

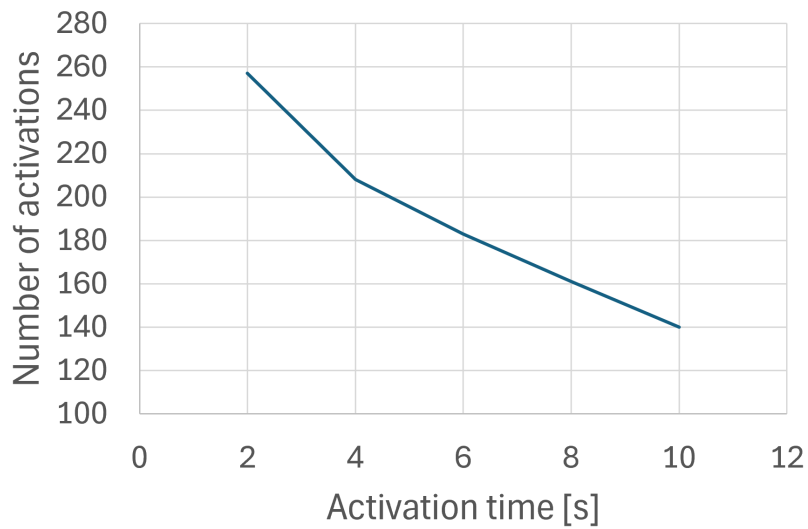
## 4. Results

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to 140 occasions and be eligible for charging for 2.2 to 1.9 hours per day, on average. Figures 4.4 and 4.5 show how the potential charger utilisation decreases with increasing activation times.



**Figure 4.4:** Charging time, new charger.

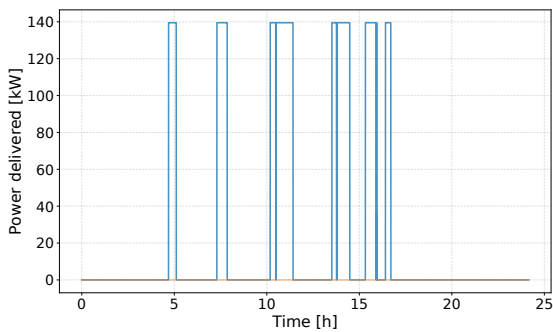


**Figure 4.5:** Number of activations, new charger.

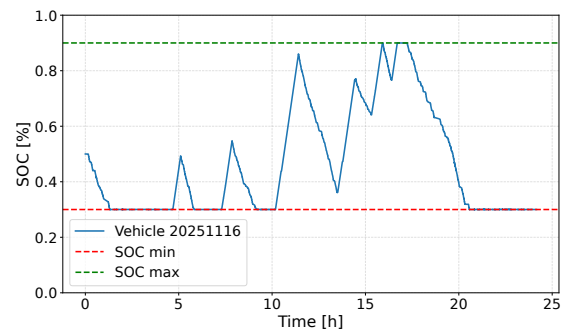
### 4.3 One PHEV - Today's Situation

Today there only exists one PHEV logstacker on the site and one 150 kW charger, and thus the existing situation was investigated. Assuming an efficiency of 93% for the charging process, the charger was on average able to deliver 556 kWh to the logstacker. This amounts to approximately 54% of the average energy demand for the logstacker, offsetting 139 litres of diesel.

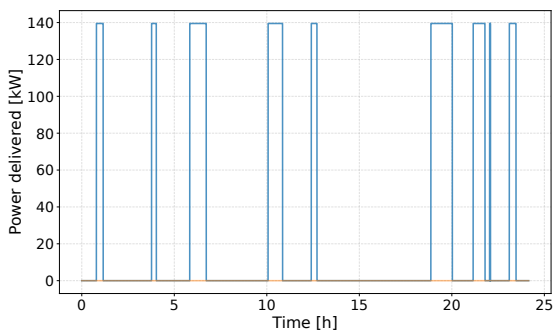
The distribution of charging events for two representative driving cycles, vehicle 20251116 and vehicle 20250801, respectively, can be seen in figures 4.6 and 4.8. The corresponding SOC evolutions are shown in figures 4.7 and 4.9. Vehicle 20251116 charges 558 kWh distributed across six occasions. Two of the charging sessions are interrupted for approximately one second each making it look like eight charging sessions in figure 4.6. Vehicle 20250801 charges 669 kWh divided between eight charging sessions. One of the charging sessions is interrupted similar to how the charging sessions for vehicle 20251116 were interrupted, making it appear like the vehicle charged on nine separate occasions, see figure 4.8.



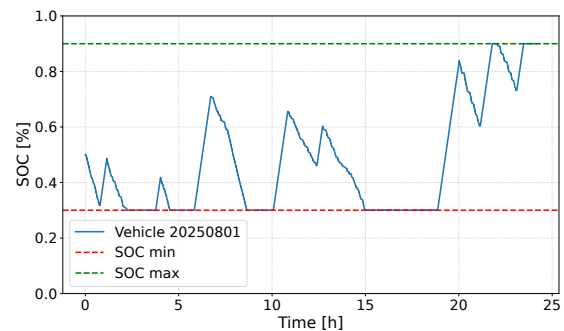
**Figure 4.6:** Charging profile for vehicle 20251116 with only the existing charger installed.



**Figure 4.7:** SOC profile for vehicle 20251116 with only the existing charger installed.



**Figure 4.8:** Charging profile for vehicle 20250801 with only the existing charger installed.



**Figure 4.9:** SOC profile for vehicle 20250801 with only the existing charger installed.

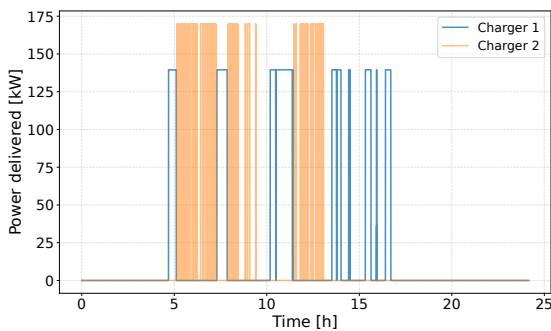
## 4.4 One PHEV - New Charger Installed

In the case of only one PHEV operating on the site but with a new charger installed on the site (see figure 4.3), the level of electric operation increased significantly for almost all tested driving cycles. To assess the impact of charger capacity for the new charger, charging power levels between 100 kW and 300 kW were evaluated. The new charger was assumed to have an activation time of 10 seconds and to charge the logstacker with 85% efficiency. The existing charger was assumed to remain unchanged. The results in table 4.2 show an increase in the amount of energy delivered and consequently that the share of electric operation is increased. By installing a new charger with a capacity in the range of 100 kW to 300 kW it is possible to achieve an average share of electric operation of 70% to 87%.

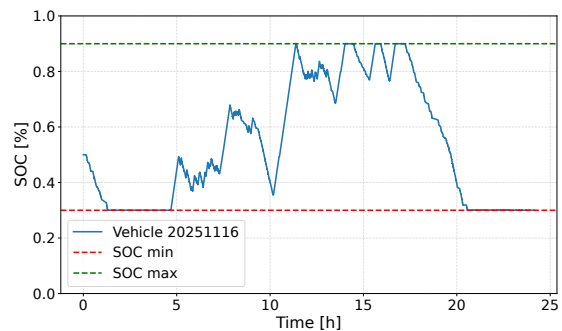
**Table 4.2:** Comparison of impacts of installing a new charger of different capacities. The energy delivered is the sum of energy charged from both the existing and the new charger.

Charger 2 capacity [kW]	Average energy delivered [kWh]	Diesel offset [l]	Share of average energy demand charged [%]
100	720	180	70
150	783	196	76
200	832	208	80
250	870	218	84
300	899	225	87

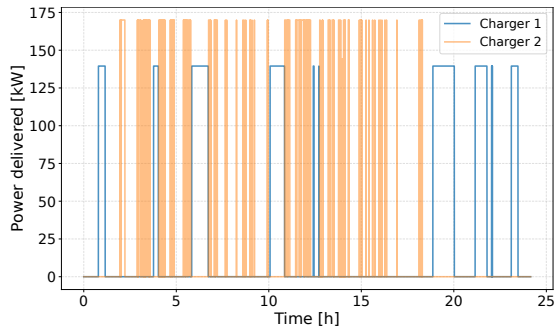
In the case where charger 2 is installed with a 200 kW capacity, the charging profiles for driving cycles 20251116 and 20250801, shown in figures 4.10 and 4.12, show how the new charger is used on many short occasions throughout the driving cycles. Charger 2 delivers 270 kWh across 62 occasions to vehicle 20251116 and 416 kWh across 116 occasions to vehicle 20250801. This is also reflected in the corresponding SOC profiles shown in figures 4.11 and 4.13 where additional spikes in SOC can be seen when compared to figures 4.7 and 4.9.



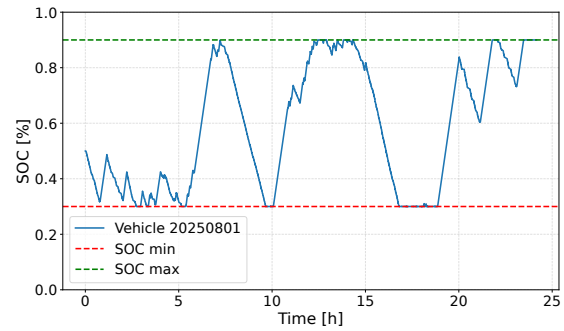
**Figure 4.10:** Charging profile for vehicle 20251116 when charger 2 is installed with a 200 kW capacity.



**Figure 4.11:** SOC profile for vehicle 20251116 when charger 2 is installed with a 200 kW capacity.



**Figure 4.12:** Charging profile for vehicle 20250801 when charger 2 is installed with a 200 kW capacity.



**Figure 4.13:** SOC profile for vehicle 20250801 when charger 2 is installed with a 200 kW capacity.

#### 4.4.1 One PHEV and One Conventional

When simulating charger utilisation for a fleet of logstackers, a subset of representative driving cycles was selected. For simulations involving two logstackers, it was assumed that at least one logstacker out of the pair must remain available for operation at all times during normal production. Therefore, pairs of driving cycles with minimal overlapping parking time at charger 1 were chosen.

In the case of one PHEV operating on the site together with a conventional logstacker, the CFC model was used to assess the maximum charging potential of the second charger under ideal conditions and how this affects the usage of charger 1. Since the CFC model assumes perfect synchronisation of vehicle tasks and charging decisions, this setup represents an upper-bound estimate of charger utilisations. The simulations were run for six different pairs of combinations of logstackers and the averaged results in table 4.3 show that as the capacity of charger 2 increases, the amount of energy delivered from it also increases. Simultaneously, the energy delivered from charger 1 decreases but, in total, the amount of energy delivered increases.

**Table 4.3:** Results from CFC-simulation for one PHEV logstacker operating together with one conventional logstacker.

Charger 2 capacity [kW]	Average energy delivered [kWh]			Diesel offset [%]
	Charger 1	Charger 2	Total	
100	553	236	789	76
150	526	341	867	84
200	489	437	926	90
250	451	526	977	94
300	425	593	1017	98

When increasing the capacity of charger 2 from 100 kW to 300 kW, the amount of energy delivered from charger 2 increased by 152%, while the amount of energy delivered from charger 1 decreased by 23%. Overall the total amount of electrical energy delivered increased by 29%. As a result, installing a charger

with a capacity in the range of 100-300 kW may enable an average share of electric operation between 76% and 98%, corresponding to a displacement of up to 254 litres of diesel through electrification.

## 4.5 Two PHEVs

For simulations involving two PHEVs, the three driving-cycle pairs with the least overlap in parking time at charger 1 were selected. With charger 1 kept unchanged, the effect of varying the charging capacity of charger 2, up to 650 kW, was then investigated. Simulations were conducted for the three charging strategies considered, and the results are presented below.

### 4.5.1 FCFS

The results from FCFS-simulations are summarised in table 4.4. The results show an offset of charger 1 utilisation with increasing capacity of charger 2. When compared to the annual average energy demand of a logstacker, the average achieved share of electrical operation, corresponding to the share of diesel offset, ranges from 67% to 81% per logstacker for charger 2 capacities between 100 kW and 300 kW. This represents a reduction in the electric-operation share compared to scenarios without competition for chargers, see table 4.2. However, when increasing the capacity of charger 2 up to 650 kW, a 92% share of electric operation may be achieved.

**Table 4.4:** Results from FCFS-simulation for two PHEV logstackers operating simultaneously.

Charger 2 capacity [kW]	Average energy delivered [kWh]			Diesel offset [%]
	<i>Charger 1</i>	<i>Charger 2</i>	<i>Total</i>	
100	1116	274	1390	67
150	1095	396	1491	72
200	1059	516	1575	76
250	1002	631	1633	79
300	943	730	1673	81
350	895	808	1702	82
400	842	888	1730	84
450	816	948	1764	85
500	809	989	1799	87
550	803	1032	1834	89
600	795	1075	1870	90
650	782	1122	1904	92

### 4.5.2 LSF

The results from LSF-simulations can be seen in table 4.5. The results show less charger utilisation than the FCFS strategy yielded. This is likely due to switching which incurs a time penalty as the charger must be reconnected. In this case also, charger 1 utilisation is offset by increasing charger 2 capacity. Compared to the FCFS strategy, LSF on average yielded 2.4% less energy across all power-levels which also is reflected in the share of diesel offset.

**Table 4.5:** Results from LSF-simulation for two PHEV logstackers operating simultaneously.

Charger 2 capacity [kW]	Average energy delivered [kWh]			Diesel offset [%]
	<i>Charger 1</i>	<i>Charger 2</i>	<i>Total</i>	
100	1105	248	1353	65
150	1083	365	1448	70
200	1058	480	1539	74
250	1012	581	1593	77
300	959	683	1642	79
350	920	758	1677	81
400	873	826	1700	82
450	831	893	1724	83
500	808	944	1751	85
550	801	980	1781	86
600	794	1015	1809	87
650	787	1052	1839	89

### 4.5.3 CFC

The results from CFC-simulations in table 4.6 show a further increase in the total amount of energy delivered compared to other charging strategies. The charger utilisation follows the same pattern previously observed, with decreasing utilisation of charger 1 as the capacity of charger 2 increases.

Under this scenario, logstackers are able to meet up to 67-106% of the average energy demand with electricity if a 100-650 kW charger is installed. This implies that, at higher charging capacities, the electrical energy supplied is sufficient to fully cover more than the average operational demand. For charger 2 capacities up to 300 kW the level of electrical operation is comparable to the case with a single logstacker operating alone and where no competition for chargers exists (see table 4.2). This indicates that CFC can largely mitigate the effects of charger contention during operations with two PHEV logstackers.

**Table 4.6:** Results from CFC-simulation for two PHEV logstackers operating simultaneously.

Charger 2 capacity [kW]	Average energy delivered [kWh]			Diesel offset [%]
	<i>Charger 1</i>	<i>Charger 2</i>	<i>Total</i>	
100	1113	281	1395	67
150	1090	418	1509	73
200	1062	552	1614	78
250	1028	680	1708	83
300	978	800	1777	86
350	932	908	1840	89
400	898	1006	1904	92
450	864	1102	1966	95
500	832	1193	2025	98
550	806	1281	2087	101
600	781	1360	2141	104
650	758	1427	2185	106

## 4.6 Three PHEVs

As there may be up to three logstackers operating simultaneously, it was investigated how these may use the chargers. To accommodate the three logstackers, the existing charger was assumed to be upgraded with an additional outlet capable of supplying 150 kW, meaning the total capacity of charger 1 is 300 kW. Charging simulations with charger 2 capacities up to 500 kW were run for three trios of driving cycles.

### 4.6.1 FCFS

The results from FCFS-simulations for three logstackers operating simultaneously are presented in table 4.7. The results show that it is possible to offset 71-91% of the total diesel consumption through electrification when charger 2 is installed with capacities ranging from 100 kW to 500 kW. The charger utilisation pattern is consistent with previous simulations for one- and two-vehicle simulations: the utilisation of charger 1 decreases with increasing capacity of charger 2. Compared to the results from FCFS simulations with two PHEVs operating simultaneously (see table 4.4), similar levels of performance are achieved for equivalent total installed charging capacity.

**Table 4.7:** Results from FCFS-simulation for three PHEV logstackers operating simultaneously.

Charger 2 capacity [kW]	Average energy delivered [kWh]			Diesel offset [%]
	<i>Charger 1</i>	<i>Charger 2</i>	<i>Total</i>	
100	1765	423	2188	71
150	1728	602	2331	75
200	1670	780	2451	79
250	1610	940	2550	82
300	1538	1086	2624	85
350	1462	1213	2676	86
400	1384	1333	2718	88
450	1328	1437	2766	89
500	1300	1518	2817	91

#### 4.6.2 LSF

The results from LSF-simulations for three logstackers operating simultaneously can be viewed in table 4.8. Compared to the FCFS strategy, LSF on average yielded 3.0% less charging across the trio of vehicles. Compared to results from simulations with two PHEV logstackers operating simultaneously, this indicates that the performance of the LSF strategy further declines as the fleet size increases, likely due to an increased occurrence of switching.

**Table 4.8:** Results from LFS-simulation for three PHEV logstackers operating simultaneously.

Charger 2 capacity [kW]	Average energy delivered [kWh]			Diesel offset [%]
	<i>Charger 1</i>	<i>Charger 2</i>	<i>Total</i>	
100	1729	384	2113	68
150	1701	563	2264	73
200	1660	716	2376	77
250	1596	871	2468	80
300	1524	1021	2545	82
350	1453	1155	2608	84
400	1377	1269	2646	85
450	1306	1378	2683	86
500	1259	1467	2726	88

### 4.6.3 CFC

For CFC-simulations, the results in table 4.9 show it is possible to achieve a share of electrical operation in the range of 72-110% by installing charger 2 with capacities in the range of 100-500 kW. This represents an increase in electric operation compared to the CFC case with only two operating vehicles, indicating that the additional charging infrastructure can mitigate the increased competition for chargers as the size of the fleet grows.

**Table 4.9:** Results from CFC-simulation for three PHEV logstackers operating simultaneously.

Charger 2 capacity [kW]	Average energy delivered [kWh]			Diesel offset [%]
	<i>Charger 1</i>	<i>Charger 2</i>	<i>Total</i>	
100	1788	441	2229	72
150	1767	657	2424	78
200	1733	871	2604	84
250	1682	1087	2769	89
300	1616	1301	2917	94
350	1543	1503	3046	98
400	1473	1687	3159	102
450	1421	1864	3285	106
500	1367	2032	3399	110

## 4.7 Electrical Power Demand

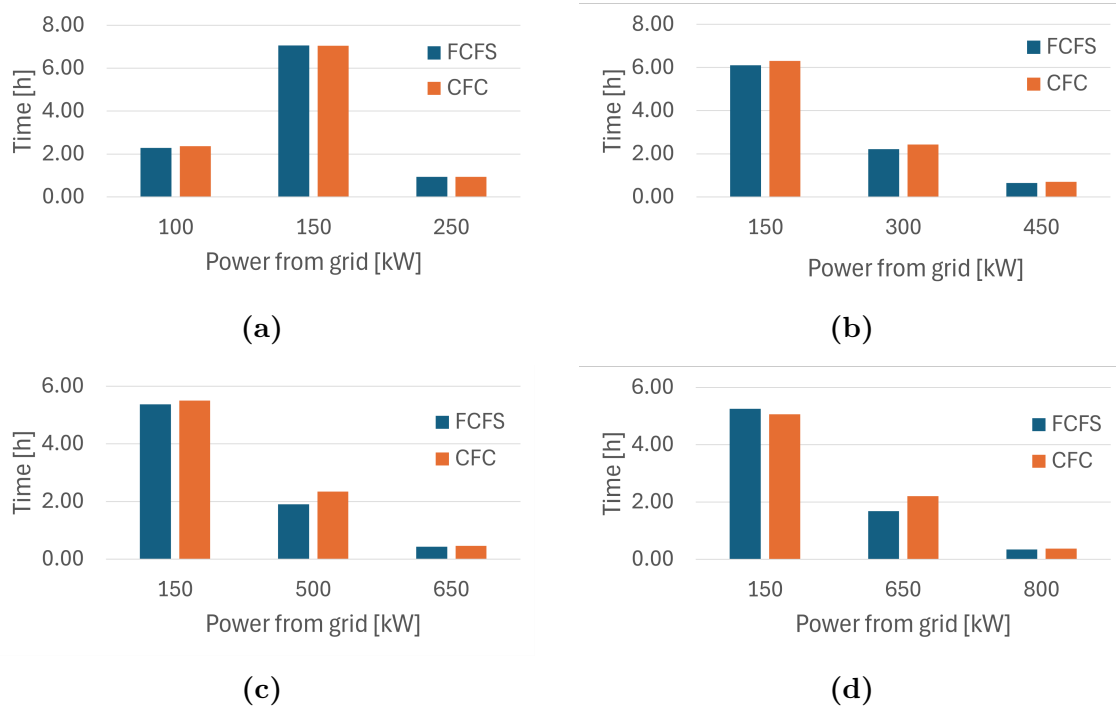
To analyse the impact of charging infrastructure on the site energy system, charger utilisation was analysed. Since the results of this study have shown that the LSF strategy is consistently outperformed by the simplest charging strategy, FCFS, in terms of energy delivered and achievable electric operation of logstackers, LSF was not considered further for detailed analysis. As FCFS is both simpler to practically implement and yields better performance, additional assessment of LSF charging profiles was deemed unlikely to provide additional insights.

In today's situation, the logstacker is able to charge 556 kWh on average, distributed across four hours of charging. This means the peak power usage from charging is 150 kW sustained for four hours per day.

### 4.7.1 Two PHEVs

In the case where two PHEV logstackers operate simultaneously and charger 2 is installed, the peak power demand increases as both chargers may be used simultaneously. However, the duration of peak charging power decreases with increasing capacity of charger 2 as can be seen in figure 4.14. If charger 2 is installed with a capacity of 100 kW, the peak power demand reaches 250 kW, occurring for approximately 0.94 hours per day for both the FCFS and CFC strategies. If the capacity

of charger 2 is increased to 650 kW, the peak power demand reaches 800 kW, but only for 0.35 hours and 0.37 hours per day under the FCFS and CFC strategies, respectively.

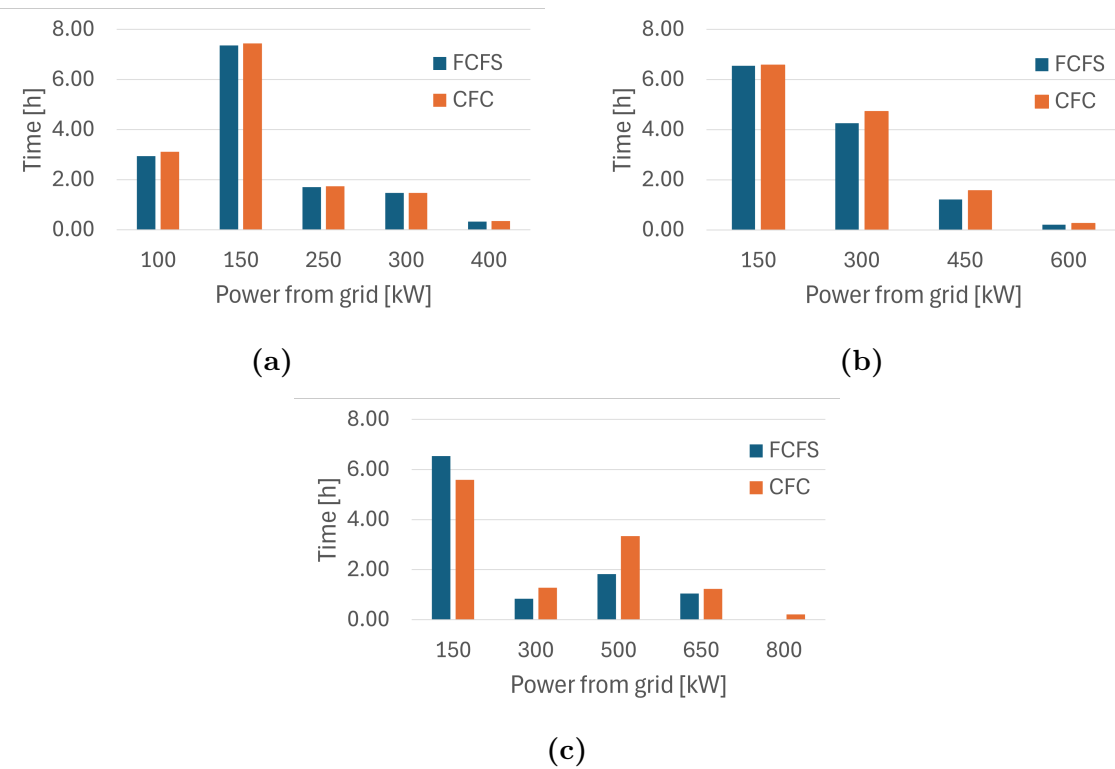


**Figure 4.14:** Average charging-power demand for two simultaneously operating PHEV logstackers. Charger 1 has a fixed capacity of 150 kW, while the capacity of charger 2 is varied: (a) 100 kW, (b) 300 kW, (c) 500 kW, and (d) 650 kW. The column plots illustrate the distribution of charging power drawn from the grid under FCFS and CFC simulations.

### 4.7.2 Three PHEVs

In the case where three PHEV logstackers operate simultaneously the charger utilisation follows the same trend as for two vehicles: the peak power demand increases with increasing installed charger capacity, while the duration of these peaks decreases, as shown in figure 4.15. When charger 2 is installed with a capacity of 100 kW, the peak power demand reaches 400 kW, occurring for approximately 0.33 hours and 0.35 hours per day for the FCFS and CFC strategies, respectively. If the capacity of charger 2 is increased to 500 kW, the peak power demand rises to 800 kW occurring for 0.02 hours (1.4 minutes) per day for the FCFS strategy and 0.21 hours per day for the CFC strategy.

## 4. Results



**Figure 4.15:** Average charging-power demand for three simultaneously operating PHEV logstackers. Charger 1 has two slots with 150 kW capacity each, while the capacity of charger 2 is varied: (a) 100 kW, (b) 300 kW, and (c) 500 kW. The column plots illustrate the distribution of charging power drawn from the grid under FCFS and CFC simulations.

# 5

## Discussion

### 5.1 Selection of Data

When processing the data from the logstacker some days were omitted from further analysis. This was in some cases done due to the vehicle logging data despite it not operating that day, for example if the vehicle had been left running unintentionally. From discussions with personnel it was noted that there had been periods where the logstacker had been taken out of service due to various reasons. During some of these periods there existed logged data from when they had been testing the vehicle, for example, in a garage. These days were filtered out on intuition, and from analysing GPS data to see where and if the vehicle actually had been operating on the site. Some days were also omitted due to the vehicle being operated very little. During these days it was difficult to determine if the limited amount of operation depended on a limited workload or the vehicle not running properly and being taken out of service. Some days with low energy demand were still kept for analysis as there does exist days with less production and where the logstackers are used more sparingly.

### 5.2 Parking Profiles and New Charger Location

For the generation of parking profiles, the vehicle was considered parked if it had a speed lower than 0.5 km/h. This value was chosen to compensate for inaccuracies and noise in the data. Data from the GPS logger was also chosen over the ECU data as the GPS data appeared more stable than the ECU data with less fluctuations. Variations in the ECU-speed data may be due to wheel slippage but it is difficult to pinpoint the exact reason behind the fluctuations. The GPS data was also not perfect as there existed some periods where the signal appeared to be lost, resulting in sudden and unrealistic position changes across the site. The selection of data for deriving parking events introduces a degree of uncertainty in the resulting parking profiles. One example of this can be seen in figure 4.6 where parking events are interrupted likely because of inaccuracies in either the positional data or the speed data used. Furthermore, the impacts of different speed thresholds have not been studied, and the chosen threshold was determined purely by intuition from visually examining speed data.

The parking profiles were generated using geofences to identify when the vehicle was located within predefined areas. The geofence for the new charger was constructed to be quite large based on the assumption that if operators are aware of an

available charging point, they will preferentially park within its vicinity whenever operationally feasible. In the current operating conditions there exists no clearly designated parking location on the site, resulting in operators parking in various locations across the whole site. Consequently, although the larger geofence may include some parking events that would be unrealistic in practice, it may also exclude many parking events that could have been utilised for charging if operators were aware of a nearby charging point. This highlights the uncertainty associated with defining geofences in the absence of established parking patterns and charging routines.

The dataset used in this study spans a large number of operational days and includes contributions from multiple operators, capturing a wide range of individual driving and parking behaviours. While this adds robustness to the analysis by reflecting diverse real-world practices, it also introduces additional variability in the data meaning the results should be interpreted as general trends rather than exact values.

### 5.3 Fleet Simulation

For simulations involving multiple logstackers, data from a single vehicle operating on different days was used to represent multiple vehicles by aligning individual driving cycles on a common time axis. Using data from one vehicle across multiple days to represent several vehicles operating simultaneously inevitably introduces some unrealistic behaviours, such as overlapping operations and spatial or temporal conflicts that would not occur in reality. For example, this approach risks overestimating the number of charger conflicts. However, this approach also allows the analysis to capture a wide range of operational patterns and variability observed in real-world use. While these simplifications introduce some uncertainty, they provide a practical means of investigating multi-vehicle charging behaviour in the absence of detailed data from multiple simultaneously operating logstackers.

For simulations involving two vehicles, complementing driving cycles were selected by analysing the amount of overlapping parking time at charger 1. During normal operations of the mill, at least one logstacker must remain available at all times to continuously feed the conveyor belts. Therefore, driving-cycle pairs with minimal overlap at charger 1 were chosen for these simulations. This selection reduces the occurrence of unrealistic charging conflicts and better reflects operational requirements, while still allowing the investigation of cooperative charging behaviour under constrained infrastructure availability.

For simulations involving three vehicles, the driving-cycle pairs with minimal overlapping parking time at charger 1 were extended by adding an additional average driving cycle. The selection of the third driving cycle was largely arbitrary and no consideration was given to overlapping parking events. This was deemed acceptable as the operational demand of having at least one logstacker available at all times was already satisfied by the original driving-cycle pairs.

## 5.4 Charging Strategies

Three different charging strategies were investigated and they all impose different demands on the operators. The simplest strategy, FCFS, consistently produced better results than LSF across all tested cases. While LSF to some extent tended to even out SOC-differences between the vehicles, the total amount of energy delivered was lower than for FCFS. This reduction is likely due to the time penalties associated with reassigning the charger as vehicles may need to be repositioned or charging cables reconnected in practice. Such interruptions reduce effective charging time and highlight a trade-off between SOC balancing and charger utilisation. In addition, LSF generally require more active involvement and coordination between operators as they would have to actively monitor their SOC levels and reassign chargers based on that, whereas FCFS aligns better with existing operational routines and imposes a lower workload for the operator.

The most complex charging strategy is CFC which also produced the best results across all tested scenarios. This strategy yielded the highest amount of energy charged, and consequently the greatest displacement of diesel consumption across all tests. These performance gains however comes at the cost of a substantially increased workload for the operators which may limit the practical feasibility of the approach in real-world operations. CFC requires a very high degree of coordination between operators to continuously optimise charger utilisation which may be difficult to achieve in practice. Thus, the strategy should primarily be interpreted as a theoretical upper bound on achievable charging performance and electrification of operations given available infrastructure. Furthermore, CFC assumes all logstackers are functionally interchangeable which may not be true in reality. It also assumes perfect coordination between operators and vehicles to maximise charging opportunities, an assumption that is unlikely to be fully satisfied in practice.

## 5.5 Charging Technology

The charging technology and charger behaviours in this study have been simplified and do not account for factors such as thermal limitations of batteries and chargers and their impact on charging power and efficiency, nor were variations in charging efficiency at different SOC considered. The chargers were also assumed to deliver their rated power whenever active with no ramp-up or ramp-down behaviour or power modulation over time. While these assumptions allow for a comparison between charging strategies and infrastructure scenarios, they may lead to optimistic estimates of achievable charging performance.

The new charger was modelled to resemble a static inductive charging system, as this technology is well suited for opportunity charging in locations characterised by many short and frequent parking events. Static inductive charging was considered particularly relevant because it allows for automated charging without the need for physical cable connections, reducing operator involvement and making it compati-

ble with the observed operational patterns in the proposed charger area. However, the use of an inductive charger would still impose certain demands on operators, particularly due to its sensitivity to alignment relative to the charging pad. To ensure reliable and repeatable charging, care would need to be taken in the physical design and placement of the charger so it is easily accessible. Poor placement can force operators to park in an awkward manner or require additional manoeuvres, such as reversing into the charging position, which could increase the workload and discourage using the charger during daily operations.

For this study, charger capacities of up to 800 kW were considered, corresponding to the maximum power the installed transformer can supply. The PHEV logstacker currently in operation is equipped with a 300 kWh battery and has a maximum C-rate of 0.5, which limits the allowable charging power to 150 kW. As a result, higher charger capacities cannot be fully utilised with the existing battery configuration. However, with the future introduction of battery technologies that allow higher C-rates, it may become possible to take advantage of chargers with substantially higher power ratings. For example, in the case where one PHEV operates together with a conventional logstacker, CFC simulations show that a capacity of 300 kW for charger 2 would be sufficient to achieve nearly 100% electric operation for the PHEV.

The transformer currently installed on the site has a rated capacity of 800 kVA. This implies that, for example, in a scenario with three PHEV logstackers supplied by two 150 kW conductive chargers at the existing charger location, approximately 500 kW of additional capacity would remain available. This excess capacity could potentially be allocated to one or more additional chargers or an upgrade of installed chargers, allowing higher charging power or an increased number of simultaneously charging vehicles, depending on future infrastructure and battery capabilities. However, it should be noted that in all cases simulated, the utilisation of charger 1 decreased with increasing capacity of charger 2. This means that charger 1 is freed up from charging logstackers and could perhaps be used to charge other vehicles within the material handling fleet or a battery energy storage system. In the longer term, such infrastructure could also enable bidirectional charging.

### 5.5.1 Energy System Impacts

The electrification of logstacker operations demonstrates a strong potential to significantly reduce diesel consumption, thereby shifting energy demand from on-site fuel use to electricity supply. This transition increases the importance of the local energy system, as charging demand becomes dependent on electricity availability, pricing, and tariff structures. In particular, the concentration of charging power within limited time periods can lead to higher peak loads, making the operation more sensitive to power-dependent tariffs and demand charges. While this effect may be of limited importance at the studied site, given its energy intensive nature and its self sufficiency in electricity production, it may be a significant consideration for other industrial sites with greater exposure to electricity pricing and grid con-

straints. Furthermore, it may be noted in figures 4.14 and 4.15 that the duration of peak charging demand is very limited. This suggests that peak loads have a limited impact under the studied conditions.

## 5.6 Societal, Ethical, and Ecological Aspects

The electrification of heavy-duty material-handling equipment, such as logstackers, carries several societal and ethical implications. From a societal perspective, replacing diesel operation with electric operation has the potential to significantly reduce GHG emissions and local air pollutants, contributing to climate-mitigation efforts and improved local air quality. This is particularly relevant in industrial environments where such machinery operates for extended periods and in close proximity to personnel. Reduced noise levels and exhaust emissions may also lead to an improved working environment.

At the same time, electrification introduces new technical and organisational requirements that may affect operators and site personnel. More advanced charging strategies and increased coordination between vehicles and charging infrastructure can lead to higher demands on operator awareness, planning, and decision-making. From an ethical standpoint, it is therefore important that technological solutions are designed to support operators, ensuring that efficiency gains do not come at the cost of increased stress or unclear responsibilities.

From an ecological perspective, while electrification reduces local emissions and noise, it also introduces indirect environmental impacts that should be considered. These include the environmental footprint associated with electricity generation, the sourcing and lifecycle of battery materials, and the installation of charging infrastructure. Addressing these aspects is important to ensure that local emission reductions do not lead to increased environmental impacts elsewhere in the energy system.

## 5.7 Future Work

Based on this study there exists many different aspects and opportunities for future investigations. Regarding data selection and preprocessing, future work could focus on developing a more systematic method for filtering and validating operational data. This would reduce reliance on manual interpretation and improve reproducibility of the analysis.

For the generation of parking profiles and for finding an optimal charger location, further studies involving field measurements with designated parking locations would be suitable to accurately identify charging opportunities in the proposed charger area under real operating conditions. Such studies would also enable a more reliable assessment of operator behaviour and how charging infrastructure placement influences utilisation in practice.

For fleet simulations, measurements from multiple simultaneously operating logstackers would enable more realistic modelling of interactions between vehicles. Future work could also investigate scenarios in which the back-up logstacker is also electrified. In such a scenario, additional operational flexibility may be introduced by allowing vehicles to be rotated during the day, where one logstacker can be taken out of operation for charging while another is utilised. This could reduce the need for high instantaneous charging power and enable more efficient use of the installed charging infrastructure.

Regarding charging technologies, future work should consider more detailed modelling of charger and battery behaviour, including variations in efficiency and dynamic charging characteristics. In addition, the interaction between battery design and charging infrastructure could be further investigated, particularly how battery capacity and allowable charging power can be adapted to different operational requirements. By co-designing these, it may be possible to achieve similar performance across a wider range of system configurations.

From an energy system perspective, the potential for bidirectional charging and the provision of grid or site services represents an interesting area for future research. Periods where vehicles are idle and connected to the charging system may enable the use of battery capacity to support the local energy system, for example through peak shaving or load smoothing. As the present results indicate that peak loads are both short in duration and relatively infrequent, such functionality could help mitigate the impact of electrification on the site's energy system. While this may be of limited importance for the studied site since it is a net exporter of electricity, it may be more relevant for other sites considering electrification, particularly those with greater exposure to electricity pricing and grid constraints.

# 6

## Conclusion

This thesis investigated the electrification potential of logstacker operations at an industrial site, focusing on charging infrastructure requirements, operational constraints, and impacts on the local energy system. By combining operational data with simulation-based analysis, the study provides insights into how different charging configurations and strategies influence the achievable share of electric operation and overall system performance.

The results demonstrate that electrification of logstackers can significantly reduce diesel consumption, with high shares of electric operation achievable under a wide range of conditions. The installation of a charger for opportunity charging was shown to substantially increase the amount of energy delivered and improve electrification levels, particularly when higher charging capacities are available. At the same time, the results highlight that the effectiveness of electrification is strongly influenced by operational factors such as parking behaviour and competition for charging infrastructure.

Among the charging strategies considered, the CFC approach consistently yielded the highest performance, effectively mitigating the impacts of charger contention. However, these gains come at the cost of increased operational complexity, indicating a trade-off between charging performance and practical feasibility. Simpler strategies, such as FCFS, whilst easier to implement, yields lower overall performance.

From an energy system perspective, the results show that peak charging demand increases with installed charger capacity, while the duration of these peaks remains limited. This indicates that high power demand occurs only during short periods, reducing its overall impact on the local energy system. At the studied site, this impact is likely minor due to its high overall energy demand and self sufficiency in electricity production. However, for industrial sites with greater dependence on grid supplied electricity, peak loads from charging may have a more significant influence on system performance and costs.

Overall, the findings indicate that electrification of heavy duty material handling equipment offers substantial potential for emission reductions. However, successful implementation depends on a careful balance between infrastructure investments, operational constraints, and integration with the surrounding energy system. Further work is required to assess the impact of future battery technologies, refined charging strategies, and site specific implementation considerations.



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# A

## Appendix 1

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