SMART CHARGING ZERO EMISSION CONSTRUCTION VEHICLES

GRADUATION THESIS FINAL REPORT

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Executive summary

The electrification of heavy machinery presents a new difficulty as the construction industry moves toward zero-emission operations, how to effectively charge these machines without putting an excessive strain on the local grid. This thesis explores the ways in which load cycle monitoring and intelligent charging techniques can use electric construction vehicles on actual construction sites.

The study's findings, which are based on data from TNO-monitored excavators and operational insights from GMB, show that medium and large electric machines use 200/ 415 kWh daily, with hourly peak reaching 52 kW. By distributing the load over a 12-hour period, a grid-friendly ramp-based charging profile was created using this data, reducing peak demand and guaranteeing full overnight charging.

Real-time parameters such as charging priority, power use, and state of charge were integrated into a digital dashboard design. Well-known protocols including OCPP, ISO 15118-20, and OpenADR were used to communicate between the system levels (vehicle, charger, backend, and grid). The technical architecture is prepared for future use, even though OEM support for interoperability is still lacking. The study also suggests a battery swapping technique to overcome charging limitations during day-time operation, which is normally from 7:00 to 16:00.

The feasibility of this strategy is confirmed by experts, although there are still issues, with standardization, DSO collaboration, and operational logistics. However, a solution is offered by smart charging with load-aware scheduling. For contractors, OEMs, and energy stakeholders looking to apply zero-emission construction, this thesis offers a practical, data-supported approach to electrified construction.

Abbreviations and Acronyms

ACRONYMS TABLE

Acronym	*Full Term*	*Short Explanation*
TNO	Netherlands Organisation for Applied Scientific Research	Dutch national research institute
GMB	GMB Civiel B.V.	Dutch construction company
HAN	HAN University of Applied Sciences	Dutch educational institution
DSO	Distribution System Operator	Entity managing the power distribution grid
CPO	Charge Point Operator	Operator of EV charging infrastructure
EV	Electric Vehicle	Vehicle powered by an electric battery
EVSE	Electric Vehicle Supply Equipment	EV charging station hardware
SoC	State of Charge	Battery's remaining charge level
TOU	Time-of-Use (Tariff)	Electricity price varying by time of day
OCPP	Open Charge Point Protocol	Standard for communication with EV chargers
OSCP	Open Smart Charging Protocol	Protocol for smart charging communication
Open ADR	Open Automated Demand Response	Protocol for grid demand response signals
API	Application Programming Interface	Interface for software communication
IEC	International Electrotechnical Commission	Global standards organization for electrical tech.
ISO	International Organization for Standardization	International standards body
HVAC	Heating, Ventilation, and Air Conditioning	Climate control systems
OEM	Original Equipment Manufacturer	Equipment manufacturer
MATLAB	Matrix Laboratory	Numerical computing software
RAP	Regulatory Assistance Project	Organization for energy policy research
ID	Identification	Unique identifier for vehicles or chargers

SYNONYMS TABLE

Term	*Synonym*	*Description*
Charging session	Charging event	One complete cycle of charging a vehicle
Peak load	Peak demand	The highest power demand at a given time
Off-peak hours	Low-demand hours	Times when electricity demand and prices are lower
Smart charging	Intelligent charging management	Optimized charging based on grid/pricing signals
Charging schedule	Charging plan	Planned timing or sequence for charging vehicles
Backend system	Server-side system	System handling data processing and control tasks
Battery capacity	Energy storage capacity	Total energy the battery can store
Load distribution	Load balancing	Spreading demand to avoid overloading the grid
Grid	Electricity network	System for delivering electric power

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Introduction

The transition to zero-emission construction is very important to meet Dutch climate targets under the Klimaatakkoord, Schone Lucht Akkoord, and SEB-convenant. Electrification of heavy-duty machinery introduces new challenges such as high energy demands that strain grids. Without intelligent charging strategies, this transition risks grid congestion. Smart scheduling, real-time data monitoring, are key to managing these risks.

This research, made within the build-zero program with partners ElaadNL and HAN University of Applied Sciences, investigates the feasibility of real-time smart charging for electric construction vehicles. It explores how data analysis, communication protocols, and dashboard tools can improve grid coordination and operational efficiency.

The study is guided by the main research question:

Is it technically and operationally feasible to implement real-time monitoring and data communication between grid infrastructure, chargers, and heavy-duty zero-emission construction vehicles using a dashboard-based system, and what information is required to enable visibility and control of grid congestion?

This is supported by three sub-questions:

1. What charging trends, peak loads, efficiency patterns, and energy use metrics can be extracted from real-world or simulated load cycle data?
2. How are parameters like voltage, power, and state of charge measured and communicated across vehicles, chargers, and the grid; and does the grid respond to individual values or only to total load?
3. Can a dashboard interface be developed to visualize charging data in real time, and is it feasible to integrate planning features like slot reservations and equipment scheduling?

These questions are addressed through the first three chapters:

- Chapter 1 **–** Load cycle analysis
- Chapter 2 **–** Data communication and parameter extraction
- Chapter 3 **–** Feasibility of a Dashboard integration

The first three chapters act as a base for the next 4 chapters. Chapter 4 provides a scope analysis and the results of the main and sub-questions, recommendations for contractors and grid stakeholders is addressed in chapter 5, expert reflections is spoken about in chapter 6, and finally the concluding's of the report with a summary of findings and suggestions for future work comes in the final chapter of this report, chapter 7.

1. Load Cycle Analysis

1.1 INTRODUCTION

This section presents the results of the data analysis conducted based on field-monitored data from electric construction vehicles, charger types, and grid interactions. Based on data from TNO and GMB, the data was processed and visualized in MATLAB. The aim is to identify charging patterns, peak loads, and efficiencies to make a smart charging strategy.

1.2 HOURLY CHARGING DEMAND

Figure 1.1 –DX165W (top) and DX355LC (bottom). These two electric excavators were used in the TNO study to collect energy consumption data for heavy-duty zero-emission construction. The DX165W (17-ton wheeled) represents a medium-sized vehicle based on SEB categories, while the DX355LC (35-ton tracked) is classified as large. *Source: TNO (2024), "Technische eindrapportage Bouwplaats van Morgen", P11947.*

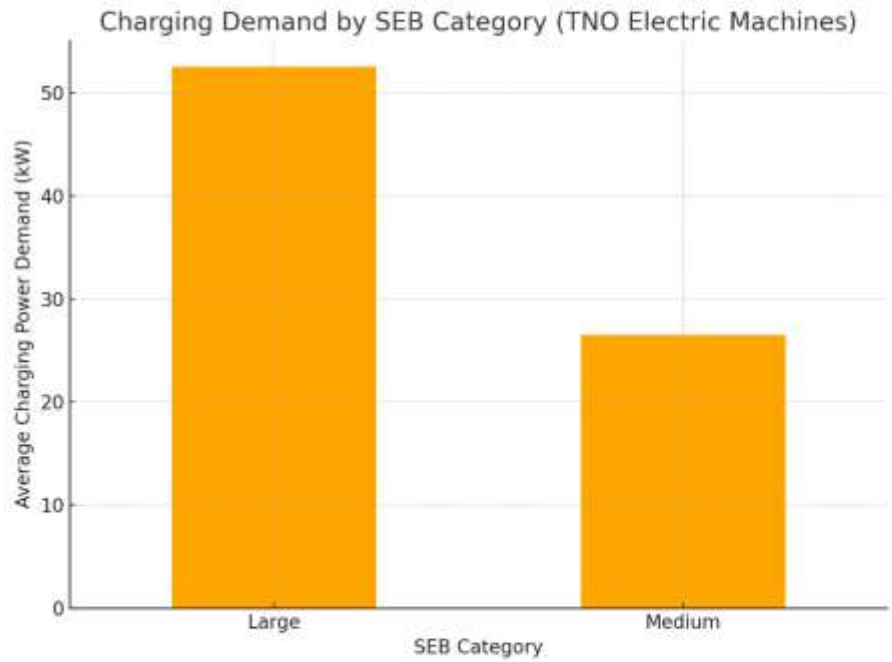


Figure 1.2– Hourly charging demand based on electric construction vehicle data from the TNO dataset.

The chart shows the average hourly charging demand by SEB category, based on electric machine data from the TNO field study, *for the source and the dataset extracted from the source please refer to* ***appendix B and C***. The 'Large' SEB category represents the 35-ton DX355LC, while the 'Medium' category shows the 17-ton DX165W. These categories align with SEB classifications, *for the source used to separate the vehicles in SEB categories please refer to* ***appendix F***. Large machines show a higher charging load per hour (52 kW) compared to medium machines (28 kW), which shows their more energy-intensive consumption.

Note: Small SEBs are not shown, as no electric vehicle data was available for this category in the TNO study.

1.3 NOMINAL DAILY ENERGY USE

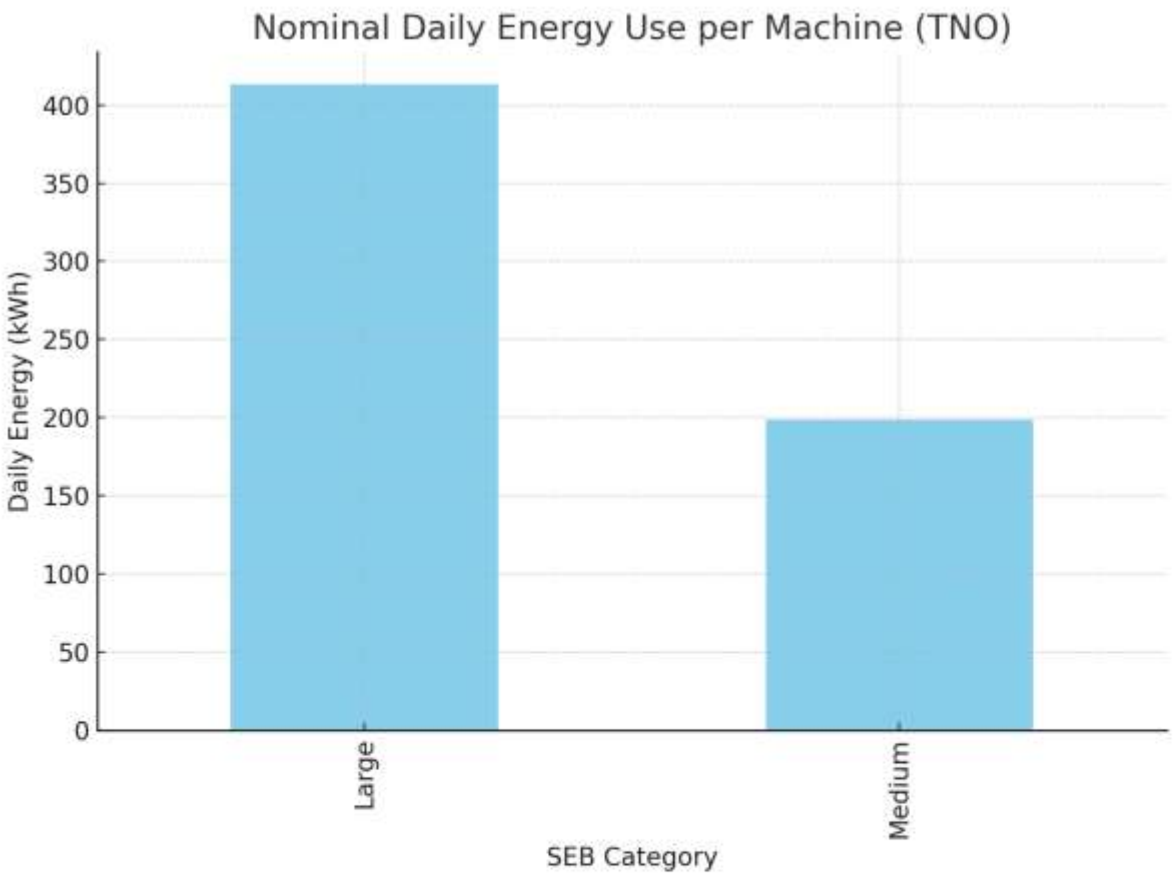


Figure 1.3 –Average daily energy consumption per machine based on electric machine data from the TNO dataset.

The graph presents the average daily energy consumption per machine for two SEB categories, based on electric machine data from the TNO dataset, *for the source and the dataset extracted from the source please refer to **appendix B and C*** and *for the source used to derive the vehicles in SEB categories please refer to **appendix F.*** Large machines consume approximately 415 kWh per day, while medium machines use around 200 kWh. These values represent average energy use under normal operating conditions, without peak loads or fluctuations. Total site demand will vary based on the number of machines in the fleet.

Note: Small SEBs are not shown due to the absence of electric vehicle data in the TNO dataset.

1.4 MOTOR LOAD EFFICIENCY ACROSS CONSTRUCTION ACTIVITIES

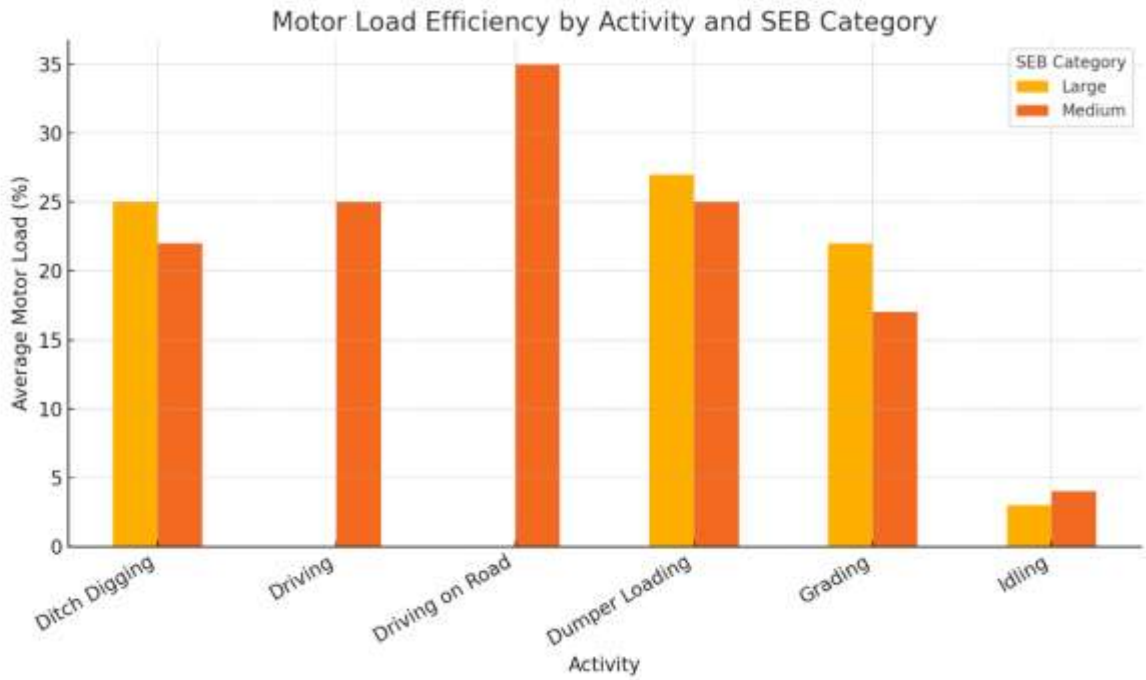


Figure 1.4 – *Average Motor Load Efficiency by Activity and SEB Category based on TNO electric machine data.*

The figure highlights how electric construction machines operate at different average motor load efficiencies (how much electric capacity is being used mechanically on average per activity) depending on activity and SEB category, *for the source and the dataset extracted from the source please refer to* ***appendix B and C*** and *for the source used to derive the vehicles in SEB categories please refer to* ***appendix F.*** The highest load efficiency is seen in the "Driving on Road" task for medium SEBs (35%), while the lowest is during "Idling" for both categories (3–4%), showing energy waste during inactive periods. The graph confirms that load demand is task-specific, which is relevant for charging infrastructure planning.

1.5 24-HOUR CHARGING LOAD CURVE (BASED ON HYBRID PROFILE)

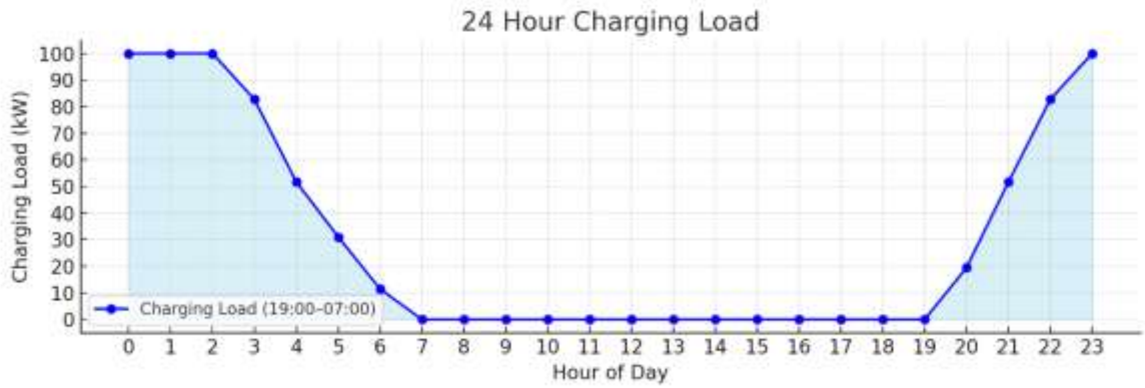


Figure 1.5 – Charging Load Curve

This graph presents a synthetic but realistic charging load on energy consumption from *the TNO P11947,* ***Appendix B and C***. It models two electric construction machines, the 17-ton DX165W (222 kWh/day) and the 35-ton DX355LC (409 kWh/day) , with a total of 631 kWh/day, across a 12-hour time frame. This graph shows a grid friendly curve where power builds up and later ramps down avoiding sudden peaks and not straining the grid. All charging is done at night because the vehicles are needed in the daytime. The off-peak rate in the Netherlands is at 23:00-07:00. [1] According to the Dutch Electricity law, consumers with a connection capacity up to 3×80 A (max. 100,000 kWh per year) are considered small consumers, while those exceeding this qualify as large consumers. Small consumers can benefit from grid management prices and tariffs during changes in on and off-peak hours however, large consumers are required to arrange their own contracts with the grid operator and metering company. [2] This is why when interviewing an expert in the field, *Gerard van der Veer, Manager Duurzaamheid Materieel, GMB Civiel B.V.*, he was asked if this would make a difference to charge at night due to off-peak limits and he said "it doesn't matter what time we charge as it would cost around 0.50 €/kwh for depot charging ", assuming from agreements with energy companies.

Using the standard three-phase power formula:

$$P = \sqrt{3} \times U \times I \times \cos(\emptyset) \quad [3]$$

- Voltage (U) = 400 V (standard in the Netherlands) [4]
- Current (I) = 80 A per phase
- Power factor (cos ϕ) = 1 (ideal case for resistive loads)

  The power is 55.4 kW.

  It is important to note that the formula assumes ideal conditions, for example no grid losses or ideal power factor.

This means a 3×80 A connection delivers a maximum continuous power of 55.4 kW, which is the maximum power to be considered a small consumer and be able to use off-peak tariffs. The total energy demand of 631 kWh**,** the connection 3×80 A would not allow enough flexibility to charge in off-peak hours without exceeding the power limit, mathematically. Therefore, the choice was for the 3x160A connection.

[5] Using the previous formula this gives a maximum continuous power of 110.8 kW which allows the 100-kW peak on the graph to be feasible. The total area under the graph was calculated by splitting it into several shapes and calculating the area of each shape giving a total of the expected 631 kWh. Below the exact method is shown:

$$100.0 \times 2 = 200.00\, kWh$$

$$½ \times (100.0 + 82.76) \times 1 = 91.38\, kWh$$

$$½ \times (82.76 + 51.72) \times 1 = 67.24\, kWh$$

$$½ \times (51.72 + 31.03) \times 1 = 41.38\, kWh$$

$$½ \times (31.03 + 11.5) \times 1 = 21.27\, kWh$$

$$½ \times (11.5 + 0.0) \times 1 = 5.75\, kWh$$

$$½ \times (19.54 + 51.72) \times 1 = 35.63\, kWh$$

$$½ \times (51.72 + 82.76) \times 1 = 67.24\, kWh$$

$$½ \times 19.54 \times 1 = 9.77\, kWh$$

$$½ \times (82.76 + 100.0) \times 1 = 91.38\, kWh$$

Total Energy = 631.03 kWh

Finally, an important thing to note on this graph is that 631 kWh divided over a 12-hour period gives 52.38 kW. However, this would only be true if it was a constant load of 52.38 kW over a 12-hour period which is not grid friendly, hence the graph shape that is represented. *For more information on how this graph was derived please refer to **appendix G.*** Lastly, this strategy assumes a depot where swappable batteries are charged across multiple chargers. While this example models only two machines, it can also be interpreted as a depot scenario which can be scaled to reflect specific site needs.

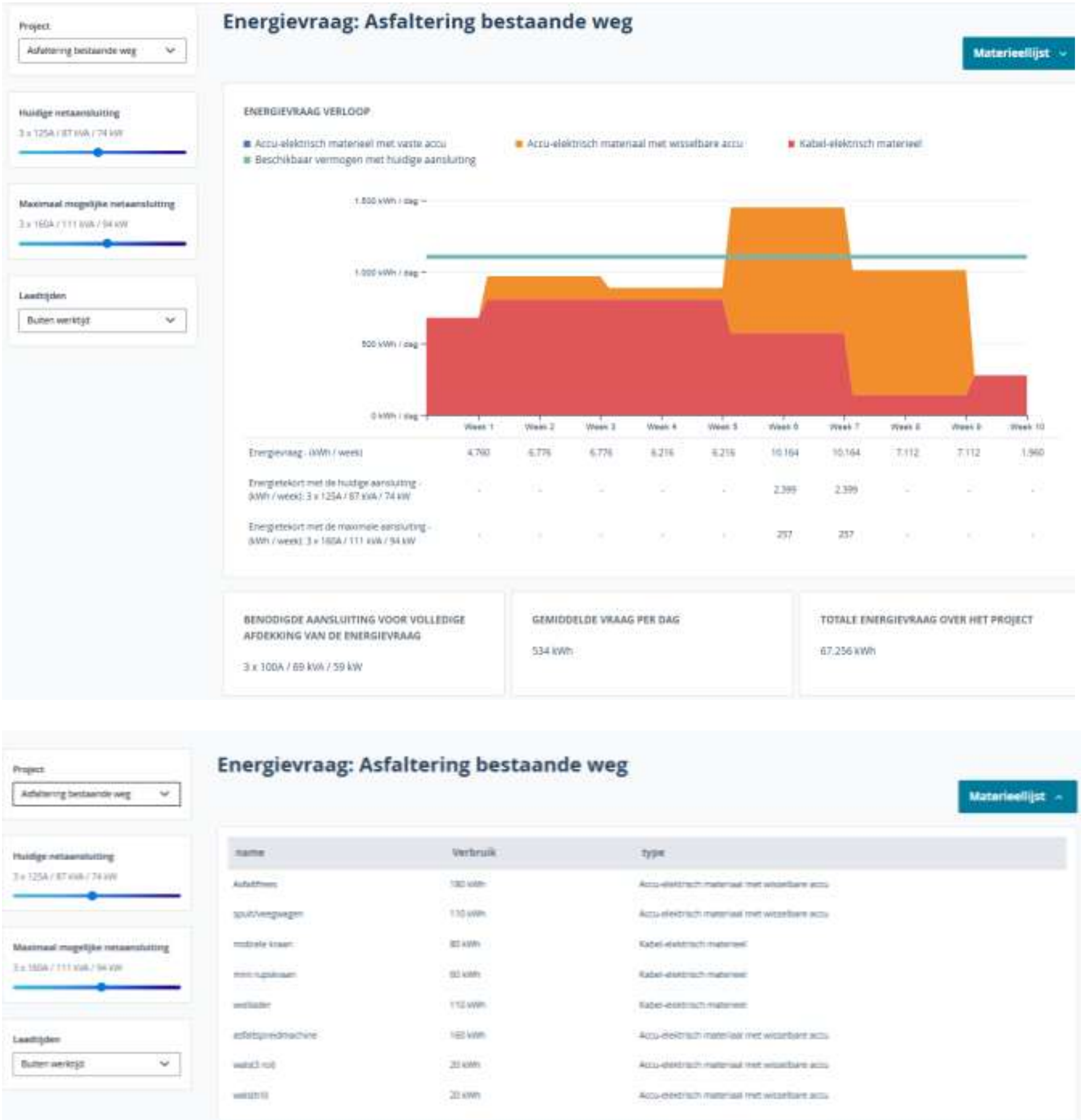


Figure 1.6 – Grid Feasibility Validation Using ElaadNL Vermogenstool ("Asfaltering bestaande weg" Scenario)

A tool is used to validate the analysis done above. [6] This simulation models eight electric construction machines with a combined average energy demand of 534 kWh, which was the closest kWh value to the 631 kWh from above, charged outside working hours. The selected connection size (3×125 A / 74 kW) gives some daily energy shortages, especially in weeks with higher demand. This simulation also uses 8 less energy intensive vehicles compared to the two very energy intensive vehicles in the analysis above.

Despite using more machines, the total daily energy consumption in the simulation remains lower than the 631 kWh/day. This shows that the two machines modelled in the original graph represent a high-load case. The tool shows that even with a 3×160 A (94 kW) connection, energy shortages can still occur when charging is restricted to off-peak hours. This validates the assumption made in the graph that a 100-kW peak demand and a 12-hour charging window would be required to recharge the vehicles overnight. The key difference is that the ElaadNL tool uses a static load profile, whereas the analysis above uses a gradual ramp-up and ramp-down to reduce grid stress. This makes the graph more grid-friendly.

1.6 APPLYING THE DATA ANALYSIS TO A CASE STUDY

We can take The Kempower charging system at WattHub with a capacity of 3.6MW, using six 600 kW power units and 36 satellite chargers. This place is designed to charge electric trucks and heavy machinery. [7]

Applying this, For WattHub, an educated estimate of **15% internal consumption** is used to account for energy required internally, including office buildings, lighting, cooling systems, and grid conversion losses. This leaves **approximately 3.06 MW of usable charging power** from the total 3.6 MW capacity.

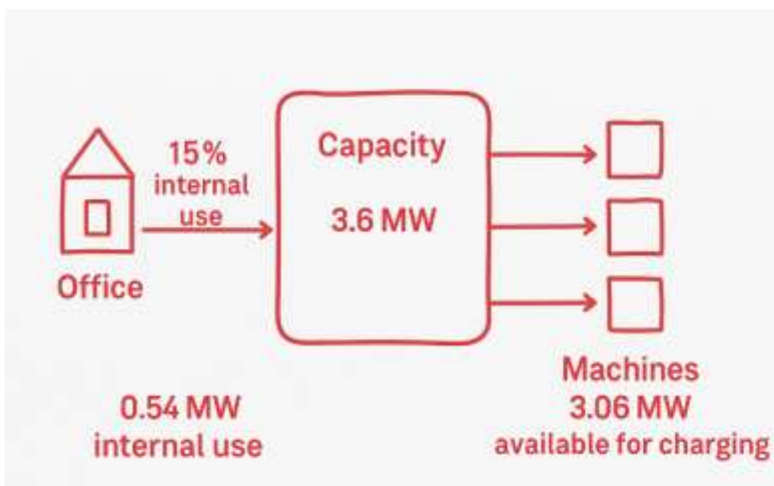


Figure 1.7– Power usage split at WattHub.

Charging Capacity Calculation

To transfer the energy requirements from the data analysis into practical charging facility needs, the total usable capacity of WattHub must be considered. Assuming WattHub offers a peak capacity of 3.6 MW and that charging is only done in off-shift hours, between 16:00 and 06:30, gives 14.5 hours per day for charging. Assuming the 15% internal energy use (0.54 MW which is more than enough for internal usage), in this scenario, the charging energy available is:

$3600\ kW \times 14.5\ hours = 52{,}200\ kWh$
$52{,}200\ kWh \times 0.85 = 44{,}370\ kWh$ usable

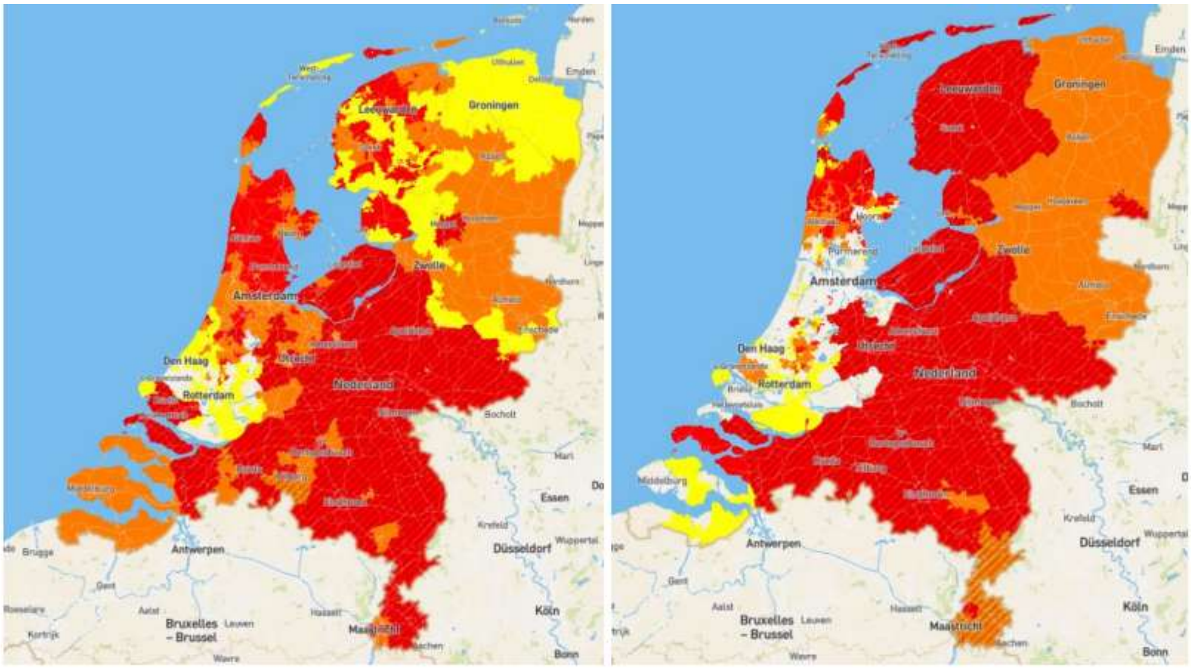
Using daily energy consumption values of approximately **200 kWh/day** for medium-sized machines and **415 kWh/day** for large-sized machines (based on figure 1.3 data analysis), WattHub could theoretically charge:

$44{,}370\ kWh \div 200\ kWh/machine$ = 221 medium-sized machines

$44{,}370\ kWh \div 415\ kWh/machine$ = 107 large-sized machines

It is important to note that no construction company charges or use this many electric construction vehicles at the moment, so this is the theoretical maximum upper bound of electric machines that Watthub can charge over a 14.5 hours.

Since the energy load exceeds way above the limit of a small consumer, we consider this as a large consumer. This means that no benefits apply to off-peak tariffs, same as the analysis in figure 1.5 but at a much larger scale. However, it is important to note that charging 221 medium and 107 large vehicles overnight is technically and mathematically possible but it does not meet the project goals. The reasons are that it is not smart to do this at the moment because doing so would place a huge load on the grid due to the current congestion in the Netherlands. This is because the electricity grid in all provinces in the Netherlands is mostly full, making many companies wait on the waiting list for grid connections for their respective needs so therefore grid infrastructure improvement would be needed to overcome this problem firstly. [8] The diagram below shows the current congestion situation in the Netherlands:



Meaning of the color codes

○Transparent: Transport capacity available
●Yellow: Limited transport capacity available
●Orange: No transport capacity available for the time being pending the outcome of the congestion management study
●Red: No transport capacity available: congestion management cannot be applied

With congestion management:

Transparent hatched: Transport capacity available based on application of congestion management
Shaded yellow: Limited transport capacity available based on application of congestion management
Shaded orange: No transport capacity available for the time being pending distribution of the released capacity over the queue based on congestion management. (it is still unclear whether and how much power will become available for new requests that are not yet in the queue)
Shaded in red: No transport capacity available: the limits for the application of congestion management have been reached.

Figure 1.8– Grid availability for new load (left) and (right) for above 3*80 A. Source: RAP (2024), "The Netherlands' Gridlock: How to Unlock the Power Grid for the Energy Transition."

To charge this many vehicles and for it to be charged in a smart and grid friendly way, it needs to follow a similar load profile as the one shown in figure 1.5, which ramps up and down gradually. This approach spreads the load, which is better for the transformer and cables logically, due to less stress. By spreading the load over time and avoiding sudden peaks, such a profile makes large-scale electrification more realistic.

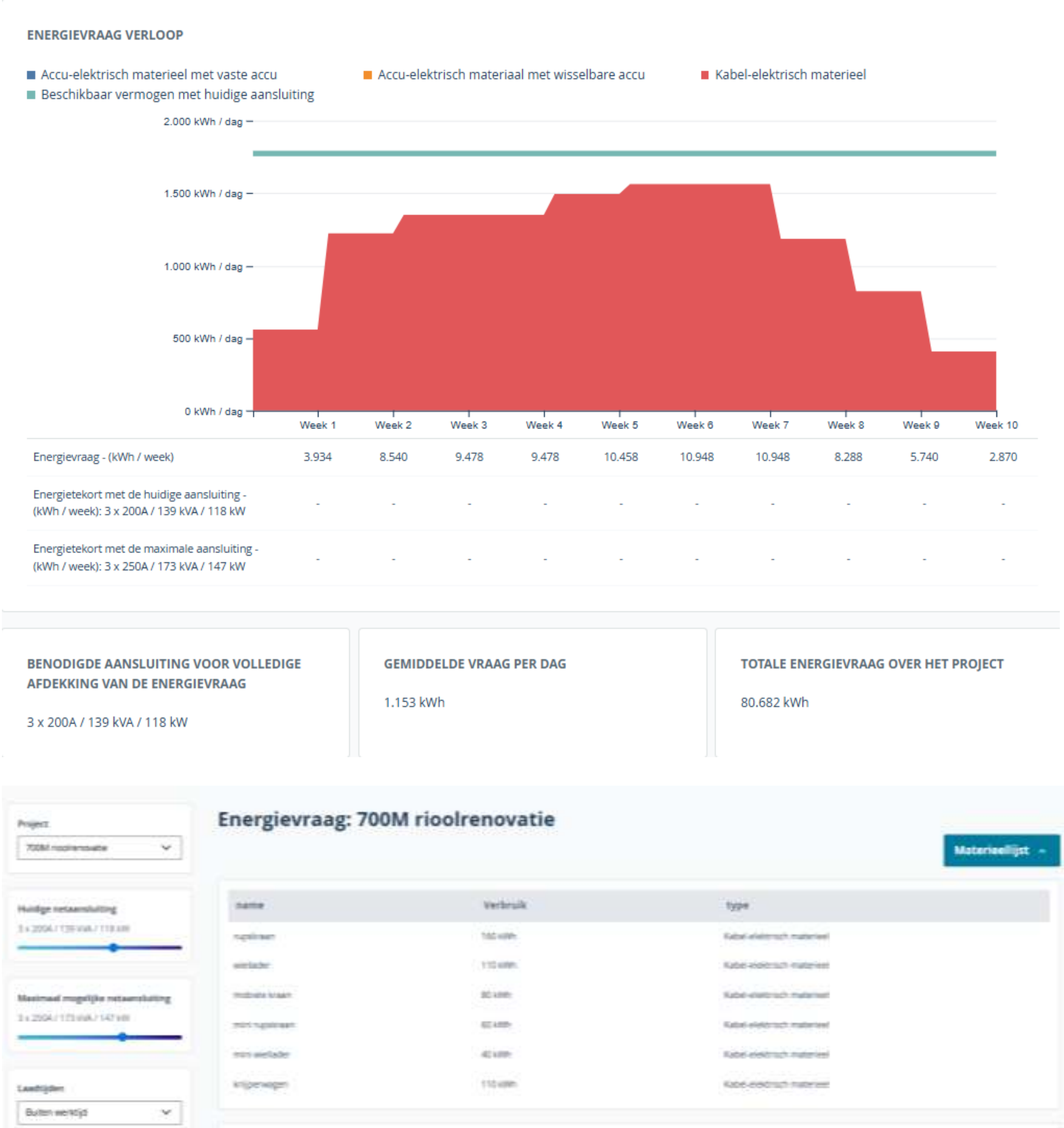


Figure 1.9 – Grid Feasibility Validation Using ElaadNL Vermogenstool ("700M rioolrenovatie" Scenario)

While the theoretical capacity of WattHub allows for a maximum charging output of approximately 44,370 kWh/day, using the tool from earlier, shows projects such as the, *700M rioolrenovatie,* show that currently realistic daily charging capacities are closer to 1,100 kWh/day. The project includes six cable-electric machines such as cranes, wheel loaders, and mini-excavators, all powered by 3×200A connection to avoid shortages throughout the project. Even under this high grid capacity and charging only during off-peak hours, the power demand remains far below the capacity of WattHub.

This shows that, under current Dutch grid infrastructure and allowable connection sizes, large-scale overnight charging of 300+ electric machines are not feasible without grid improvements. This once again shows the importance smart load distribution**,** energy management, and planning with DSOs.

1.7 CONSTRAINT SCENARIO

Even though WattHub can support 3.6 MW, let's assume a scenario where there is a constraint, and only **2.8 MW** is provided.

In the real-world, the available power often limited by the Distribution System Operator (DSO). Even if a WattHub is technically capable of delivering 3.6 MW, DSO constraints can reduce the capacity. To show this, consider a grid limitation scenario where only 2.8 MW is provided:

Accounting for internal usage (15% for offices, lighting, HVAC, etc.), the usable charging power is:

$$2.8\, MW \times 0.85 = 2.38\, MW\ usable$$

With the standard charging window of 14.5 hours (16:00–06:30), this gives a total available energy:

$$2.38\, MW \times 14.5\, h = 34{,}510\, kWh$$

This allows for charging:

- $34{,}510 \div 200 = 172\ medium - sized\ machines$
- $34{,}510 \div 415 = 83\ large - sized\ machines$

This is significantly less vehicles than the theoretical maximum previously calculated, however, if the construction site needs to charge the original fleet (221 medium or 107 large machines requiring 44,370 kWh), this energy shortage must be addressed. Two realistic options are:

1. To deliver the 44,370 kWh with reduced power (2.38 MW), but more charging time is needed:

$$44{,}370\, kWh \div 2.38\, MW = 18.64\, hours$$

   For this option it is required to start earlier (before 16:00) or continue later (after 06:30). This is only feasible if local regulations and operations allow it.

2. If the 14.5-hour window cannot be extended, apply smart charging methods:

- Do not charge all vehicles at the same time

- Prioritize based on battery SoC, job urgency, or machine type
- Add a second or third charging slot, for example during lunch break

These strategies show the need for smart dashboard for logistical purposes. While current electric construction sites use around 5–20 electric construction machines, this analysis shows the upper bounds of a depot like WattHub operating under 3.6MW capacity or a 2.8 MW constraint. This serves as a future capacity target of fully electrified construction sites.

2. Data Communication & Parameter Extraction

2.1 INTRODUCTION

Reliable data communication and parameter extraction are critical for connecting electric vehicles, charging stations, and the power grid. They enable real-time monitoring, smart energy management, and system reliability.

2.2 PARAMETER MONITORING OVERVIEW

This section determines the key charging parameters that must be monitored and communicated for effective smart charging. These are put into three categories: vehicle, charging station, and grid. These parameters are used as input for the dashboard mock up in chapter 3. These parameters were determined based on real-life observations of dashboards at ElaadNL and logical thinking of what would be needed, as well as speaking with my graduation project tutor, Rene Beem , Lecturer at HAN University of Applied Sciences / HAN Academy Engineering and Automotive.

2.2.1 Vehicle Level

Vehicle ID: Identifies the vehicle that will be charged.

State of Charge (SoC) Measurement: The SoC represents the remaining energy in the battery relative to its total capacity. Also used to decide whether charging urgency is needed or not.

Battery Capacity (kWh): Total energy storage capacity which is needed to calculate charging time period.

Arrival/departure time: Tells the system when the vehicle began and stopped charging

Charging Priority: Helps schedule urgent vehicles first.

2.2.2 Charging Station Level

Charger ID: Identifies the charging station.

Charger status: States if the charger is available or in use. It should state free/in-use/offline.

Charging capacity: Indicates how much each charger can deliver energy.

Power taken from each connection: Shows the real-time power (kW) drawn by each charger (advised by my tutor, Rene Beem).

2.2.3 Grid Level

Time-of-Use Tariffs (€/kWh by hour): Enables the system to avoid expensive time windows, if applicable.

Power Constraints alerts: Grid load limits that must not be exceeded.

Total Available Power at facility (excluding internal use): Sets the maximum combined load, the system can handle.

2.3 COMMUNICATION PROTOCOLS AND THE SHARED PARAMETERS

Communication protocols are crucial for enabling interoperability, secure data exchange, and advanced functionalities within electric vehicle (EV) charging infrastructure. They allow data exchange between EVs, chargers, backend systems, and the grid. This chapter determines the overview of the most relevant protocols. It is important to note there is no current communication standard that allows all the relevant parameters mentioned in the previous chapter, to be communicated from the grid to the dashboard for EV construction vehicle charging. This concept is strictly for possibilities for a future proof implementation. However, the protocols mentioned are all currently used for EVs just not the exact way intended for this thesis assignment.

Firstly, it is important to talk about the backend and API as they play a very big role here. The server-side part of a program that manages data processing, business logic, and storage is called a backend system. It serves as the application's brain, handling calculations and communicating with databases and other data sources. Python, Java and other programming languages can be used to create backend systems. Client applications (web, mobile, or other third-party services) and backend systems are connected by APIs. They give customers an interface which they can communicate with the backend system, requesting information and carrying out actions. In order to provide smooth communication and data sharing, backend systems and APIs must be integrated. The API layer receives a request from a client application to this endpoint, retrieves the required parameters and then interacts with the backend system to retrieve the user data that was requested. [9]

The section below shows the protocols needed the parameters they share and a small explanation from the grid to the dashboard:

1. DSO (distribution system operator) → *CPO (charge point operator) backend (mainly one way)*

    - **Purpose**: Allows CPO to know when and how much power is drawn and allows backend for smart load management.
    - **Protocols used:** Open ADR and OSCP
    - **Parameters shared:** Power capacity (power available) is shared with the OSCP protocol which can then determine power constraints and give alerts in case of this. TOU tariff data is shared via the Open ADR protocol.

2. CPO backend ⇄ Charging station, EVSE (bidirectional)

- **Purpose**: Charging station gives real-time data to backend which backend then sends commands such as, reduce power or delay.
- **Protocols used:** *OCPP*
- **Parameters shared**: Charging limit (capacity), charging schedule (status, available or in use), metering information (power drawn), charger ID

3. EVSE ⇄ EV (bidirectional)

- **Purpose**: Allows exchange of vehicle data and charging preferences with the charging station to optimize charging.
- **Protocols used:** *ISO 15118-20, because it is the most modern version from IEC 61851 and ISO 15118-2, therefore more options and possibilities*
- **Parameters shared:** Vehicle ID, State of charge, charging schedule (such as arrival/departure time and charging priority) and battery capacity. [10]

4. CPO backend →/⇄ Dashboard

- **Purpose**: Provides real-time monitoring and system control by merging data from EVs, chargers, and the grid and visualising on the dashboard.
- **Protocols used:** *API*
- **Parameters shared:** All parameters gathered via previous protocols (SoC, TOU tariff, vehicle ID, etc.)

  [11]

Below is a representation of how the system works and the protocols used to transport information between each component:

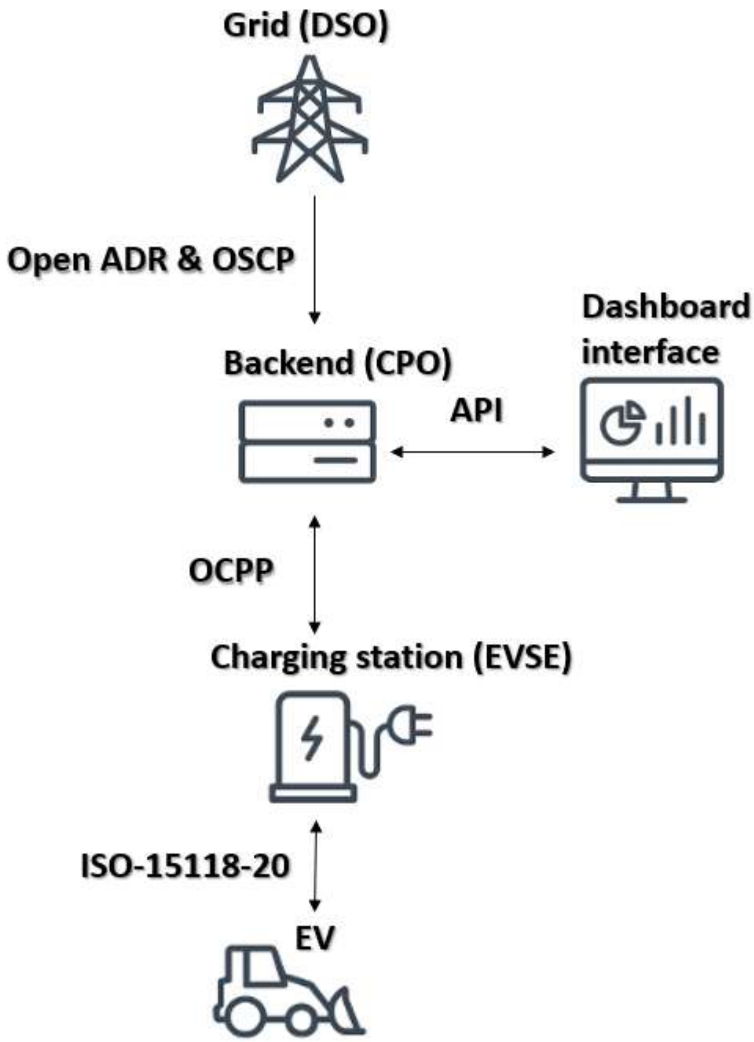


Figure 2.1: Communication architecture showing protocols between grid, charging station, construction EV, and dashboard. *This image was generated using AI (ChatGPT by OpenAI).*

At the top of the diagram is the Grid (Distribution System Operator, DSO), which manages the distribution of electrical power. Communication between the grid and the Backend system operated by the Charge Point Operator (CPO) occurs via Open Automated Demand Response (Open ADR) and Open Smart Charging Protocol (OSCP). These protocols enable the grid to send demand response signals and manage power loads by informing the backend about available capacity and power constraints.

The Backend (CPO) acts as the central data processing and control hub and communicates with both the charging stations and the dashboard interface. Interaction between the backend and the Dashboard interface takes place through standardized APIs, which enable real-time data visualization and system monitoring for operators.

Communication between the backend and the Charging Station (Electric Vehicle Supply Equipment, EVSE) is made via the Open Charge Point Protocol (OCPP). This bidirectional protocol manages charging sessions, including status updates, charging schedules, and commands such as start and stop.

Between the Charging Station (EVSE) and the Electric Vehicle (EV) the communication used is the modern ISO 15118-20 standard. This protocol supports bidirectional exchange of data such as vehicle state of charge, battery capacity, and arrival/departure times.

2.4 BATTERY CAPACITY IDENTIFICATION VIA SOC INTEGRATION ON THE DASHBOARD

Battery capacity is a very important parameter to analyse logistically. To determine the battery capacity of electric construction vehicle the dashboard captures:

- SOC initial in %
- SOC final in %
- ΔSOC= $\frac{SOCfinal-SOCinitial}{100}$
- Ib(t) current at each time step in Amperes (A)
- Δt sampling interval in seconds
- Iloss(t) current loss in Amperes (A)

Using these values, it applies the programmed formula:

$$\mathrm{SOC}(t0+\tau) = \mathrm{SOC}(t0) + \frac{1}{\mathrm{C\ rated}} \int_{t0}^{t0+\tau} (\mathrm{Ib}(t) - \mathrm{Iloss}(t))\, dt \quad [12]$$

$$\Delta\mathrm{SOC} = \mathrm{SOC}(t0+\tau) - \mathrm{SOC}(t0)$$

$$\Delta\mathrm{SOC} = \frac{1}{\mathrm{C\ rated}} \int_{t0}^{t0+\tau} (\mathrm{Ib}(t) - \mathrm{Iloss}(t))\, dt$$

Rearranging:

$$\boldsymbol{C\ rated} = \frac{\int_{t0}^{t0+\tau} \left(\mathbf{Ib}(\mathbf{t}) - \mathbf{Iloss}(\mathbf{t})\right)}{\boldsymbol{\Delta}\mathbf{SOC}}$$

It is important to note that any error in SOC or current will result in an inaccurate reading from the formula. It also must be mentioned that Battery capacity is temperature dependent.

On the dashboard it will be implemented in this format considering the data samples:

$$C\ rated = \frac{\sum (Ib[k] - Iloss[k])\Delta t}{\Delta SOC}$$

Where k is the discrete time index in a sample.

The estimated capacity is then stated next to vehicle ID in the dashboard and is used to validate charging predictions, to support charging adjustments (e.g., reduce power if battery is smaller than expected) and helps identify problems such as degraded batteries or incorrect SoC sensors.

2.5 THIRD PARTY ACCESS AND CHALLENGES

This section is about the third-party access and challenges of real-time data and communication within EV charging networks, based on current technologies.

2.5.1 Data Access for Third Parties

Many EV charging networks have Application Programming Interfaces (APIs) that makes it possible for companies to use EV charging software solutions that can improve station administration, integrate third-party systems, and offer new experiences.

For example, platforms like EV Bahan, who are one of the best in the API market, allow access to data on power usage, and station status, and manage energy distribution. With the help of these APIs, developers may enable the industry to provide software solutions that easily interface with a wide range of hardware.

These APIs typically expose parameters such as:

- Charging station status (e.g., available, in use)
- Power usage
- Charging session history
- Billing and payments

Below is shown an image of how an API works:

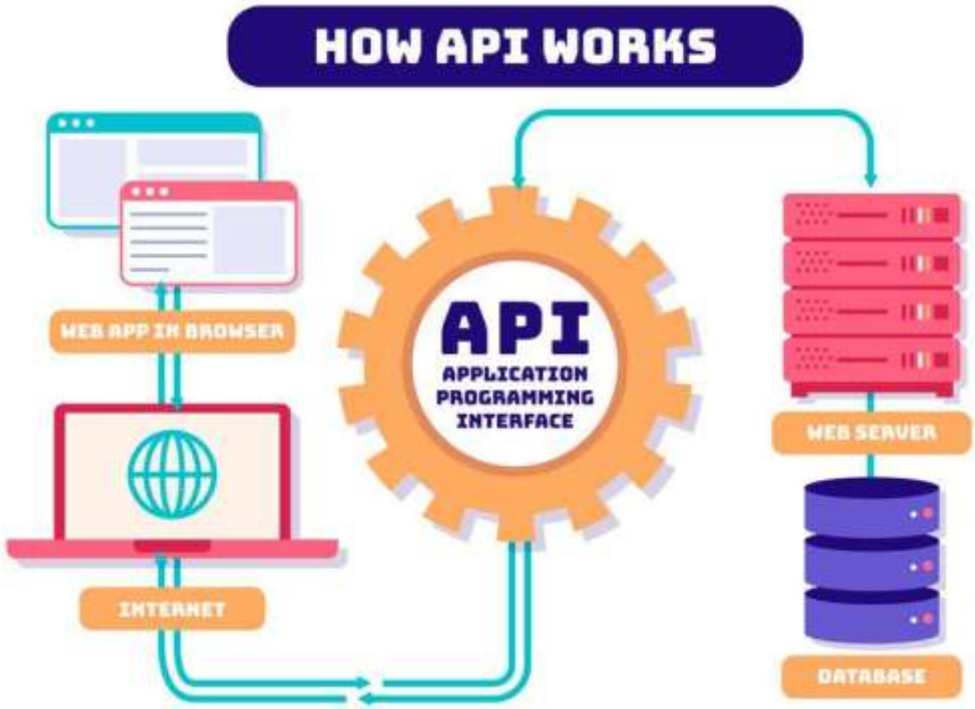


Figure 2.2: An example of an API in action. A web application is accessed by a user via a browser that connects to an API (Application Programming Interface) via the internet. By sending queries to the web server, which retrieves data from the database, the API serves as a link between the web application and the backend system, as mentioned previously. For a smooth data interaction, the response is sent back to the user interface via the API. Source: EV Bahan control "Ev charger API: the ultimate guide."

Restrictions and Authentication:

- Registration: The first step in the process is to submit a request for API access to the manufacturer on the charger OEM's platform.
- API Key: You will receive an API key upon registration, unique identification to the API.
- Documentation: Every manufacturer makes detailed API documentation available to the public, explaining authentication queries, and how to get data.
- Testing: You will have access to sandbox environments prior to going live, which will allow you to test your integrations.
- API Integration: After that, you'll include the API into your software program and make sure that every endpoint is operational for your use case.
  [13]

2.5.2 Challenges

- **Data Accuracy and Update Delays:** Drivers may become irritated by delays in real-time updates, particularly when chargers are listed as available but are actually being used.
- **Integration Challenges with Legacy Systems:** These systems might not be able to meet the needs of processing data in real time, which could result in inconsistent user experiences.
- **Interoperability Issues Among Service Providers:** A major obstacle to interoperability is the usage of incompatible systems by various service providers. Providing dependable real-time support requires that all providers be able to collaborate easily.
- **Data Privacy and Security Concerns:** When it comes to providing EV drivers with real-time help, data security and privacy are crucial issues. Gaining confidence in these systems requires protecting drivers' financial and personal data.
  [14]

3 Feasibility of Dashboard Integration

3.1 INTRODUCTION

With the rise of electric construction vehicles, the need for management of their charging is becoming more necessary. A dashboard can allow operators to monitor, plan, and manage energy use on-site. By visualizing the necessary parameters, dashboards help reduce energy waste and improve logistics. Features, like slot reservations and scheduling, allow for this to happen. This section explores the feasibility of a dashboard designed for zero-emission construction sites, focusing on its key components, planning capabilities, and technical disadvantages.

3.2 DASHBOARD DESIGN

Figure 3.1 – Dashboard Interface Mock-Up for EV Charging *This image was generated using AI (ChatGPT by OpenAI).*

The smart charging dashboard mock-up (figure 3.1), shows the parameters required for effective energy management of zero-emission construction vehicles. The interface is structured around three key data levels, Vehicle, Charging Station, and Grid (from chapter 2.2), and is designed to show real-time data updates, prioritize charging order, and align with power constraints.

At the vehicle level, the dashboard includes five construction vehicles with indicators needed for decision-making. These are:
- Vehicle ID: Unique identifier (e.g., EX-002)
- State of Charge (SoC): Battery fill level in %
- Battery Capacity (kWh): Indicates the total energy storage of the vehicle
- Arrival and Departure Times: Defines available time frame for charging
- Charging Priority: Indicates urgency (High, Medium, Low)

This structure allows operators to make smart scheduling decisions. For example, vehicle TR-007 has a large battery (400 kWh), a low SoC (25%), and high priority, indicating it should be charged early at the time of available power .

At charger station level, it shows the status and performance of each charger unit, including:
- Charger ID and Status (In Use / Free)
- Charging Capacity (kW): Max delivery rate per charger

- Total Available Power: Site power limit, taken from Chapter 1 WattHub grid constraint scenario, 2800 kW. This data is taken from grid level to the EVSE via the backend which is then presented on the dashboard with the API. This information is relevant for charging station level because it allows it to adjust charging based on the amount of power available.
- Connected Vehicles: Shows how many EVs share the charger.
- Power Taken (kW): Actual real-time power drawn, which must stay within charger limits, for example CH-04 has a capacity of 250 kW and serves three machines (EX-002, EX-003, TR-007), together drawing 220 kW. This remains within its 250-kW capacity.

The grid level contains two indicators that help operators manage logistics:
- Power Constraints – Alerts: Warns if site depot is close to maximum load or any other technical errors.
- Time-of-Use (ToU) Tariffs: A graph showing electricity prices throughout the day. Operators avoid peak-rate charging during high-tariff times (e.g., €0.60/kWh between 13:00 and 17:00). These ToU values were determined by speaking with a grid infrastructure professional, *Gerard van der Veer, Manager Duurzaamheid Materieel, GMB Civiel B.V.* It is important to mention that this is only applicable to "Small consumer depots" and not "Large consumer depots" as they make their own agreements with DSOs, *refer to back chapter 1.5*.

Real time data should potentially build up to be updated almost instantly with upcoming technologies in order to maintain situational awareness. [15]

3.3 PLANNING FUNCTIONALITIES

Planning functionalities in EV charging dashboards are crucial for operational efficiency on zero-emission construction sites. Key features include slot reservation, and charge queuing systems, which prioritize charging based on urgency and SoC levels. Below is a diagram of how this process would plan out.

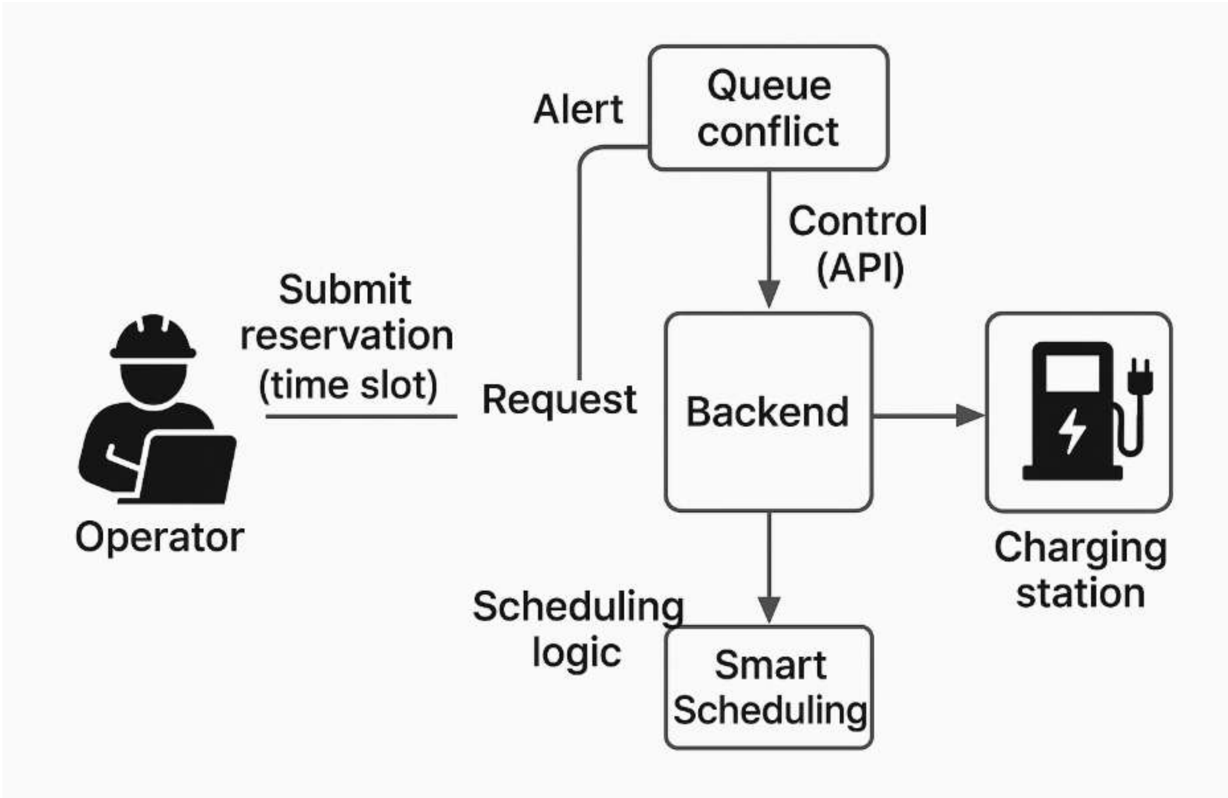


Figure 3.2 – Smart Scheduling Logic for EV Charging *This image was generated using AI (ChatGPT by OpenAI).*

This diagram shows a smart scheduling architecture specifically for electric vehicle (EV) charging on construction sites. In this system, when an operator submits a reservation request for a specific time slot, it is first processed by the backend. The backend acts as a central hub that handles communication between the operator, the smart scheduling, and the charging stations. It uses APIs to control and monitor the charging infrastructure in real time. Based on factors such as State of Charge (SoC), urgency, and station availability, the backend uses the smart scheduling logic to make the sensible charging slot. If a conflict arises, for example multiple vehicles requesting the same time slots, an alert is generated and sent to the operator, who allows him to correct this action.

Modern backend systems enable automated scheduling through external API tools. For example, Smartcar's API allows access to a vehicle's SoC and charging status, allowing automation of when and how long to charge. [16]

In construction site, this allow users to:

- Reserve charging slots during availabilities.
- Automatically assign stations to high-priority vehicles.
- Receive alerts when delays or constraints disturbs the schedule.

These planning tools help not only reduce energy costs and prevent overloads, but also assign operations with grid availability.

3.4 CHALLENGES AND DRAWBACKS

While the report has discussed already that real-time dashboard for electric vehicle (EV) charging on zero-emission construction sites is technically feasible and beneficial but like everything, it comes with challenges.

To better present pros and cons, Table 1 presents a SWOT analysis of dashboard feasibility:

Strengths	**Weaknesses**
Reduced energy costs and better operational efficiency	Technology not fully up to date to be implemented yet
Better user satisfaction due to access and transparency of data and being able to adjust them based on preferences.	Current insufficient authentication
Keeps an eye on system health and therefore it's possible to solve problems at early stages, reduced maintenance costs.	Employee training is needed to train employees on the technology which requires needed extra costs

Opportunities	**Threats**
Allows integration of system in real time.	Dashboards rely on APIs (for billing, scheduling, user access). If these are not properly validated or secured it can create data theft or unauthorized control over infrastructure
Grid interaction, and future readiness as EV demand increases are ensured by a smart EV charging dashboard's smooth integration with technologies like V2G (vehicle to grid) and smart grids.	Virus and malware attacks through third parties
Scalability opportunities, platform can grow with the business, adding more vehicles, stations, and users	Complex systems can cause applicational vulnerabilities

Table 1 – SWOT Analysis of Dashboard Feasibility for EV Charging

[17], [18], [19]

4 Research Question Analysis and Findings

This chapter uses the research done on chapter 1-3 to answer the main research question and the three sub-questions mentioned in the Plan of approach document.

4.1 SUB-QUESTION 1: LOAD CYCLE BEHAVIOR AND ENERGY METRICS

What charging trends, peak load behaviours, energy efficiency patterns, and total energy consumption metrics can be extracted from real-world or simulated load cycle data?

Electric construction machines need to be charged at night in order to be usable during the day, according to the data presented in Chapter 1. The best way to reduce grid stress is to use a ramp-up/ramp-down profile that is compatible with the grid.

Medium cars (like the DX165W) have peak hourly demands of about 28 kW, whereas large vehicles (like the DX355LC) have peak hourly demands of about 52 kW. The 631-kWh total daily demand is spread out over 12 hours by the charging curve, which prevents sudden spikes.

Depending on the activity, motor load efficiency varies. Compared to large machines, medium-sized machines have higher mechanical efficiency (up to 35%). The least efficient activities are those that are idle (3–4%).

Medium-sized machines use about 200 kWh/day of energy each day, whereas large machines need about 415 kWh/day. Depots such as WattHub have a theoretical capacity of 34500+ kWh/day which allows them to charge over 250 medium and large vehicles a day theoretically.

4.2 SUB-QUESTION 2: PARAMETER MONITORING AND GRID RESPONSIVENESS

How are key charging parameters such as voltage, power, and state of charge currently measured and transmitted between electric construction vehicles, chargers, and the grid, and does the grid respond to each parameter individually or only to the total energy demand?

At vehicle level the Vehicle ID, SoC, battery capacity, charging priority, and arrival/departure times are monitored. At charger level the power taken (kW), charger ID, charger status, and charging capacity are communicated in real-time. At the grid level, TOU tariffs and power constraint and loads are shared with the OSCP and OpenADR protocols. Here is how they communicate:

1. DSO → CPO backend (via OpenADR, OSCP): Shares available load capacity, tariffs, and constraints.
2. CPO backend ⇄ Charger (OCPP): Sends control commands and communicates real-time charger data.
3. Charger ⇄ EV (ISO 15118-20): Exchanges SoC, charging scheduling, etc.
4. CPO backend → Dashboard (via API): Gathers all the data from the whole system for visualisation and control.

The grid does not respond to each parameter independently. Instead, it responds based on total power capacity and sends alerts to CPOs when thresholds are exceeded.

4.3 SUB-QUESTION 3: DASHBOARD VISUALIZATION AND PLANNING FEASIBILITY

Can a conceptual dashboard interface be developed to visualize real-time charging data effectively, and would it be feasible to integrate planning functionalities such as slot reservations or equipment scheduling?

Yes, the dashboard prototype includes all the necessary data from sub question 2 from vehicle, charger and grid level. Users can book time slots and the system would use priority scheduling to automatically assign vehicles based on urgency, SOC and battery capacity. The system can also manage load balancing and avoid conflicts by the alerts that is sent to it. APIs and backend make integration possible. However, real-time responsiveness depends on hardware and standardization across the vehicles and the systems.

4.4 MAIN RESEARCH QUESTION: FEASIBILITY OF REAL-TIME SMART CHARGING

Is it technically and operationally feasible to implement real-time monitoring and data communication between grid infrastructure, chargers, and heavy-duty zero-emission construction vehicles using a dashboard-based system, and what information is required to enable visibility and control of grid congestion?

Yes, technically the infrastructure already exists using the communication protocols, OCPP, OpenADR, OSCP, ISO 15118-20, APIs for data integration across systems and dashboards for control and monitoring. However, operationally it is partially feasible. Small-scale applications (5–20 EVs) are currently practiced but large scale such as 300+ machines (WattHub example chapter 1) is currently limited due to Dutch grid congestion. Accurate real time SOC, battery capacity, charger status, power draw, grid availability (e.g load constraints) and swappable battery logistics are needed for visibility and control of grid congestion.

Swappable Batteries work by charging batteries offline at depots and swapping them on-site into machines on-site without needing to charge during the workday. This avoids putting pressure on the grid and works with the dashboard’s scheduling system.

5 Smart Charging Strategy and Final Recommendations

5.1 INTEGRATED SMART CHARGING STRATEGY

Apart from electrification it is also needed to make the switch to zero-emission building sites as well as a logistically effective energy ecosystem. This section presents an integrated smart charging approach that is concluded based on the study presented in Chapters 1-4.

System Overview:

Real-time parameters are used to modify this charging architecture. Vehicle state of charge (SoC), machine priority, depot-level power availability, grid limitations, and tariff schedules (based on the category) are all included in this. Through the use of industry-standard communication protocols (ISO 15118-20, OCPP, OpenADR, OSCP, and APIs), these variables are tracked and processed through a single dashboard.

The strategy operates in three levels:

1. **Vehicle level**: Real-time battery data and usage analysis.
2. **Charger level**: Load balancing and scheduling.
3. **Grid level**: Response to capacity constraints and alerts and peak/off-peak pricing, if applicable.

However, the system's true innovation is integration of swappable batteries. By charging batteries offline at depots and swapping them into vehicles during low-demand hours, operational activity is separated from grid stress. This prevents high-load spikes at night and allows machines to remain operational during the day.

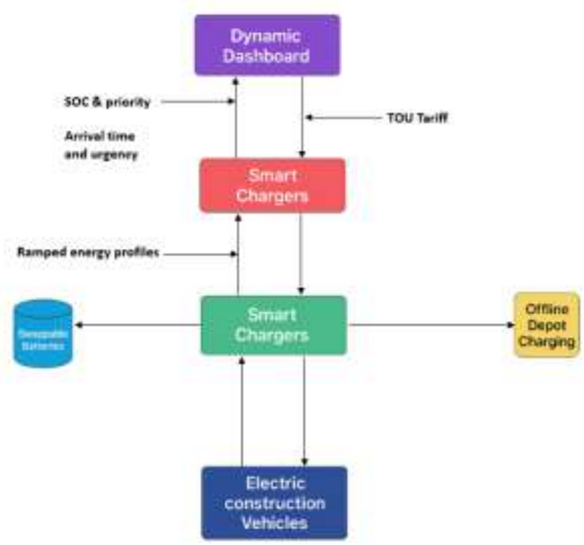


Figure 5.1 – Smart charging system overview with swappable battery implementation

This diagram shows a smart charging system with swappable batteries intended for construction sites with zero emissions. The Dynamic Dashboard, located at the top of the system, serves as the central controller by obtaining important data from the fleet, including State of Charge (SoC), vehicle priority, arrival times, and urgency. Additionally, it gathers time-of-use (TOU) tariff data from the grid. The dashboard provides the Smart Chargers above and below with instructions based on these inputs. While the lower chargers use ramping energy profiles to make a grid-friendly charging behaviour, the higher chargers manage scheduling and coordination. These smart chargers provide energy to electric construction vehicles either directly or through swappable batteries while simultaneously charging batteries in the off-shift hours which are then swapped out for empty ones on-site. This design reduces peak load stress and grid congestion while allowing for continuous daily machine usage. Communication loops that enable real-time adjustments in response to operational or grid changes are represented by the bidirectional arrows.

Ramp-Based Load Profiles

The method uses ramp-up and ramp-down charging curves instead of flat or static charging schedules. This lessens the strain on cables and transformers and guarantees grid-friendly behaviour by spreading the load, which is crucial for the grid congestion circumstances in the Netherlands. The smart dashboard is programmed with these ramp profiles, which are scaled according to charger availability and fleet size.

In reality, a medium/small sized depot can:

1. Analyse daily energy requirements using dashboard-integrated APIs.
2. Based on machine urgency and battery supply levels, reserve charging slots.
3. During off-shift hours, swap fully charged batteries into high priority cars.
4. Keep an eye on grid availability and move energy use away from periods of highest tariffs.

5.2 STRATEGIC IMPLEMENTATION LEVELS

Four essential levels are needed order realize an intelligent charging infrastructure for electric construction sites:

1: Energy Infrastructure Readiness

- Ensure depot connections meet minimum capacity limits (e.g., less than 3×160A for medium-sized fleets).
- Communicate with DSOs to validate off-peak availability or long-term capacity agreements.
- Include energy buffers (e.g., small battery storage) to manage disruptions to not mess up the schedules.

2: Smart Software & Dashboard Integration

- Install dashboard interfaces that can analyse real-time data from the grid, charges, and vehicles.
- To even out demand, use load-balancing methods with ramping profiles.
- Display battery capacity, SoC levels, charger status, and alerts on a single operator screen.

3: Logistical Fleet Planning with Battery Swaps

- Establish swappable battery hubs at depots.
- Introduce reservation and prioritization systems for vehicle charging and swapping batteries.
- Teach operators how to manage battery swap cycles effectively so that operations don't delay.

4: DSO & Grid compliance

- Work together with grid operators to schedule site expansions or new connections.

5.3 FINAL RECOMMENDATIONS

Based on the research in this thesis, the following recommendations are proposed for industry operators, policymakers, and energy planners:

1. Use swappable batteries to allow daytime operation and lessen reliance on the grid without interfering with charging schedules.
2. Make use of intelligent dashboards that have load-aware scheduling and prioritizing according on battery size, urgency, and SoC.
3. Avoid flat charging loads and instead use ramped profiles that spread load and reduce stress on transformers and grid.
4. Prioritize electrification of medium-sized machines, which offer better load efficiency and lower average daily energy consumption.
5. Integrate appropriate protocols to enable interoperability and real-time machine-to-grid communication.
6. Apply smart queuing systems that automatically schedule based on fleet conditions.
7. Collaborate closely with DSOs to guarantee reliable connections and that the depot's power profile aligns with local grid regulations.
8. Monitor battery health and SoC to prevent overcharging or scheduling errors.
9. To prevent underestimating total load demand, set aside 10–15% of the total depot power for inside systems (cooling, lights, and HVAC).
10. In order to allow construction businesses to expand into electrification without totally redesigning their companies, infrastructure should be designed ranging from 5 to 50 vehicles. They can then expand into larger fleets as they expand.

With the help of these suggestions, construction sites can gradually introduce electric equipment without overloading the system.

5.4 CONCLUSION AND OUTLOOK

The findings of this thesis confirm that with the implementation of intelligent system design, real-time smart charging of electric construction equipment is technically possible.

The Netherlands' present grid limitations can be effectively addressed by combining ramp-based charging, smart dashboards, and swappable battery depots. Operators may automate decision-making, visualize all required charging parameters and optimize energy usage based on real-time vehicle, charger and grid data with a smart dashboard.

But there are still difficulties. With the current grid congestion, large-scale deployment, charging more than 300 machines daily is not possible. Future plans must therefore:

1. Collab and partner with OEMs and DSOs
2. Integrate upcoming technologies such as vehicle-to-grid (V2G) ,where appropriate to lessen the stress on the grid even more
3. Keep improving API dashboards, in terms of software and security, for construction use

6 Expert Feedback and Industry Validation

This section is based of feedback collected from 3 industry experts who reviewed my findings and design decisions made across the three scopes of this project. The experts consulted were:

1. Nazir Refa, Team Lead Data & Market Analytics, ElaadNL
2. Tobias Stöcker, Manager Duurzaamheid / Circulariteit, GMB Beheer B.V.
3. Gerard van der Veer, Manager Duurzaamheid Materieel, GMB Civiel B.V.

The following questions were asked to the experts:

Scope 1: Load Cycle and Energy Analysis

1. Does a daily energy consumption between 150–250 kWh for 15–35-ton electric machines seem realistic to you under normal use? Are peaks up to 400 kWh/day reasonable in heavy-use scenarios?
2. From your experience, do medium-sized electric machines usually charge during the day, and larger machines (20+ tons) more often at night?
3. Do you agree that using the SEB national power classes is a good way to group machines by charging and emissions needs?
4. Are these typical prices accurate in your experience?
   - WattHub: €0.42/kWh
   - Depot charging: €0.50/kWh
   - Public fast charging: €0.70/kWh

Scope 2: Data Communication

5. Are chargers on construction sites today able to measure and send real-time data like power use, voltage, and SoC (State of Charge)?
6. Is it technically feasible to send those parameters using protocols like OCPP or ISO 15118 to backend systems?

7. Do grid operators like Liander typically get load updates from transformers every 5 minutes, or has that become more frequent?

Scope 3: Dashboard Integration

8. Can you imagine a dashboard being used on-site that shows real-time parameters such as SoC and power draw? What do you think is the main challenge to making this happen in practice?
9. Do you believe it's realistic to have features like charging reservations built into such a dashboard?

Smart Charging Strategy

10. Do you agree with the idea to charge medium machines during the day and larger ones overnight?
11. As a system operator or expert, what extra options would you want to see in a smart charging system to make it work reliably?

A following table is made to show the answers of each expert for each question:

Question	Tobias Stöcker (GMB Beheer B.V.)	Gerard van der Veer (GMB Civiel B.V.)	Nazir Refa (ElaadNL)
Q1	Yes, these numbers seem accurate.	Yes, these numbers seem accurate.	Yes, these numbers seem accurate.
Q2	No, we use swappable batteries because you need all vehicles small medium large during the day.	No, we use swappable batteries only small machines charge during the day and that is only in urgent/needed cases called "convenient charging" but this should be avoided as it messes up the schedule.	Yes, this could work on a small scale of electric machinery.
Q3	We don't usually use SEB but now we are starting to use it more often.	No, but it will be more commonly used.	Yes, it should be used as a standard.
Q4	Yes, these numbers seem accurate.	Yes, the numbers are accurate.	Yes, the numbers are accurate.
Q5	Yes, because we use chargers with built-in API access that allow such monitoring.	Not yet. For swappable battery systems, the SoC is visible, but there's a lack of integrated data dashboards. OEMs tend to prioritize the machinery itself over developing dashboards for logistics.	Yes, because we use chargers with built-in API access that allow such monitoring.

Q6	ISO 15118 not but OCPP is a standard for backend systems.	Yes, but depends on OEMS.	Yes, mainly OCPP.
Q7	I don't know, this is out of my field/knowledge.	It's usually per 15 minutes.	It's usually between 5-15 minutes.
Q8	Yes, that's actually something we want for logistical planning. The main challenge is the lack of standardization, different machine brands use different protocols, and there's no single platform that can easily combine and visualize all this data.	Yes, I can imagine it to be useful. The main challenge is OEMs focus more on machines not logistics.	Yes, I imagine it to be useful. The main challenge is no standard agreement yet with OEMS.
Q9	Should be in an algorithm, prioritize more important machines over others and if you know this program it into the dashboard.	It's a must have for the near future at the moment electric machines are limited so it is possible to manage without it but as the scale of electric machines increase it becomes a necessity.	Any planning tool would be useful in a logistical aspect.
Q10	This is nonsense as you need all machines during the work hours 7am – 4pm.	No. We rely on swappable battery systems, so charging during work hours is avoided.	All vehicles are needed if we are talking about a large scale.
Q11	State of charge and charging rate and ability to manage charging section.	Interoperability with all chargers.	Interoperability with all chargers.

The conversations with the three experts gave an idea of where things stand with electric construction equipment. While the energy consumption numbers in this research were confirmed to be accurate, the experts were clear that all machines are needed throughout the workday, so swappable batteries are currently the most practical solution.

They also agreed that the technology to share data like state of charge or power draw exists, especially through OCPP. OEMs still focus more on building machines, not on making life easier for planners or site managers. This means dashboards sound great on paper, but are hard to implement currently. However, everyone saw a clear role for smart dashboards in the future, especially as electric machines increase on construction sites.

Ultimately, the expert feedback supports the project's direction. Although the industry is moving toward smart charging, the technologies we develop must function for those who work in the field on a daily basis. This means focus on what is feasible right now while working toward what may be achievable in the future.

7 DISCUSSION

7.1 EVALUATION OF RESULTS

The study's conclusions point to a number of trends that arise from the interaction of grid capacity, construction logistics, and electrification. The difference in energy profiles between medium and large electric construction vehicles, average daily consumption is approximately 200 kWh and 415 kWh, is among the most obvious findings. These values can be controlled, but when applied to fleet operations, they have a strain on grid capacity.

An effective grid-friendly substitute for flat charging loads was shown by modelling a ramp-based charging profile across a 12-hour night window. This load shape avoids sudden surges, which compares to real-world power availability. The modelling study also showed that when there are grid limitations, even facilities like WattHub, with 3.6 MW capacity, may encounter difficulties when expanded to charge hundreds of machines.

Operational value is increased by integrating real-time parameters into a dashboard environment. Tracking arrival windows, priority, and state of charge would allow site managers to move from reactive to proactive planning. However, as the expert comments highlighted, inconsistent OEM support continues to be a barrier for dashboards.

7.2 ASSUMPTIONS AND LIMITATIONS

The technical and strategic assessments in this thesis are based on a number of assumptions. Instead of using real-time data, the approach is based on reconstructed datasets. This caused the data analysis to be on synthetic models and average consumption numbers. The lack of machine data means that the differences may not be fully captured, even though the DX165W and DX355LC data from TNO provide usable information. For charging infrastructure, the models assume perfect circumstances, including full grid availability during the 12-hour off-peak window, no cable losses, and ideal power factor ($\cos \phi = 1$). In real site conditions, voltage drops and transformer degradation, may differ from the constraints that DSOs use in practice.

Although many modern chargers and machines still rely on outdated systems and protocols, the dashboard also assumes complete compatibility via modern communication protocols (OCPP, ISO 15118-20). Furthermore, although swappable batteries are a good method to on-site charging during business hours, their effectiveness depends on logistics related to battery handling, employee education, and OEM compatibility. The load feasibility study was also tested using simulation tools (ElaadNL vermogenstool). Despite their trustworthiness, these technologies oversimplify complicated characteristics like concurrent loads from non-construction equipment or weather impact.

7.3 SUGGESTIONS FOR REAL-WORLD APPLICATION

There are both opportunities and risks associated with implementing a smart charging strategy in construction projects. On the one hand, our study shows that off-peak charging with the Dutch infrastructure is possible with a small fleet (e.g., 5–20 electric machines), particularly when assisted by ramping charging profiles and real-time scheduling tools. However, more than 100 machines will encounter obstacles because of congestion. Swappable batteries can improve this, but doing so needs spending money on battery logistics, storage space, and skilled personnel. Additionally, it brings safety issues that aren't covered in this thesis.

7.4 OTHER OPTIONS AND TRADE-OFFS

Although ramp charging during off-peak hours is the recommended approach in this thesis, other solution is worth considering. Daytime AC charging, for instance, if solar generation is high and grid rates are not crucial, may be an option, particularly for smaller worksites. Although this differs from the overnight-only concept, it might provide flexibility in locations with renewable energy sources.

Another trade-off results from choosing battery swapping over daytime charging. Although it is operationally simpler, it also adds logistical complexity and capital investment. It is assumed that staff can handle substitutions without interfering with schedules. Despite the additional strain on the grid, some businesses might find it more feasible to include partial daytime charging during breaks.

7.5 BROADER IMPACT

In addition to helping to decarbonize the building industry, this study discusses how energy-intensive sectors may work with constrained electrical grids. Furthermore, the report shows the need for frameworks that support interoperability between EV machines, chargers, and grid operators. Without this, communication breakdowns could slow the spread of zero-emission construction more than technology. In the end, the OEMs, and DSOs' desire to work together around digital infrastructure, standardized protocols, and smart energy systems will determine the shift to zero-emission construction.

Appendix Overview

The following appendix contains datasets, references, plan of approach, literature review and the reflection report used for this report. They provide transparency for the calculations and technical assumptions used in this report.

APPENDIX A– PLAN OF APPROACH

Approved POA document showing the research context, objectives, methodology, deliverables, and timeline.

FINALVERSPOAgrda
utionprojectV4.pdf

APPENDIX B – LOAD CYCLE & EMISSION DATA (EXCEL)

Extracted dataset of energy demand estimates for GMB machines. SEB categories were derived from machine type and power class (appendix F).
Source: Load_Cycle_SEB_Classified_TNO_P11947.xlsx

Load_Cycle_SEB_Clas
sified_TNO_P11947 (5

APPENDIX C – TNO FIELD REPORT: ELECTRIC MACHINERY BENCHMARKS (PDF)

Official public TNO report (2024, P11947) documenting daily energy use, motor load patterns, and operational behaviour for electric excavators.
Source: TNO-2024-P11947.pdf

TNO-2024-P11947.p
df

APPENDIX D – SEB ROUTEKAART (PDF)

Official SEB guideline for emission and power class requirements for construction machinery between 2023–2040. The SEB table used is also shown.
Source: Routekaart SEB - definitief.pdf

1. Minimumniveau mobiele werktuigen:

Tabel 8. Verplicht minimumniveau mobiele werktuigen[8]

	Periode 1 1 jan. 2023 - 31 dec. 2024	Periode 2 1 jan. 2025 - 31 dec. 2027	Periode 3 1 jan. 2028 - 31 dec. 2029	Periode 4 1 jan. 2030 en verder
Licht ('minimaterieel' <19 kW)	Geen eis	Geen eis	100% ZE**	100% ZE**
Licht (19-37 kW)	Stage IIIa	Stage IIIa	Stage IIIa	100% ZE**
Licht (37-56 kW)	Stage IIIa	Stage IIIb	Stage IIIb	100% ZE**
Middelzwaar (56-130 kW)	Stage IIIa	Stage IV met roetfilter*	Stage IV met roetfilter*	Stage IV met roetfilter* (2030) 100% ZE (2035)
Zwaar (130-560 kW)	Stage IIIa	Stage IV met roetfilter*	Stage IV met roetfilter*	Stage IV met roetfilter* (2030) 100% ZE (2035)
Specialistisch (levensduur >15 jaar) Zeer zwaar (>560 kW)	Geen eis	Geen eis	Katalysator en roetfilter*	Katalysator en roetfilter* 100% ZE (2035-2040)
Stationair (generatoren, pompen, torenkranen)	Gelijk aan eisen niet-stationair	Gelijk aan eisen niet-stationair	100% ZE** <560 kW >560 kW gelijk aan eisen niet-stationair	100% ZE** <560 kW >560 kW gelijk aan eisen niet-stationair

* Met 'katalysator' wordt bedoeld een effectieve SCR-katalysator. Met 'roetfilter' wordt bedoeld een werkend, gesloten roetfilter.
** Voor Stage V-materieel is een overgangsregeling van kracht. Stage V-materieel van voor 1 januari 2028 is nog tot 1 januari 2033 toegestaan.

Routekaart SEB - definitief.pdf

APPENDIX E– DATA TRANSPARENCY AND SIMULATION ASSUMPTIONS CHAPTER 1

No direct datasets were available. Instead, the findings are based on reconstructed data from multiple sources and supported by assumptions.

A.1 Source Data Availability

Two main sources were:

- The **TNO P11947 report (2024)**, ***appendix C***, provided daily energy consumption and motor load data for a 17-ton and 35-ton electric excavator.
- The **GMB diesel fleet file**, **appendix D**, listed machine types, power ratings, and CO_2 and diesel usage.

However, none of these sources contained a full dataset suitable for load cycle analysis. Because of this, several parts of the analysis had to be simulated.

A.2 Simulated and Assumed Data

Due to the lack of direct electric machine datasets, the following graphs were made:

- **Charging Demand per SEB (Graph 1.1)**
  SEB classifications were applied based on power class and function, from the SEB guidelines.
- **Hourly Load Curve (Graph 1.5)**
  No time-series charger data was available. This graph uses real daily energy values from TNO and simulates a smart depot-charging strategy from 19:00–07:00. This reflects realistic fleet behavior with swappable battery systems.
- **Energy Distribution per Machine (Graph 1.2)**
  Real TNO measurements of daily energy use were used to compare medium- and large-class excavators. Assumptions about AC or DC charging types were applied based on estimated consumption needs.

APPENDIX F – LITERATURE REVIEW: SMART CHARGING & LOAD CYCLES

As part of the deliverables from the POA, a literature review was made during the early stages of the project. The document focused on smart charging technologies, energy consumption of electric construction machinery, and communication protocols between vehicles, chargers, and the grid. The literature review is attached to the appendix of this report.

Literaturereview.pdf

APPENDIX G – REFLECTION REPORT

The following is the full reflection report, included both here and as a separate document.

Starting Position and Expectations

At the beginning of my graduation project, I entered with a decent technical foundation in sustainable energy systems, vehicle electrification, and MATLAB data analysis. I had experience with energy-related projects, including my involvement with the Hydromotive team and internships at Alles Over Waterstof and NRF. However, I lacked direct experience with data integration in grid-based infrastructure and had no prior experience to smart charging systems for construction machinery. I found this project very interesting and was very optimistic about it to help me in my masters which I want to do in sustainable energy technology at the University of Twente, hopefully right after my thesis assignment. My expectations were to strengthen my knowledge in energy systems and grid coordination while developing a practical strategy that could be applied in zero-emission construction.

I started the project with a professional attitude, high motivation, and a clear understanding of the importance of electrification solutions. I expected to work closely with my tutors, supervisors and external partners to validate findings and receive regular support and data. One big challenge I faced was the availability of my promised and requested raw dataset for my data analysis, which later proved to be a significant problem in my thesis assignment. I really did not expect this to be happen since it was the first step into starting my thesis and I almost immediately faced this issue, and it really wasted a lot of my time.

Personal Learning Goals and Achievements

My personal goals were to:

- To process and analyse energy datasets.
- Gain insight into smart charging communication standards.
- Understand grid limitations in real-time operations.
- Develop a technically feasible smart charging framework for construction use cases.
- Gain overall experience in energy systems such as these.

Despite the obstacles, I achieved all of these objectives. Through simulation, data reconstruction, and consultations with experts, I managed to build realistic energy profiles and a data-driven load model. I learned how to justify assumptions, design high-level flow diagrams, and link simulated outputs to operational decisions. The biggest success, which was the goal of the project, was making an integrated smart charging strategy, from grid all the way to dashboard.

Obstacles and Adaptation

The biggest difficulty during the project was the lack of usable datasets and lack of support for this problem. No real-time logged data was available from chargers or machines. I was then advised to contact external partners by email through connections within ElaadNL, but due to confidentiality issues they were not able to provide me data either. I also experienced limited involvement and feedback during the early stages from senior supervisors, which slowed down my work due to no access of validation.

I addressed these issues by shifting to a hybrid methodology: combining sources (partial GMB dataset and TNO reports) with simulated profiles based on backed-up assumptions. I clearly documented which data were real, estimated, assumed, or synthetic. I also took initiative to consult experts directly through meetings and email exchanges, which significantly improved the reliability of the outcomes. Instead of waiting for guidance, I structured the report myself, and used weekly self-imposed deadlines to stay on track.

Another challenge I faced was that the documents and datasets I used were only available in Dutch, including the TNO report, the SEB report, and the GMB dataset. As I do not speak Dutch, this was a risk of misinterpretation or missing important technical details. To overcome this, I used translation tools, to extract relevant figures numbers and graphs carefully, however no one was there to confirm these findings for me, therefore I had to rely on self-trust and the translation tool that I had used. I did however contact some experts in my field to validate my data analysis graphs that I had made, and this was helpful.

This process not only improved the quality and reliability of my analysis but also strengthened my ability to work with foreign data sources, an increasingly common issue in infrastructure projects within the Netherlands and surely other parts of Europe.

I also did not receive my full amount of payment due to administration issues in the first few months, within HAN university of applied sciences. This also lacked my motivation because even though I was getting below minimum wage per month they could not meet my agreed contract payment properly.

Feedback, Self-Evaluation, and Reflection

Most of the feedback I received was based on data analysis and validation, and the realism of load peaks. These helped fix my approach and strengthened the analysis. Rather than seeing feedback as criticism, I used it as an opportunity to improve and deepen the technical content, since it came from my seniors. I also received positive remarks on the structure, clarity of graphs, and professional tone of the report. Sometimes this feedback from people from other and within my thesis company collided with the feedback my school supervisors gave me, and this was very confusing for me as it led me in several different directions due to different feedbacks.

Ultimately, I would have started expert interviews earlier had I not had any data problems. Their input was crucial, and integrating it sooner could have helped shape assumptions and simulations more effectively from the beginning. I would also like to had built in more frequent interactions and interviews with tutors by setting clearer goals and overcoming obstacles.

Development of Professional Competence

This graduation project helped me grow significantly in my ability to:

- Lead a research project independently under difficult circumstances.
- Communicate technical outcomes clearly in both visual and written formats.
- Justify system assumptions and simulation in a transparent way.
- Align technological strategy with operational goals (grid load, coordination).
- Be able to analyse modern energy systems based on modern trends.
- Critical thinking.
- Talk to my colleagues in a workplace despite language barriers.
- Make connections within my field.
- Construct emails in a more professional way.
- How to keep working and following timelines despite difficult fall backs and demotivational circumstances.

I now understand that real innovation often comes from navigating uncertainty, adapting creatively, and defending choices based on logic rather than perfect data. I've become more confident in managing challenges, and I now seek out feedback rather than wait for it.

Looking Ahead

This project made me realise my passion for energy systems, especially in applied, contexts such as construction vehicles. My next learning goal is to improve my system modelling skills, MATLAB Simulink, and deepen my understanding of V2G (vehicle to grid) and dynamic pricing algorithms. I also want to improve my stakeholder communication skills to bridge technical perspectives. Additionally, I want to be able to work in other applied energy systems like nuclear power plants to power homes and solar systems to power charging stations or homes. It is my passion and goal to work in the sustainable energy field and I hope to gain more and more experience in my student life to help me ease my way into the field once I have graduated and finished my studies.

Ultimately, this graduation phase taught me that professional success isn't just about knowing the answers but rather about asking the right questions, staying accountable to your method, and finding alternate solution in the case of missing data, vague scopes, or limited supervision. It has also taught me how important it is to have connections within your field and how easier things will be if you, especially knowing people with higher roles such as managers, CEOS and owners of companies. This is a mindset that I will carry into my career until the day I retire.

References

[1] Liander, "Enkeltarief of dubbeltarief," Liander, [Online]. Available: https://www.liander.nl/tarieven/enkeltarief-of-dubbeltarief. [Accessed 14 July 2025].

[2] Pure Energie, "Wat is het verschil tussen grootverbruik en kleinverbruik?," Pure Energie, [Online]. Available: https://pure-energie.nl/kennisbank/verschil-tussen-groot-en-kleinverbruik/. [Accessed 15 July 2025].

[3] Schneider Electric, "Definition of reactive power," Schneider Electric, [Online]. Available: https://www.electrical-installation.org/enwiki/Definition_of_reactive_power. [Accessed 15 July 2025].

[4] MHI Inc., "Typical three phase in various countries," Micropyretics Heaters International (MHI), [Online]. Available: https://mhi-inc.com/typical-three-phase-in-various-countries/. [Accessed 15 July 2025].

[5] Liander , "Soorten elektriciteitsaansluitingen," Liander, [Online]. Available: https://www.liander.nl/grootzakelijk/aansluiting/soorten-elektriciteitsaansluitingen. [Accessed 16 July 2025].

[6] ElaadNL, "Vermogensvraag tool bouwplaats," ElaadNL, [Online]. Available: https://vermogenstoolbouw.elaad.nl/. [Accessed 17 July 2025].

[7] electrive.com, "Watthub/TSG opens megawatt charging park for trucks and off-highway vehicles with Kempower," electrive.com, 5 October 2023. [Online]. Available:

https://www.electrive.com/2023/10/05/watthub-tsg-opens-megawatt-charging-park-for-trucks-and-off-highway-vehicles-with-kempower. [Accessed 28 June 2025].

[8] D. Pato, "The Netherlands' gridlock: Why it's happening and how to fix it," Regulatory Assistance Project (RAP), Brussels, 2024.

[9] T. Chiu, "Demystifying the Relationship between APIs and Backend Systems," Medium, 26 March 2024. [Online]. Available: https://medium.com/@tiokachiu/demystifying-the-relationship-between-apis-and-backend-systems-4060b92e8546. [Accessed 21 July 2025].

[10] M. Mültin, "The latest edition of ISO 15118-20 in the ISO 15118 communication standard series has arrived!," Switch, 28 May 2020. [Online]. Available: https://www.switch-ev.com/blog/new-features-and-timeline-for-iso15118-20. [Accessed 21 July 2025].

[11] R. Hensgens and G. Tezel, "Unlocking EV smart charging to reduce grid congestion- lessons from the netherlands," ElaadNL, March 2024. [Online]. Available: https://elaad.nl/wp-content/uploads/downloads/240610-Elaad-EV-smart-charging-full-report-vF10.pdf. [Accessed 23 July 2025].

[12] M. Murnane and A. Ghazel, "A Closer Look at State of Charge (SOC) and State of Health (SOH) Estimation Techniques for Batteries," Analog devices , [Online]. Available: https://www.mouser.com/pdfDocs/SOC.pdf?srsltid=AfmBOopkZyU_DSMMLSTCyo8xoZiWTKOn4-r15seHyEGc2gsFBza4SUIN. [Accessed 25 July 2025].

[13] EV Bahan Controls, "EV Charger API: The Unlimited Guide," Ev Bahan Control , 16 September 2024. [Online]. Available: https://evbahancontrols.com/blogs/ev-charger-api/#:~:text=1.,users%20alike%20over%20connected%20platforms.. [Accessed 26 July 2025].

[14] Pulse Energy, "Real-Time Support for EV Drivers: Your 24/7 Road Companion," Pulse Energy, 24 September 2024. [Online]. Available: https://pulseenergy.io/blog/real-time-support-for-ev-drivers#:~:text=Delays%20in%20real%2Dtime%20updates,%E2%80%8D. [Accessed 26 July 2025].

[15] K. Waehner, "Virta's Electric Vehicle (EV) Charging Platform with Real-Time Data Streaming: Scalability for Large Charging Businesses," Kai Waehner , 22 April 2025. [Online]. Available: https://www.kai-waehner.de/blog/2025/04/22/virtas-electric-vehicle-ev-charging-platform-with-real-time-data-streaming-scalability-for-large-charging-businesses/#:~:text=1.,Savings%20through%20Usage%2DBased%20Pricing. [Accessed 28 July 2025].

[16] smartcar, "How EV APIs accelerate mobility app development," smartcar, 17 March 2024. [Online]. Available: https://smartcar.com/blog/redefining-ev-apps-car-api. [Accessed 29 July 2025].

[17] A. Miller, "Advanced EV Charging Dashboard For Effortless Management," Multipurpose themes, 22 March 2025. [Online]. Available: https://multipurposethemes.com/blog/advanced-ev-charging-dashboard-for-effortless-management/#:~:text=Conclusion,always%20optimized%20for%20peak%20performance.. [Accessed 30 July 2025].

[18] Driivz, "Local vs Cloud Control: Which Works Best for Smart EV Charging?," Driivz, 25 October 2022. [Online]. Available: https://driivz.com/blog/local-vs-cloud-control-smart-ev-charging-management/. [Accessed 30 July 2025].

[19] U. Dorot, "EV Charging Station Applications – a Growing Cyber Security Risk," radware, 01 May 2023. [Online]. Available: https://www.radware.com/blog/application-protection/ev_charging_station_cyber_threats/. [Accessed 31 July 2025].

Declaration of AI Use

Parts of this document were written using OpenAI's ChatGPT for text drafting and editing, as well as for generating visuals. All AI-generated content was reviewed and edited by the author to ensure accuracy, relevance, and alignment with the project objectives.