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Impact of Electrified Construction Machinery on the Electricity Grid

An Analysis of Effects on Distribution Substations in Gothenburg from Charging of Battery-Electric Construction Machines

Master's thesis in Mechanics and Maritime Sciences

ALBIN AHAGEN

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES

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Abstract

The electrification of construction machinery is an important measure for reducing greenhouse gas emissions, local air pollution, and noise from construction sites. However, replacing diesel-powered machinery with battery-electric alternatives introduces new electricity demand patterns that may affect power demand in local distribution grids, particularly through high-power fast-charging and simultaneous peak loads. This thesis investigates how a fully electrified construction machinery fleet could influence the electricity grid in Gothenburg, with a focus on distribution substations operated by Göteborg Energi Nät AB.

The study develops representative charging profiles for different construction site scenarios and combines these with historical substation load data from several urban area types, including industrial, commercial, and residential zones. By comparing charging demand with available substation capacity, the analysis identifies where and under which conditions capacity exceedance may occur. Different charging strategies, including reduced fast-charging power and night charging, are evaluated to assess their potential to mitigate grid impacts. The results indicate that electrified construction sites can create significant additional peak loads, especially when several machines charge simultaneously during working hours. The risk of exceeding available substation capacity varies depending on construction site size, charging strategy, substation rating, and local load characteristics. Industrial and commercial areas generally show different capacity margins compared with residential areas, while seasonal variation further influences the available grid capacity, with winter conditions being particularly critical. Reduced charging power and night charging are shown to lower peak demand and improve compatibility with existing grid capacity.

Overall, the thesis demonstrates that the electrification of construction machinery is technically feasible but requires careful coordination between construction planning, charging strategies, and distribution grid capacity. The findings highlight the importance of integrating construction-related charging demand into future grid planning and provide a basis for identifying where mitigation measures or grid reinforcements may be required.

Keywords: Electrified, Grid, Electricity, Construction, Machinery, Power, Charging, Distribution Grid, Substation, Load, Capacity, Peak Demand, Overload, Gothenburg

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Albin Ahagen, Gothenburg, June 2026

List of Acronyms

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

BEV	Battery Electric Vehicle
CCS	Combined Charging System
CEX	Crawler Excavator
CLMS	Copernicus Land Monitoring Service
D	Dumper (Articulated hauler)
DeSO	Demographic Statistical Areas
DSO	Distribution System Operator
EO	Earth Observation
FUS	Functional Urban Area
GENAB	Göteborg Energi Nät AB
IPCC	Intergovernmental Panel on Climate Change
kVA	kilovolt-ampere
kW	kilowatt
kWh	kilowatt-hour
LC	Land Cover
LU	Land Use
MCS	Megawatt Charging System
R	Roller (Compactor)
SCB	Statistics Sweden
SOC	State of Charge
WEX	Wheeled Excavator
WL	Wheel Loader

Nomenclature

Symbol	Description	Unit
E_{battery}	Battery capacity	kWh
E_{daily}	Daily energy consumption	kWh
E_{hourly}	Hourly energy consumption	kWh
U	Voltage	V or kV
I	Current	A
S	Apparent power	kVA
t	Time	h
Δt	Time interval	h
P_{10}	10th percentile	—
P_{90}	90th percentile	—
SOC	State of charge	%
$P_{\text{available}}$	Available capacity	kW
P_{max}	Max capacity	kW
P_{load}	Historical load	kW

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1

Introduction

Climate change represents one of the most pressing societal challenges of our time. The global average temperature has already increased by approximately 1.1 °C compared to pre-industrial levels, leading to increased risks of extreme weather events, rising sea levels, and significant socio-economic consequences. Limiting global warming to 1.5–2 °C requires rapid and substantial reductions in greenhouse gas emissions across all sectors of society, particularly within energy, transport, and construction (IPCC, 2023). The construction and infrastructure sector is a significant contributor to greenhouse gas emissions, both through direct use of diesel-powered machinery and indirect energy use during construction processes. According to national statistics, emissions from non-road mobile machinery constitute a notable share of total emissions, highlighting the importance of targeted mitigation measures (Naturvårdsverket, 2025b).

In response, the European Union has established a comprehensive climate policy framework through the European Green Deal, aiming to achieve climate neutrality by 2050 (European Commission, 2019). As part of this strategy, the *Fit for 55* legislative package has been introduced, targeting a reduction of greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels (European Commission, 2021). These initiatives imply a large-scale transition toward electrification, increased energy efficiency, and reduced reliance on fossil fuels across multiple sectors.

Sweden has adopted even more ambitious national climate targets through its climate policy framework, committing to net-zero greenhouse gas emissions by 2045 (Regeringskansliet, 2017). In the city of Gothenburg, ambitious climate and environmental targets have been adopted, including requirements for emission-free construction sites in public processes (Göteborgs Stad, 2021, 2025a). These policies are actively driving the electrification of construction activities within the city. Initiatives such as emission-free construction site programs and stricter procurement requirements are accelerating the transition toward fossil-free construction practices (Göteborgs Stad, 2025b; Grönt Samhällsbyggande, 2025). Similar developments are observed at the national level, where policies and initiatives promote fossil-free construction machinery and reduced emissions from non-road mobile sources (Fossilfritt Sverige, 2024; Naturvårdsverket, 2025a). The rapid electrification of construction machinery introduces new load patterns that were not previously considered in grid planning. Göteborg Energi Nät AB (GENAB), as the local distribution system op-

erator, plays a crucial role in enabling this transition. The company is responsible for ensuring sufficient capacity in substations and distribution networks to meet future load increases. Insufficient capacity may result in connection limitations, increased investment requirements, or the need for active load management strategies.

In recent years, technological advancements have enabled the rapid introduction of battery-electric construction machinery, including excavators, wheel loaders, and transport vehicles. These technologies offer substantial reductions in local emissions, as well as improved working environments through reduced noise and elimination of exhaust gases (Fossilfritt Sverige, 2024; Klimatprotokollet Uppsala, 2023). At the same time, electrification fundamentally changes the nature of energy demand. Traditional construction sites are characterized by continuous fuel consumption, whereas electrified construction sites exhibit intermittent electricity demand with potentially high power peaks during charging events. Unlike conventional sites, where electricity demand is limited to site offices and small equipment, electrified operations may require significantly higher connection capacities. To maintain productivity comparable to diesel-powered machinery, charging may need to occur both overnight and during short breaks using high-power fast charging. This can lead to simultaneous power peaks that risk exceeding the capacity of local distribution grids (Bern, 2024). As a result, local grid operators face increasing challenges in accommodating new high-power demands.

Against this background, there is a clear need for systematic analysis of how electrified construction activities impact the electricity grid. By studying charging patterns, power demand, and the spatial distribution of loads, future load scenarios can be identified and assessed in relation to existing grid capacity. Such analyses are essential for enabling cost-effective grid planning while supporting climate objectives.

1.1 Purpose

The purpose of this thesis is to quantify how electrified construction activities, under different construction-site configurations and charging loads, affect power demand in the distribution grid of Gothenburg. Furthermore, the thesis evaluates how this additional charging demand influences the available capacity of distribution substations and the risk of capacity exceedance under different operating conditions, such as location and time of year.

1.2 Research Question

How does the electrification of construction machinery influence power demand and load patterns in the distribution grid of Gothenburg, and to what extent can the existing capacity of distribution substations accommodate future power demand of fully electrified construction sites?

To address this research question, the following aspects will be investigated:

Load and Charging

1. What power and energy demands arise from charging electric construction machinery and transport vehicles in different types of construction projects?
2. What are the typical daily and weekly charging profiles, and what simultaneous peak loads may occur?

Grid Impact

3. What available spare capacity exists today in different types of areas (e.g., residential, industrial, city center, and rural areas)?
4. How do load profiles from charging construction machinery affect the load of nearby substations relative to historical peak loads and installed capacity?
5. How many and which substations risk exceeding their available capacity under different scenarios?

1.3 Limitations

This study is geographically limited to the distribution grid within Gothenburg and focuses solely on the local network managed by GENAB. Higher-level transmission and regional grids are not included, as the primary focus is on local capacity constraints in substations and connection points where construction sites are typically connected.

The analysis primarily focuses on power demand (kW) and load profiles, as peak demand determines grid capacity requirements. Energy consumption (kWh) is considered only to the extent necessary for estimating charging needs. The results should therefore be interpreted as general estimates rather than precise predictions. Charging patterns and machine usage are based on real projects derived from interviews, literature, and industry data.

The study is limited to electrified construction activities within the construction and infrastructure sector. Only battery-electric construction machinery are considered, while alternative technologies such as grid-connected machinery, hydrogen solutions, biofuels, and hybrid systems are excluded. Machines included in the study is limited to: Crawler excavators, Wheeled excavators, Wheel loaders, Dumpers, and Rollers. These are electrified machines available or soon to be available at the market. Cranes and Piling machines are assumed connected directed to the grid with cable, and trucks for transportation are assumed not charged on site, leaving these kind of vehicles outside the scope of the study. In addition, the study does not look at current construction site loads from heating and other load drivers.

The study does not include detailed design or dimensioning of specific grid reinforcements but aims to identify potential capacity constraints and overall mitigation needs. Economic analysis is limited to high-level considerations and does not include full investment or socio-economic assessments. Furthermore, real-time optimization or implementation of smart charging strategies is not included, more than simple variants to show the concept, although such measures are discussed conceptually.

1.4 Method

This thesis evaluates the impact of electrified construction machinery on the distribution grid by combining representative charging demand from construction sites with historical substation load data. Rather than analysing individual construction projects, representative construction-site scenarios were developed and evaluated. The methodology consists of two complementary workflows that are integrated in a final capacity exceedance analysis, as illustrated in Figure 1.1.

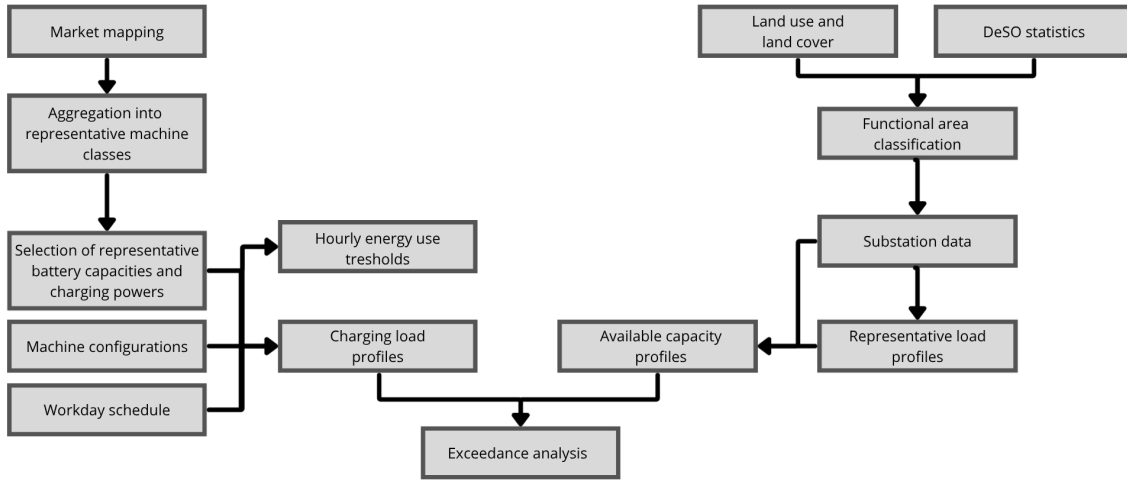


Figure 1.1: Overview of the methodology applied in this thesis.

The left workflow focuses on modelling representative electrified construction sites. Initially, the market for battery-electric construction machinery was mapped, after which the identified machines were aggregated into representative machine classes based on machine type and size. Representative battery capacities and charging powers were then assigned to each machine class using commercially available electric machines. Together with representative construction-site configurations and an assumed workday schedule, these data were used to estimate machine energy demand and construct representative charging load profiles.

The right workflow focuses on modelling the available capacity of the existing distribution grid. Land-use and land-cover data were combined with DeSO building statistics to classify the study area into functional area categories. Historical substation measurements from representative substations within each category were then processed to construct representative load profiles and corresponding available capacity profiles.

Finally, the charging load profiles were combined with the available capacity profiles to evaluate the impact of electrified construction machinery on the distribution grid. The impact was quantified through a capacity exceedance analysis, which evaluates how frequently the combined charging demand and historical background load exceed the available substation capacity under different construction-site configurations, charging strategies, seasons, and functional area categories. A detailed description of the development of representative charging profiles is presented in Chapter 4, while the methodology used to construct representative historical load and available capacity profiles, together with the exceedance analysis, is described in Chapter 5.

2

Literature Review

2.1 Electrified Construction Machinery

This section reviews previous research and relevant literature concerning electrified construction machinery. The aim is to provide an overview of existing knowledge, technological developments, and identified challenges within the field.

2.1.1 Environmental and Societal Drivers

Multiple studies show the environmental benefits of replacing diesel-powered machinery with electric alternatives. Diesel-powered construction machinery is a source of emissions and noise, contributing to urban air pollution (Yi et al., 2026). In addition, lifecycle assessments have demonstrated that electrification can reduce greenhouse gas emissions, with reductions ranging from 63% to 99% depending on the electricity mix (Willerström et al., 2015). These findings highlight the importance of clean electricity generation in maximizing the environmental benefits of electrified construction processes. Beyond emissions, electrification also offers improvements in local working conditions. Reduced noise levels and the absence of exhaust emissions contribute to better occupational health and improved urban environments, particularly in densely populated areas (Bern, 2024). This aligns with broader sustainability goals, including improved air quality and reduced environmental disturbance in cities.

2.1.2 Development of Electrified Construction Machinery

The electrification of construction machinery is still at an early stage compared to other transport sectors. While certain equipment types, such as forklifts, have achieved relatively high electrification rates, others, heavy machinery like excavators and loaders, remain largely diesel-powered. Recent years have shown a rapid increase in both academic research and industrial development, particularly since 2020, driven by technological advancements and stricter environmental regulations. The literature identifies several key technological components central to electrification, including energy storage systems, electric drivetrains, and advanced control strategies (Huang et al., 2024). Research has focused on optimizing these systems to address challenges such as energy efficiency, power delivery, and operational reliability. Despite progress, limitations related to battery energy density, cost, and durability remain significant barriers to widespread adoption (Pate et al., 2025).

At the same time, the market for electrified construction machinery has expanded rapidly in recent years. Several major manufacturers, including Volvo Construction Equipment, Komatsu, Hitachi, JCB, and Bobcat, now offer commercial battery-electric models such as compact excavators, wheel loaders, and site dumpers (Hitachi Construction Machinery Europe, 2023; Komatsu Ltd., 2023; Tice et al., 2026; Volvo Construction Equipment, 2025b). However, the market remains concentrated in smaller and medium-sized machines, while electrification of heavy-duty equipment is still limited due to high power and energy demands (Huang et al., 2024). Electric machines generally have substantially higher purchase prices than equivalent diesel-powered equipment. Nevertheless, lower operating and maintenance costs partly compensate for these investments over the machine lifetime, particularly in regions with low electricity prices and strict emissions regulations (Sweco, 2023). Norway, and especially Oslo, has emerged as an international frontrunner in this transition through ambitious public procurement requirements and pilot projects promoting zero-emission construction sites (Nykamp et al., 2023; Wiik et al., 2023).

Battery-electric construction equipment represents a small share of the total global machine fleet, e.g. 1.2% of the machines in Sweden are currently electric, mainly in the smaller sizes (Maskinentreprenörerna, 2026). Industry overview and manufacturer portfolios show that the present market is dominated by compact and light-duty machines, while medium-duty and some heavy-duty machines are now beginning to enter commercial or pre-commercial deployment (Hitachi Construction Machinery Europe, 2023; Tice et al., 2026; Volvo Construction Equipment, 2026c). This is further discussed in Section 3.7.

2.1.3 Electrified Construction Sites and System Perspective

Early research primarily focused on individual machines, while more recent studies looks at machines on a system level, considering the entire construction site as an integrated energy system. Demonstration projects, such as the Electric Worksite initiative in Sweden, have shown that electrified machinery can perform comparably to diesel-powered equipment in real-world applications (Bern, 2024). These projects also highlight the importance of integrating machinery with charging infrastructure, grid connections, and energy storage systems

Similarly, feasibility studies on electrified infrastructure construction indicate that fully fossil-free construction sites are technically achievable from a machine standpoint. Battery-electric solutions are often identified as the most energy-efficient option, although challenges related to energy distribution and system integration remain. These findings underscore the need for coordinated planning across the value chain, including contractors, equipment manufacturers, and energy providers (Hjertström et al., 2021). Mapping studies further demonstrate that electrified construction sites are increasingly being implemented in practice, particularly in

countries with strong climate policies such as Norway (Wiik et al., 2023). However, the availability of electric machinery varies significantly across regions, indicating an uneven pace of adoption.

2.1.4 Charging Infrastructure and Grid Implications

A critical aspect of electrified construction sites is the provision of adequate charging infrastructure. Studies show that electrifying heavy construction equipment introduces substantial new loads on the electrical grid, with peak demands potentially reaching tens of megawatts at the substation level in the regional grid (Callanan et al., 2024). These findings highlight the importance of grid capacity planning and the need for flexible solutions such as on-site energy storage and smart charging strategies.

Research also emphasizes the diversity of charging solutions, including fast and slow charging, battery swapping, and hybrid systems combining grid connection with mobile energy storage (Käck & Jansson, 2024). The choice of solution depends on site-specific conditions, operational requirements, and grid availability. Consequently, electrification requires not only technological innovation but also new approaches to site planning and energy management.

2.1.5 Economic Considerations and Barriers

Despite its environmental benefits, electrification faces significant economic challenges. Studies indicate that the total cost of ownership for electric construction machinery remains higher than for diesel alternatives, primarily due to high upfront investment costs and additional infrastructure requirements (Sweco, 2023). While operational costs, particularly energy costs, are generally lower for electric machines, these savings are often insufficient to offset the higher capital costs in the short term.

Industry perspectives further reveal concerns regarding reliability, maintenance, and performance, particularly for heavy-duty applications (Pate et al., 2025). As a result, many stakeholders anticipate a gradual transition, with hybrid solutions serving as an intermediate step before full electrification becomes economically viable.

2.1.6 Current Status and Research Gaps

Overall, the literature indicates that electrified construction sites represent a promising pathway toward reducing the environmental impact of the construction sector. Pilot projects and early deployments demonstrate not only technical feasibility, but also substantial reductions in greenhouse gas emissions, noise, and local air pollution compared to conventional diesel-powered operations (Bern, 2024; Willerström et al., 2015). In addition, electrification can improve energy efficiency and contribute to better working conditions in urban environments. The rapid increase in industrial investments, demonstration projects, and policy initiatives, particularly in countries such as Norway and Sweden, further suggests strong momentum toward

wider adoption (Bern, 2024; Fossilfritt Sverige, 2024; Nykamp et al., 2023; Wiik et al., 2023). However, several challenges remain, including technological limitations, high costs, and the need for robust energy infrastructure. Furthermore, existing research has largely focused on either individual machines or specific case studies, with fewer studies addressing large-scale implementation and system-level analysis. Existing studies primarily focus on individual machines, pilot projects, or site-level feasibility. Few studies quantify how electrified construction machinery affects local distribution substations using historical grid load data.

3

Theory

3.1 The Electrical Power Grid

The electrical power grid is a complex infrastructure system responsible for the generation, transmission, and distribution of electricity from production units to end users. It consists of interconnected components that enable the continuous supply of electrical energy over large geographic areas. Electricity is typically generated at power plants and transmitted over long distances using high-voltage transmission lines to minimize energy losses. These transmission systems, often operating at voltage levels of 220 kV or higher, form the backbone of the grid and are sometimes referred to as the super grid (Circuit Globe, 2023). The transmitted electricity is subsequently stepped down in substations and distributed through lower voltage networks to consumers. The grid can be structured at different hierarchical levels, typically consisting of transmission, regional, and local distribution networks (Svenska kraftnät, 2023). Interconnection between these levels allows for efficient utilization of generation resources, improved reliability, and enhanced system flexibility (Circuit Globe, 2023).

3.1.1 Grid Interconnection and Operation

Modern power systems are typically interconnected to form regional or national grids. A regional grid consists of multiple transmission systems connected within a specific geographic area, while a national grid interconnects several regional grids into a unified system. Interconnection improves system reliability by allowing regions to exchange power in response to variations in demand or generation availability. When a sudden increase in load or loss of generation occurs in one area, power can be imported from neighboring regions (Circuit Globe, 2023; Hitachi Energy, 2024).

3.1.2 Structure of the Swedish Power Grid

The Swedish power grid is organized into three main levels (see figure 3.1): the transmission network, the regional network, and the local distribution network (Svenska kraftnät, 2023). The transmission network operates at very high voltage levels, typically 400 kV and 220 kV, and is responsible for transporting electricity over long distances across the country. It connects major generation facilities with consumption centers and also links Sweden to neighboring countries through international

interconnections (Svenska kraftnät, 2023). The regional network connects the transmission system to the local distribution networks and typically operates at voltage levels around 130 kV. It supplies electricity to large consumers and medium-sized production units (Svenska kraftnät, 2023). The local distribution network represents the final stage of electricity delivery and operates at voltage levels of 40 kV or lower. Electricity is distributed to households, commercial buildings, and smaller consumers, with voltage reduced to standard levels of 400 V and 230 V (Svenska kraftnät, 2023).

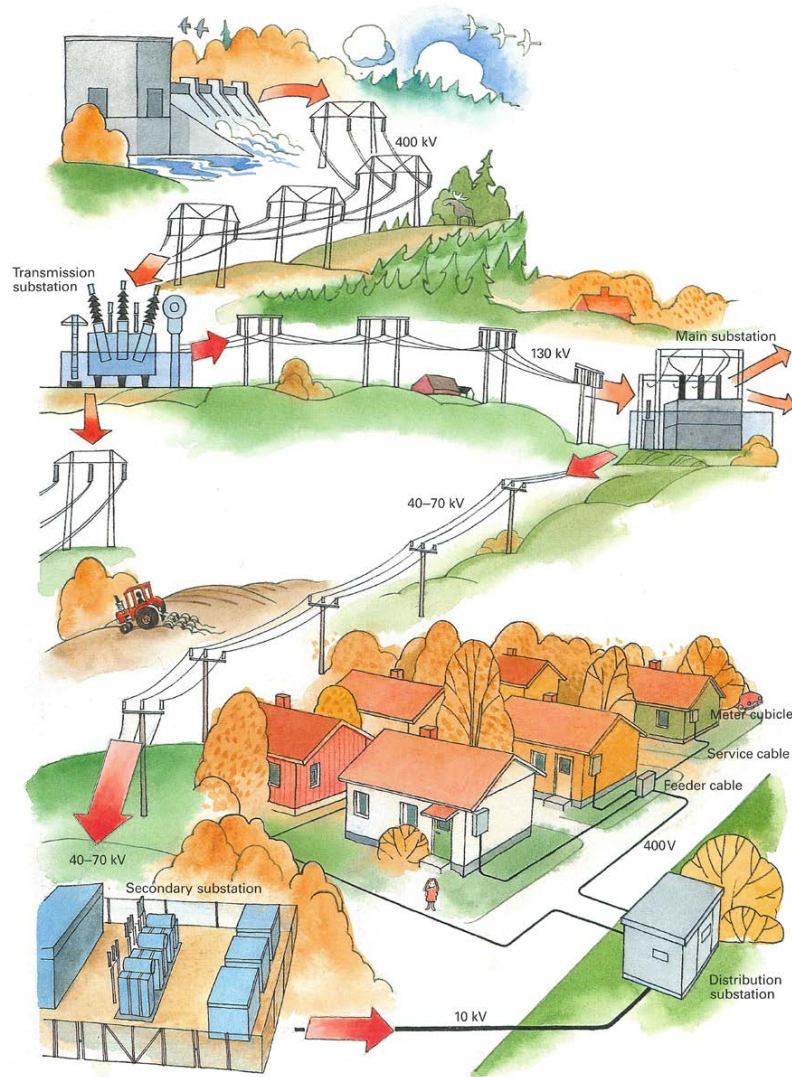


Figure 3.1: The Swedish grid structure (Energiföretagen Sverige, 2014)

The Swedish electricity grid operates under a regulated monopoly structure, where each network operator has exclusive rights within a specific geographic area. This reflects the natural monopoly characteristics of electricity distribution systems (Svenska kraftnät, 2023).

high reliability and operational flexibility, enabling efficient handling of variations in electricity demand. In recent years, the increasing electrification of industry and transport has placed additional demands on the local grid, necessitating both infrastructure upgrades and new operational strategies (Invest in Gothenburg, 2023).

3.1.4 Distribution Substations

Distribution substations play an important role in the local electricity grid, acting as the interface between medium-voltage and low-voltage systems. These substations typically receive electricity at medium voltage levels between 10 kV and 20 kV and transform it to low voltage (400 V) suitable for end users (Energimarknadsinspektionen, 2023; Sunabacka, 2017). The distribution transformer reduces the voltage to levels suitable for consumption and is typically rated between 200 kVA and 1000 kVA, which roughly can be translated to between 200 kW and 1000 kW. These transformers are commonly configured to provide both three-phase (400 V) and single-phase (230 V) supply, ensuring compatibility with a wide range of electrical loads (Energimarknadsinspektionen, 2023; Sunabacka, 2017). A distribution substation can have one or multiple transformers, resulting in a total transformer capacity ranging from a few hundred kW to a few thousands kW.

3.2 Load Profiles in Electrical Power Systems

A load profile describes how electrical demand varies over time for a given system, region, or type of consumer. These variations occur across multiple time scales, including daily, weekly, and seasonal patterns, and are influenced by factors such as climate, human activity, economic structure, and electrification levels (International Energy Agency, 2022; Kundur, 1994).

3.2.1 Base Load and Peak Demand

The base load represents the minimum level of electricity demand over a given period, typically reflecting continuous consumption from essential services, industrial processes, and always-on infrastructure (Glover et al., 2012). This portion of the load tends to be relatively stable and predictable. In contrast, peak demand refers to periods of maximum electricity usage, which often occur during specific times of day when residential, commercial, and industrial activities coincide. In many regions, daily peaks are observed in the morning and evening, driven by household activities such as cooking, heating, and appliance use, as well as commercial operations (International Energy Agency, 2022). Peak demand is of particular importance because it determines the required capacity of generation, transmission, and distribution systems.

3.2.2 Daily and Seasonal Load Variations

Load profiles exhibit characteristic daily patterns. In urban residential areas, electricity demand is typically lowest during nighttime, increases in the morning as people begin daily activities, stabilizes during midday, and reaches a second peak in the evening (Number Analytics, 2025). Commercial areas, by contrast, often display a more pronounced daytime peak corresponding to working hours, followed by a significant reduction in demand after business hours. Seasonal variations further influence load profiles. In colder climates, electricity demand often peaks during winter due to heating requirements, while in warmer regions, summer peaks are driven by air conditioning loads (International Energy Agency, 2022). These seasonal differences can significantly affect long-term planning, as systems must be designed to handle the highest expected demand periods.

3.2.3 Load Profiles in Different Urban Areas

Within cities, load profiles vary significantly depending on land use and consumer type. Residential areas are characterized by strong variation, with pronounced morning and evening peaks and relatively low daytime consumption (Richardson et al., 2010). Commercial districts, including offices and retail centers, exhibit high daytime demand and relatively low nighttime consumption, resulting in a profile that is more aligned with working hours. Industrial areas tend to have more stable and continuous load profiles, particularly where processes operate continuously or in multiple shifts. This results in a higher base load contribution and fewer pronounced peaks compared to residential and commercial sectors (Glover et al., 2012).

3.3 European Urban Atlas

Copernicus Land Monitoring Service (CLMS) provide geographical information on land cover and land use for Europe (Copernicus Land Monitoring Service, 2026). Land cover refers to the physical characteristics of the Earth’s surface (e.g., vegetation, built-up areas), while land use describes the function of that land (e.g., residential, industrial, transport) (Spatial Post, 2024). The integration of land use and land cover information makes it possible to gather areas that have similar structure together.

The Urban Atlas is a high-resolution land use/land cover dataset developed within the CLMS. It provides information across European Functional Urban Areas (FUAs) and is derived primarily from Earth Observation (EO) data combined with ancillary datasets such as navigation data and topographic maps (European Environment Agency, 2018). The dataset is designed to support the analysis of urban spatial structures and allows for consistent comparison across European cities. The primary purpose of the dataset is to provide a baseline for analyzing urban characteristics, including spatial patterns of development, density, and infrastructure (European Environment Agency, 2018).

The Urban Atlas classification system is hierarchical and consists of 27 land use/-land cover classes grouped into five main categories: artificial surfaces, agricultural areas, natural and semi-natural areas, wetlands, and water (European Environment Agency, 2018). Artificial surfaces are described with a higher level of detail than other classes, reflecting the complexity of urban environments. Within artificial surfaces, the classification distinguishes between several functional categories, including residential areas (urban fabric), industrial and commercial zones, transport infrastructure, construction sites, and green urban areas. This detailed classification enables the identification of areas with different functional roles within the urban system.

Urban Fabric and Density

Urban fabric represents built-up areas and their associated land. These areas are differentiated primarily by the degree of soil sealing, which reflects the proportion of surfaces covered by buildings and other artificial materials (European Environment Agency, 2018). Continuous urban fabric is defined by a high degree of soil sealing (greater than 80%), while discontinuous urban fabric is subdivided into density classes based on lower sealing levels. These distinctions capture variations in building density and spatial structure within urban areas.

Industrial, Commercial, Public and Institutional Units

Within the Urban Atlas classification, industrial, commercial, public, military, and private units constitute a distinct class of artificial surfaces characterized by a dominant presence of built structures and sealed surfaces (European Environment Agency, 2018). From a land cover perspective, these units are primarily composed of artificial structures such as buildings and infrastructure, as well as sealed surfaces including asphalt, concrete, or other stabilized materials. From a land use perspective, this category encompasses a wide range of functions related to industrial production, commercial activities, public administration, and institutional services.

Industrial units include production sites, storage areas, energy generation facilities, and utility infrastructure such as water and sewage treatment plants. These areas are typically characterized by large building footprints, specialized structures, and strong connectivity to transport networks. In contrast to residential areas, industrial zones often exhibit large-scale buildings that do not require natural lighting and are frequently located in the city outskirts.

Commercial units comprise areas dedicated to retail, services, and business activities, including office buildings, retail parks, and commercial complexes. Purely commercial zones are often spatially separated from residential areas, although mixed-use configurations may occur (European Environment Agency, 2018). Public, military, and institutional units include areas used for governmental, educational, healthcare, and administrative purposes. Examples include schools, universities, hospitals, administrative buildings, military facilities, and cultural institutions.

3.4 Demographic Statistical Areas

Statistics Sweden (SCB) has developed a national geographic division known as Demographic Statistical Areas (DeSO), to enable spatially detailed analysis at a sub-municipal level. This system divides Sweden into approximately 6,000 small areas, each typically containing between 700 and 3,000 inhabitants (Statistiska centralbyrån (SCB), 2025b). The purpose of this classification is to provide a consistent and stable spatial framework for statistical analysis at a fine geographic scale. DeSO areas are designed to follow existing administrative boundaries, such as municipalities and counties, while maintaining relatively homogeneous population sizes. Each area is uniquely identified by a numerical code rather than a name, enabling systematic aggregation and comparison across regions. Furthermore, DeSO can be aggregated into larger statistical units, such as Regional Statistical Areas (RegSO), allowing analyses at multiple spatial scales (Statistiska centralbyrån (SCB), 2025b).

To complement spatial land use classifications, statistical data on the built environment can be obtained from SCB. The SCB statistical database provides detailed information on buildings, including the number of buildings and associated land area, categorized by region and building type (Statistiska centralbyrån (SCB), 2025a). These data are primarily derived from the Swedish property register and related geospatial datasets, ensuring a high level of completeness and consistency. The data is available for each DeSO region.

3.5 Construction Sites

Construction sites can be described as complex and dynamic systems, characterized by variability in activities and operational conditions. Unlike stationary industrial production, construction sites are temporary and project-specific, resulting in continuously changing configurations of machinery, workflows, and infrastructure. These characteristics make construction sites heterogeneous, both in terms of physical layout and operational requirements. According to the Electric Worksite II project, construction activities such as excavation, earthmoving, and foundation work account for a significant share of energy use and emissions within the construction sector (Bern, 2024). These activities are typically performed using heavy machinery, including excavators, wheel loaders, and transport vehicles, which dominate energy consumption on site. At the same time, the report highlights that construction sites vary considerably depending on project type, ranging from small urban projects to large-scale infrastructure developments.

This variability was also confirmed in interviews with major Swedish contractors, which was done as a part of this project, indicating that machine fleets, workflows, and operational intensity differ significantly between projects. The composition of machinery is not linearly related to project size, but rather determined by task-specific requirements, ground conditions, and logistical constraints. For example, large infrastructure projects often require extensive fleets of dumpers and excavators

for mass handling, while urban projects rely more on smaller and more flexible equipment due to space limitations.

3.5.1 Construction phases of a construction site

Construction projects when machine are used are commonly divided into phases that reflect both the technical progression of the project and the evolving resource requirements over time. Within Swedish construction practice, particularly in infrastructure and civil engineering projects, a used classification includes **Groundwork**, **Foundation work**, **Structural frame**, and **Structural completion** (Bern, 2024), confirmed from the interviews with Swedish contractors.

Groundwork

The initial phase, Groundwork, involves site preparation, excavation, mass handling, and installation of underground infrastructure such as water, sewage, and electrical systems. This phase is typically the most machine-intensive in terms of heavy equipment usage. Machine configurations during this phase can include multiple excavators, dumpers, wheel loaders, and transport vehicles operating at the same time.

Foundation Work

The Foundation work follows site preparation and includes activities such as piling, stabilization, and construction of foundations. Compared to groundwork, this phase involves more specialized machinery. Interview data indicate that the transition from groundwork to foundation work often results in a reduction in the total number of active machines, reducing excavator usage and adding machines like e.g. concrete trucks.

Structural Frame

The Structural frame phase involves the erection of the main structural elements of the building or infrastructure. This phase is typically less dependent on earth-moving machinery and instead relies on cranes, and transport vehicles.

Structural Completion

The final phase, Structural completion, includes finishing works such as installation of facades, interior, and final adjustments. Interviews suggest that this phase is characterized by a significant reduction in heavy equipment usage and an increase in manual and semi-mechanized tasks. Mainly transporting vehicles and a few heavy duty machinery on wheels are used at this phase for the finalization of the construction.

3.5.2 Workdays

Workdays are typically structured around fixed start and end times, combined with scheduled breaks that create interruptions in machine operation. Detailed work schedules were obtained from interviews with three Swedish contractors carrying out construction projects throughout Sweden. In infrastructure projects, workdays typically begin at 06:30 and extend until 18:30 during the first part of the week, and then from 06:30 to 14:30 on Thursdays, without lunch break. Scheduled breaks include a morning break (09:00–09:30) and lunch break (13:00–13:30). In contrast, urban and local market projects generally follow more standardized working hours, working Monday to Friday from 07:00 to 16:00 and the same break structure as in Infrastructure projects. Work on weekends are generally avoided if possible for both markets. Table 3.1 shows the different schedules.

Table 3.1: Typical workday schedules for a construction site for Infrastructure and Urban market

Construction type	Day	Start-End	Break 1	Break 2
Infrastructure	Mon–Wed	06:30–18:30	09:00–09:30	13:00–13:30
	Thu	06:30–14:30	09:00–09:30	–
Urban market	Mon–Fri	07:00–16:00	09:00–09:30	13:00–13:30

These time schedules can be seen as general with some variations occurring, e.g. lunch can start within the time period 12:00–13:30, with every break being 30 minutes long.

3.6 Construction Machinery

Construction activities rely on a diverse set of heavy duty machinery to perform tasks such as excavation, material handling, transport, and compaction. These machines are mainly diesel-powered today and are associated with high energy consumption and emissions. Typical machine categories identified through interviews include:

- Crawler excavators
- Wheeled excavators
- Wheel loaders
- Dumpers
- Trucks
- Rollers
- Cranes

The configuration of machine fleets varies depending on what phase the project is in and the project characteristics. There are more machine types than presented, but these are specialized for specific work tasks, thus not as commonly utilized. In this study, Cranes and Trucks appears outside the scope and are therefore not taken into consideration.

3.6.1 Crawler Excavators

Crawler excavators are earthmoving machinery designed for excavation, material handling, and lifting operations. They are characterized by their use of tracks instead of wheels, making crawler excavators particularly suitable for operation in challenging and uneven terrain conditions, allowing effective operation on soft, muddy, or unstable ground where wheeled machines may struggle, with the trade off of high energy consumption (EMS Sverige, n.d.-a; Foria, n.d.-a). Crawler excavators are available in multiple size classes, as seen in table 3.2, ranging from compact machines suited for confined environments to large-scale units capable of handling deep excavation and heavy-duty operations. The definition of the sizes varies depending on source, thus are the categorisation represented by the available machines on Volvo CE's website and their categorisation.

Table 3.2: Machinesize categories for excavators (Volvo Construction Equipment, n.d.)

Category	Size
Compact	<10 tons
Medium	10-30 tons
Large	>30 tons

Crawler excavators are used in construction, infrastructure development, and large-scale earthmoving projects (EMS Sverige, n.d.-a). For construction work, excavators in the size categories Compact to Medium are the usual sizes used.

3.6.2 Wheeled Excavator

Wheeled excavators are construction machinery designed for excavation, material handling, and lifting operations. Unlike tracked excavators, wheeled excavators are mounted on tires, enabling mobility on paved and hard surfaces, reducing energy consumption compared to crawler excavators. This allows them to travel between job sites without the need for transportation equipment, making them particularly advantageous in urban and infrastructure-related applications (EMS Sverige, n.d.-c; Hydrema, n.d.-b). Wheeled excavators in the size 15-18 tons are usually used in construction based on interviews.

3.6.3 Wheel Loader

Wheel loaders are heavy construction machinery designed for material handling, loading, and transportation tasks within the construction site. These machines are specifically engineered to move large volumes of material such as soil and gravel (EMS Sverige, n.d.-b; Nordtag, 2026). Wheel loaders are widely utilized in construction and infrastructure projects. Their availability in various sizes, up to 20 tons in construction, and configurations further enhances their suitability for different working conditions, from urban environments to large-scale construction sites (EMS Sverige, n.d.-b; Nordtag, 2026).

3.6.4 Dumper

Dumpers are heavy-duty construction vehicles specifically designed for the transportation and unloading of large volumes of bulk materials, such as soil, gravel, rock, and demolition waste (Foria, n.d.-b; Hydrema, n.d.-a). They are engineered to operate in demanding environments where conventional transport vehicles are unsuitable, allowing them to travel rough and uneven terrain commonly encountered in large-scale construction and earthmoving projects (Foria, n.d.-b; Hydrema, n.d.-a). In construction, articulated haulers are typically used. Dumpers are mostly utilized in construction, infrastructure development, and mining operations. Their primary role is to move masses of materials across construction sites, especially in scenarios involving a lot of earthworks or excavation activities. The size of these machines varies depending on geotechnical aspects, but generally are dumpers that are able to carry up to 30 tons used in construction and infrastructure projects, mainly during the groundwork phase based on interviews.

3.6.5 Roller/Compactor

Rollers, also referred to as compactors, are construction machinery used to increase the density and stability of soil, asphalt, and other materials through mechanical compaction. This compaction process is critical in ensuring the long-term performance and structural integrity of infrastructure such as roads, pavements, and foundations (Dikkwell, 2025; SH Machines, 2025). In practical applications, rollers are widely employed in road construction, earthworks, and foundation preparation (SH Machines, 2025). Machines weighing up to 25 tons are generally used in construction and infrastructure projects and are operated during the end of groundwork phase and foundation work based on interviews.

3.7 Battery-Electric Construction Machinery

The market offering remains uneven across machine classes. Compact machines are the most commercially mature because their duty cycles, power demands and battery requirements are comparatively manageable. By contrast, larger excavators, wheel loaders, articulated haulers and other high-energy machines are only

now becoming available in limited series, pilot projects or selected markets (Tice et al., 2026; Volvo Construction Equipment, 2025b, 2026b). Volvo CE, for example, now presents an electric portfolio that spans compact excavators and wheel loaders, but also includes larger machines such as the EC230 Electric crawler excavator, the L120 Electric wheel loader, and the A30 Electric and A40 Electric articulated haulers (Volvo Construction Equipment, 2025b, 2026b, 2026c). Similarly, Hitachi has expanded from smaller electric excavators toward larger battery-powered excavator classes, reflecting a wider industry trend in which manufacturers electrification into heavier application (Hitachi Construction Machinery Europe, 2023, 2026).

For larger crawler excavators, cable-connected machines may also be used as an alternative to battery-electric operation, based on information obtained through interviews. In addition, some battery-electric machines support battery swapping during the workday, thereby reducing or eliminating the need for daytime fast charging. One example is the Develon DX355 Electric excavator (DEVELON, 2024).

3.8 Charging of Battery-Electric Construction Machinery

Charging is a central aspect of battery-electric construction machinery, as overall machine productivity depends not only on installed battery capacity but also on how efficiently and reliably energy can be delivered on site. In contrast to diesel refueling, which is rapid, charging processes are more time-dependent, infrastructure-intensive, and sensitive to operational conditions. As a result, charging must be considered both as a machine-level characteristic and as part of the broader site energy system.

Electric construction equipment typically utilizes a combination of alternating current (AC) and direct current (DC) charging solutions, with the choice depending on machine size, battery capacity, and operational requirements. For compact machines, AC charging remains common (Volvo Construction Equipment, 2025a). Typical AC charging power levels range from approximately 2 kW to 22 kW, which is generally sufficient for overnight charging of smaller machines (Compact Equipment, 2024; United Rentals, 2024). However, AC charging is limited in terms of power delivery, which constrains its suitability for high-utilization operations. To address this limitation, DC charging solutions are deployed for larger machine categories. A key enabling technology is the Combined Charging System (CCS), particularly CCS2 in the European context, enabling higher charging power levels compared to AC systems (Recharged, 2024; Volvo Construction Equipment, 2025a).

Charging power levels vary significantly depending on machine class and battery size. Compact construction equipment, characterized by relatively small battery packs, may utilize DC charging systems in the range of approximately 20 kW to 150 kW to enable faster turnaround between operations (Compact Equipment, 2024; Volvo Construction Equipment, 2026a). In contrast, larger construction machinery re-

quires substantially higher charging capacities due to increased energy demand and battery size, with DC charging power levels reaching up to 400 kW in current applications (Volvo Construction Equipment, 2026a). Although charging infrastructure with capacities up to 400 kW exists, individual machines may still be limited to lower maximum charging powers due to onboard battery and thermal management constraints. For example, Volvo's L120 Electric wheel loader is designed for a maximum charging power of 165 kW (Volvo Construction Equipment, 2026d).

Charging times for electric construction machinery vary depending on battery capacity, charging infrastructure, and charging strategy. Manufacturers generally distinguish between slow charging, typically based on AC charging, and fast charging, commonly based on DC charging. Slow charging is primarily intended for overnight charging or charging during extended idle periods. Across currently available electric construction machinery, manufacturers commonly specify charging times in the range of approximately 8–12 hours for a full recharge for larger machines (ForConstructionPros, 2021; Volvo Construction Equipment, 2021). Fast charging enables substantially reduced charging durations by utilizing higher charging powers. Reported fast charging times are generally within 0.5–2 hours depending on battery capacity and charger power (Komatsu Ltd., 2023; KTEG GmbH, 2024; Volvo Construction Equipment, 2021). In many cases, manufacturers report charging times from 0–80% state of charge (SoC), since charging power is commonly reduced above this level to limit battery degradation and thermal stress. For compact electric excavators, charging times are often below one hour when fast charging is available. For example, the Volvo ECR25 Electric can be charged in approximately one hour using DC fast charging, compared to approximately six hours using AC charging (ForConstructionPros, 2021). Similarly, the KTEG ZE85 electric excavator, equipped with a 100 kWh battery, can reportedly charge from 0–100% in approximately 45 minutes using a 150 kW DC charger (KTEG GmbH, 2024). As battery capacities increase for larger machine classes, charging times would naturally increase if charging power remained constant. However, manufacturers compensate for this through the implementation of higher charging powers, commonly in the range of 150–300 kW for larger machines (Komatsu Ltd., 2023; Volvo Construction Equipment, 2021). Consequently, fast charging durations for larger electric construction machinery are typically maintained below approximately two hours.

An important technical characteristic of battery charging is the non-linear charging behavior, commonly referred to as the charging curve. Lithium-ion batteries, which are predominantly used in construction machinery, typically charge rapidly at low and medium states of charge but experience a gradual reduction in charging power as the battery approaches full capacity. This phenomenon is primarily driven by electrochemical and thermal constraints within the battery system (eStation, 2024). As a result, the final portion of the charging process (e.g., from approximately 80% to 100% state of charge) can take disproportionately longer than the initial charging phase. This behavior underlies the commonly referenced “20–80% rule,” which suggests that optimal battery operation often occurs within a partial state-of-charge

window. Charging within this range allows higher average charging power, reduces total charging time, and can also contribute to improved battery longevity by limiting stress associated with high states of charge (EnergySage, 2024; eStation, 2024).

3.9 Python for Data Processing and Analysis

Python is a high-level, general-purpose programming language widely used in scientific computing, data analysis, and engineering applications. It is designed to emphasize code readability and simplicity, allowing users to develop programs efficiently and integrate systems effectively (Python Software Foundation, 2024a, 2024b). A key strength of Python lies in its large ecosystem of libraries and built-in functions. The standard library provides a wide range of modules for tasks such as file handling, data processing, and mathematical operations, enabling users to perform complex operations without requiring extensive external dependencies (Python Software Foundation, 2024c). In addition, Python supports third-party libraries that extend its capabilities for scientific computing and data analysis.

In the context of this study, Python is used as a primary tool for processing and analysing large datasets. Its flexibility allows integration of different data formats and sources, including tabular data and geospatial datasets. This enables efficient handling of spatial information, such as land use classifications and infrastructure data, as well as time-dependent data such as load profiles.

4

Load Profile of Electrified Construction Sites

This chapter describes the methodology used to construct representative charging load profiles for electrified construction sites. The purpose of the methodology is to estimate the charging demand introduced by battery-electric construction machinery under different construction scenarios. Since electrified construction machinery introduces new and potentially high power demands to the electricity grid, representative charging profiles are required in order to evaluate how these loads may affect the available capacity in local distribution substations. The constructed charging load profiles form one of the main inputs to the study. In later chapters, the charging demand profiles developed here are combined with historical substation load data and available capacity profiles in order to assess the risk of capacity exceedance under different construction scenarios. Consequently, the methodology presented in this chapter provides the link between electrified construction activities and their potential impact on the local electricity grid. Figure 4.1 presents an overview of the methodological workflow applied in this chapter.

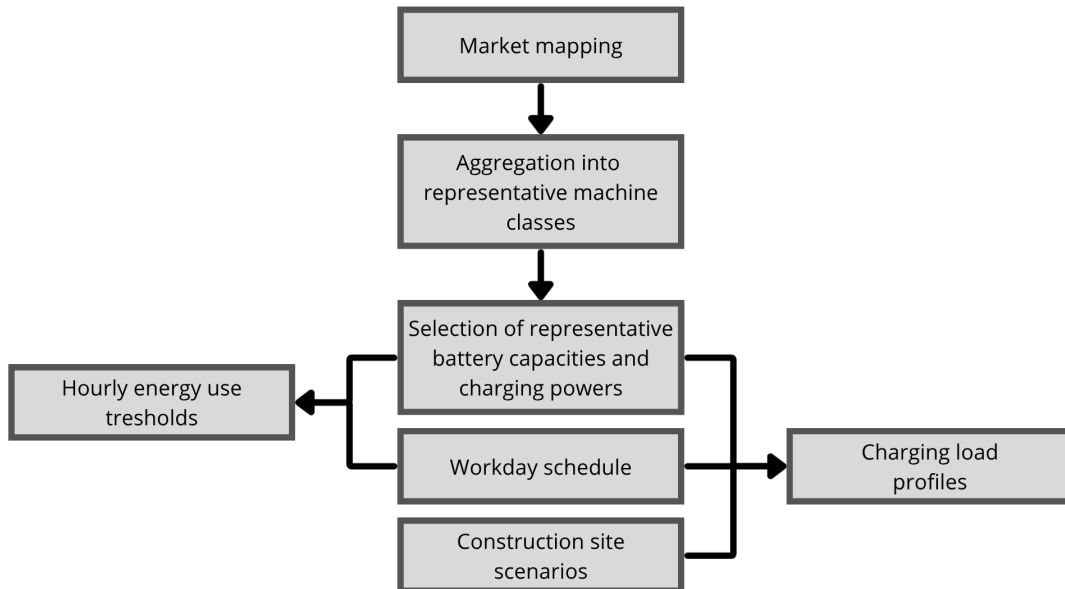


Figure 4.1: Overview of the workflow used to construct charging load profiles and hourly energy use thresholds for electrified construction site scenarios.

The workflow begins with a market mapping of available battery-electric construc-

tion machinery in order to identify relevant machine types, sizes, and technical specifications currently available on the market. Since the market consists of a large number of machine models with varying characteristics, the identified machines are aggregated into representative machine classes to reduce model complexity while maintaining representative machine behavior within the analysis. Representative battery capacities and charging powers are then selected for each machine class using manufacturer specifications and available market data.

These technical characteristics are combined with representative workday schedules and construction site scenarios, where the number and composition of machines vary depending on project type and operational conditions. The workday schedules define when machinery is assumed to operate and when charging opportunities occur during the day. Based on these combined inputs, charging load profiles are generated for different construction site scenarios. In addition, hourly energy-use thresholds for the machines considered in this study are calculated to estimate the maximum hourly energy demand under different charging conditions, thereby providing a reference for when these charging loads can be applied.

4.1 Mapping of the Market and Dataset Construction

A market review of battery-electric construction machinery was conducted to identify and map machines that are commercially available today, as well as machines announced for introduction in the coming years. The mapping consisted of systematically identifying electric construction machines from publicly available sources and compiling technical data relevant for charging and energy-system analysis. The market mapping was carried out through a systematic review of manufacturer web-pages, product brochures, dealer pages, press releases, and technical specification sheets. Only machines described by the manufacturer or authorized distributor as fully electric were included. The review covered several machine categories, including crawler excavators, wheeled excavators, wheel loaders, articulated haulers/dumpers, and rollers.

For each identified machine, a dataset was compiled. The following variables were recorded whenever they were available in the source material: manufacturer, model name, machine type, machine size, battery size, slow charging power, quick charging power and rated power. Since manufacturers do not report specifications in a fully standardized format, the level of detail varied between machines. Some sources provided multiple charging alternatives, of which the highest alternative was chosen for the fast-charging, whilst some sources only mentioned battery size or rated power. As a result, the dataset contains missing values for several variables. Battery size was recorded in kWh, charging power in kW, rated power in kW and machine size as weight in kg.

From the mapping and market research, a total of 82 different models of battery-electric construction machinery was documented of varying manufacturers and sizes. Crawler excavators dominates the dataset with 48 different models, with wheel loaders coming second with 22 different models, showing the lack of alternatives of the other machine types.

4.1.1 Aggregation into Representative Machine Classes

The collected machine-specific data were aggregated into representative size classes. These size ranges were defined based on groups of machines with similar weight, battery capacity and rated power. The resulting machine classes can be seen in Appendix A.1. For the analysis, not every size class is used. In Table 4.1, the machines used in this study is shown, together with what class they classifies as.

Table 4.1: Construction machinetypes and sizes used in this study

Machine type	Size class
38t CEX	35t-42t
30t CEX	27t-34t
25t CEX	20t-27t
5t CEX	5t-9t
2t CEX	1t-2.5t
18t WEX	17t-18t
20t WL	18t-21t
8t WL	4t-7t
30t AH	29t
25t R	27t

The vehicle mass values used in this study correspond to the weight of the diesel-powered variants currently in operation. For the corresponding battery-electric alternatives, an equivalent vehicle mass was assumed wherever feasible. In cases where exact weight was not available, the closest comparable vehicle weight was adopted based on manufacturer specifications.

4.1.2 Battery Sizes and Charging Power

The aim of this section was to define representative machine classes with respect to battery capacity, slow charging power, and fast charging power, thereby creating a representative machine dataset for use as input to the model. Battery capacities within each size class exhibited considerable variation. For the smaller machine classes, the variation was typically limited to a few tenths of a kWh, whereas for

the larger classes the variation could amount to several hundred kWh. No clear proportional relationship between machine weight and battery capacity could be identified. Consequently, the largest existing battery capacity within each size class was selected as the representative battery size for the model, as presented in Table 4.2. The rationale for this approach is that the upper bound of battery size better reflects the charging infrastructure requirements, as larger batteries impose higher demands on charging power and represent possibility to operate longer period without charging.

Similarly, both slow and fast charging powers varied significantly between machines within the same size class, largely depending on the manufacturer. The representative slow charging power for each class was therefore determined by calculating the average charging power of the machines within the class and selecting the closest commercially available charging level. For example, the CEX (27t–34t) class had an average slow charging power of 56.75 kW, for which 60 kW was selected as the representative value.

For fast charging power, the representative value was generally chosen as the maximum available charging power within each size class. This approach was adopted to reflect current manufacturer trends, where high-power DC charging is increasingly implemented in order to maintain practically feasible charging times despite increasing battery capacities, as discussed in Section 3.8. However, exceptions were made for the three largest excavator size classes included in the model. The 19t–27t class exhibited reported fast charging powers ranging from 120 kW to 300 kW, the 27t–34t class ranged from 260 kW to 300 kW, while the 35t–42t class was represented by a charging power of 240 kW. Using the maximum available values directly would therefore not provide a consistent progression in charging capability relative to the increasing battery capacities of the machine classes. Consequently, representative fast charging powers of 250 kW, 300 kW, and 360 kW were instead selected for these three classes in order to better reflect the expected increase in charging power with increasing battery size. The value of 360 kW was derived from the only identified machine in the machine class above 35t–42t, although this larger machine class itself was not included in the model.

For certain machine classes, complete charging data could not be obtained, either for slow charging power, fast charging power, or both. In these cases, representative charging powers were estimated based on battery capacity by comparing the machines to other classes with similar battery sizes. The charging characteristics of the machine with the closest comparable battery capacity were then adopted as representative values. The resulting representative machine parameters for each size class are presented in Table 4.2.

Table 4.2: Representative battery capacities and charging powers for the machine classes included in the model

Machine type	Battery size	Slow charging	Fast charging
	[kWh]	[kW]	[kW]
38t CEX	800	80	360 ^a
30t CEX	528	60	300
25t CEX	451	44	250 ^a
5t CEX	180	22	150
2t CEX	32	3	17
18t WEX	400	44	250
20t WL	400	40	240
8t WL	100	11	60
30t D	270	22 ^b	350
25t R	425	40 ^b	250 ^b

^a Representative fast-charging power levels were selected based on the anticipated progression of charging power in relation to battery capacity, rather than the maximum reported charging power within each vehicle class. A charging power of 360 kW represented the highest value identified across all reviewed cases.

^b Charging power values were estimated through comparison with machines of similar battery capacity due to limited availability of charging data.

4.1.3 Hourly Energy-Use Thresholds

To provide reference values for the charging powers considered in this study, hourly energy-use thresholds were calculated for the included machine types based on the established battery capacities and charging powers. These thresholds represent the maximum average hourly energy use that can be sustained under different charging configurations, thereby indicating the approximate energy-use levels at which fast-charging during breaks becomes necessary. Three charging configurations were considered: overnight charging only, a reduced fast-charging configuration, and a baseline fast-charging configuration. The latter two configurations are further defined and applied in the charging scenarios described in Section 4.2.

The thresholds are calculated based on the operational assumptions presented in Section 4.2. Detailed calculation procedures are provided in Appendix A.2. The resulting hourly energy-use thresholds are presented in Table 4.3. These values are intended as reference values for interpreting the charging scenarios and indicate the approximate average hourly energy-use levels that can be supported by the considered charging powers.

Table 4.3: Hourly energy-use thresholds for the included machine types under different charging configurations

Machine Type	Average hourly energy use [kWh/h]		
	Baseline fast charging	Reduced fast charging	Overnight charging only
38t CEX	125.0	102.5	80.0
30t CEX	90.3	71.6	52.8
25t CEX	76.4	60.7	45.1
5t CEX	36.8	27.4	18.0
2t CEX	5.4	4.3	3.2
18t WEX	71.3	55.6	40.0
20t WL	70.0	55.0	40.0
8t WL	17.5	13.8	10.0
30t D	70.8	48.9	27.0
25t R	80.0	61.3	42.5

In Table 4.3, the values presented under “Overnight charging only” represent the maximum average hourly energy use that can be sustained using only night charging. The “Reduced fast charging” column represents the corresponding threshold when the daytime fast-charging power is reduced by 50%, while “Baseline fast charging” represents the threshold for the documented fast-charging capability of each machine. For example, the 25 t CEX can operate using only overnight charging if the average hourly energy use remains below 45.1 kWh/h. If the energy use exceeds this value but remains below 60.7 kWh/h, reduced fast charging during work breaks is sufficient. Higher energy-use levels require the baseline fast-charging configuration. The same interpretation applies to the remaining machine types included in the table.

It should be noted that the thresholds for the reduced fast-charging configuration are not equal to 50% of those for the baseline fast-charging configuration, since the total daily available energy includes both overnight charging and fast charging, while only the fast-charging contribution is reduced by 50%.

4.2 Construction Site Charging Profiles

Using the compiled data on battery capacities and charging power requirements, in combination with different configurations of machine types and machine sizes, representative charging profiles can be established. These charging loads are based on a typical urban operational schedule, discussed in Section 3.5.2, and on interviews conducted with contractors.

Assumptions

It is assumed that each conventional machine is replaced by a battery-electric of comparable size and operational performance. Furthermore, all machines are assumed to operate under high-workload conditions throughout the working day, thereby necessitating fast charging during scheduled work breaks. Consequently, all machines are assumed to charge simultaneously during these breaks, creating peak charging loads. In addition, the battery state of charge (SOC) is assumed to decrease to 20% at the end of each working day, as discussed in Section 3.8.

To evaluate the influence of charging power, two distinct fast-charging configurations are considered in all charging profiles. The first configuration uses the documented fast-charging capability of each machine and is hereafter referred to as *full fast charging*. The second configuration considers a reduced fast-charging power, where the charging power during work breaks is decreased by 50% for each machine. This configuration is denoted as *half fast charging* and is represented by solid lines in the figures. For example, under full fast charging, a 30 t CEX has a charging power of 300 kW, which is reduced to 150 kW in the half fast-charging configuration. In both configurations, the overnight charging strategy remains unchanged.

Based on these assumptions, six charging scenarios, denoted CS1 through CS6, are generated using the two fast-charging configurations. Each scenario corresponds to a specific construction-site configuration, differing in the number of machines, machine types, and machine sizes.

4.2.1 CS1: Medium-Sized Infrastructure Project

CS1 represents a medium-sized infrastructure project. Infrastructure projects are generally distributed over extended geographical areas, which increases the likelihood of access to multiple substations when operating within urban environments. For this reason, the machine fleet configuration was divided into two operational groups. The machine fleet consisted of:

- 2×30 t crawler excavators
- 1×20 t wheel loader
- 1×18 t wheeled excavator
- 1×30 t dumpers
- 1×25 t roller

In total, six machines are assumed to operate simultaneously within the area. The corresponding charging profile is presented in Figure 4.2.

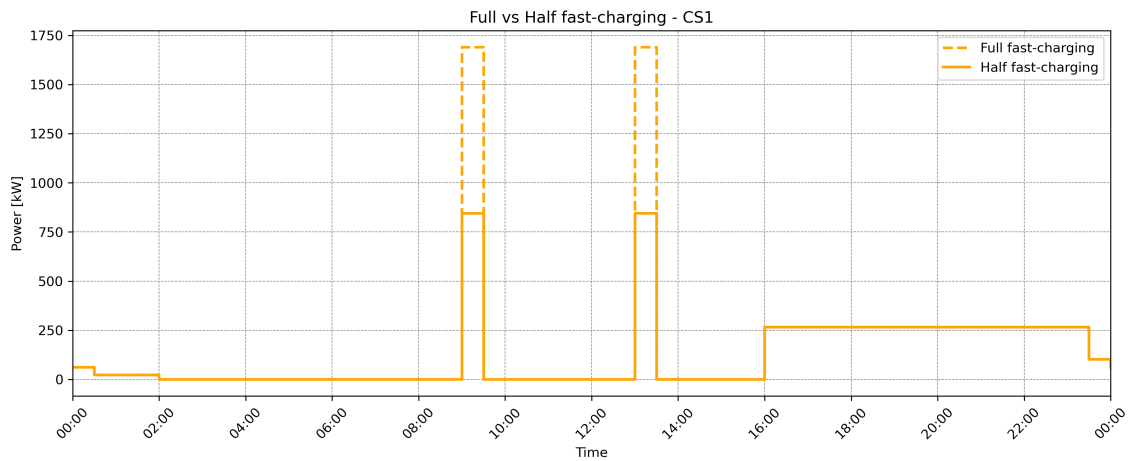


Figure 4.2: Charging profile of construction site scenario 1 (CS1). Dashed lines represent the full fast-charging strategy, while solid lines represent the half fast-charging strategy.

For the full fast-charging scenario, the charging demand reaches a peak of approximately 1690 kW during work breaks, whereas the overnight charging demand remains comparatively low, with a maximum power demand of approximately 266 kW.

4.2.2 CS2: Urban Construction Project

CS2 represents an urban construction project focused on excavation, mass handling, and material transportation within a city environment. The project configuration includes the following machine types:

- 3×25 t crawler excavators
- 2×20 t wheel loaders

A total of five machines are assumed to operate simultaneously within the construction area. The charging profile is shown in Figure 4.3.

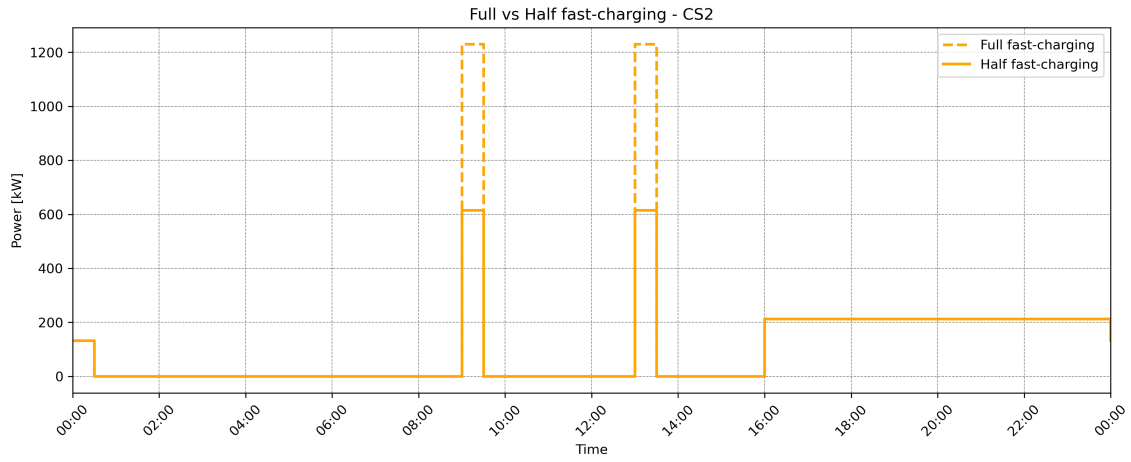


Figure 4.3: Charging profile of construction site scenario 2 (CS2). Dashed lines represent the full fast-charging strategy, while solid lines represent the half fast-charging strategy.

Under the full fast-charging strategy, the peak charging demand reaches approximately 1230 kW during work breaks, while the overnight charging demand reaches a maximum of approximately 212 kW.

4.2.3 CS3: Medium-Sized Construction Project

CS3 represents a medium-sized construction project primarily focused on excavation activities. The machine fleet consists of:

- 1 × 38 t crawler excavator
- 2 × 25 t crawler excavators
- 1 × 2 t crawler excavator
- 1 × 8 t wheel loader

A total of five machines are assumed to operate simultaneously on-site. The charging profile is presented in Figure 4.4.

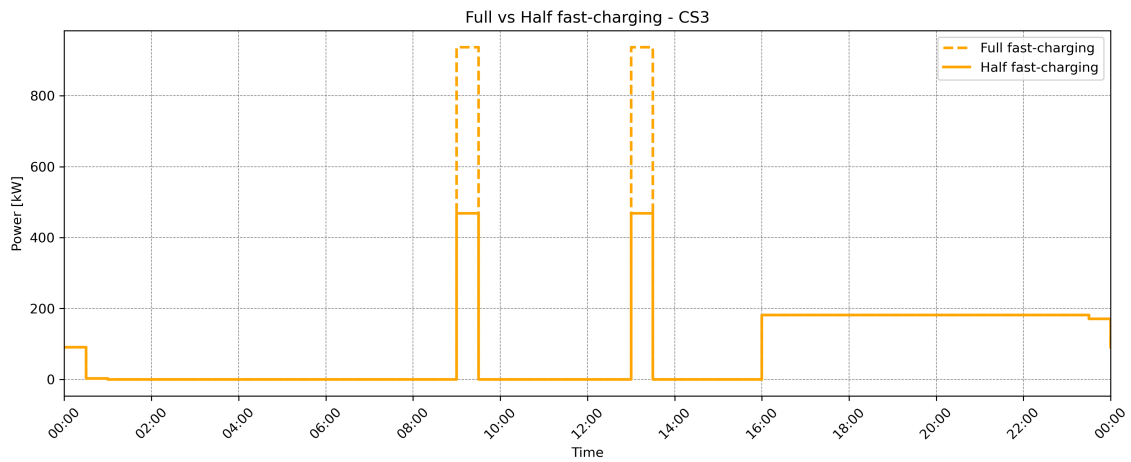


Figure 4.4: Charging profile of construction site scenario 3 (CS3). Dashed lines represent the full fast-charging strategy, while solid lines represent the half fast-charging strategy.

For the full fast-charging strategy, the charging demand peaks at approximately 937 kW during work breaks, while the overnight charging demand reaches a maximum of approximately 182 kW.

4.2.4 CS4: Urban Infrastructure Project

CS4 represents an urban infrastructure project focused on excavation, mass handling, and material transportation within a constrained urban environment. The project utilizes the following machines:

- 2×18 t wheeled excavators
- 1×5 t crawler excavator
- 1×8 t wheel loader

A total of four machines are assumed to operate simultaneously within the project area. The charging profile is shown in Figure 4.5.

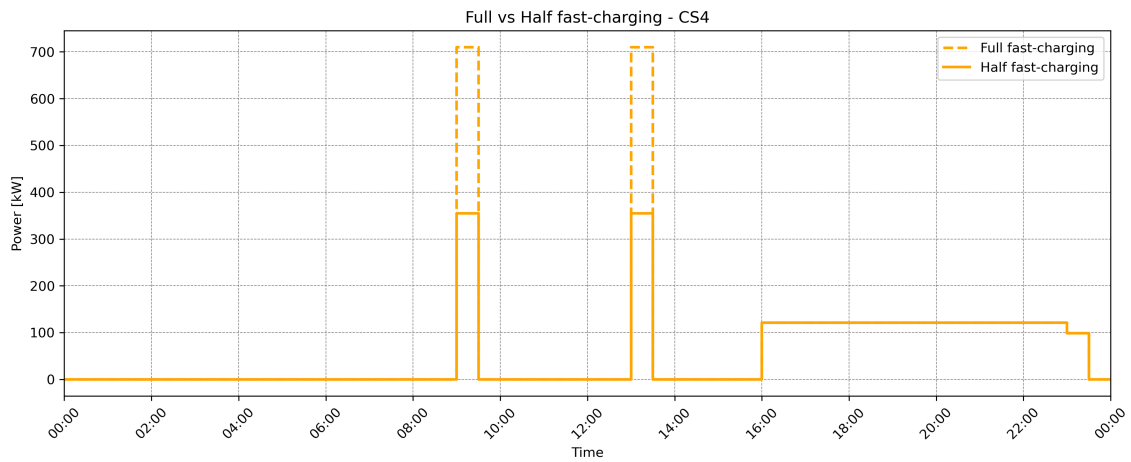


Figure 4.5: Charging profile of construction site scenario 4 (CS4). Dashed lines represent the full fast-charging strategy, while solid lines represent the half fast-charging strategy.

The full fast-charging strategy results in a peak charging demand of approximately 710 kW during work breaks, whereas the overnight charging demand reaches approximately 121 kW.

4.2.5 CS5: Small Infrastructure Project

CS5 represents a small-scale urban infrastructure project characterized by limited operational space and excavation-focused activities. The machine fleet includes:

- 1×18 t wheeled excavator
- 1×8 t wheel loader

In total, two machines are assumed to operate simultaneously on-site. The charging profile is presented in Figure 4.6.

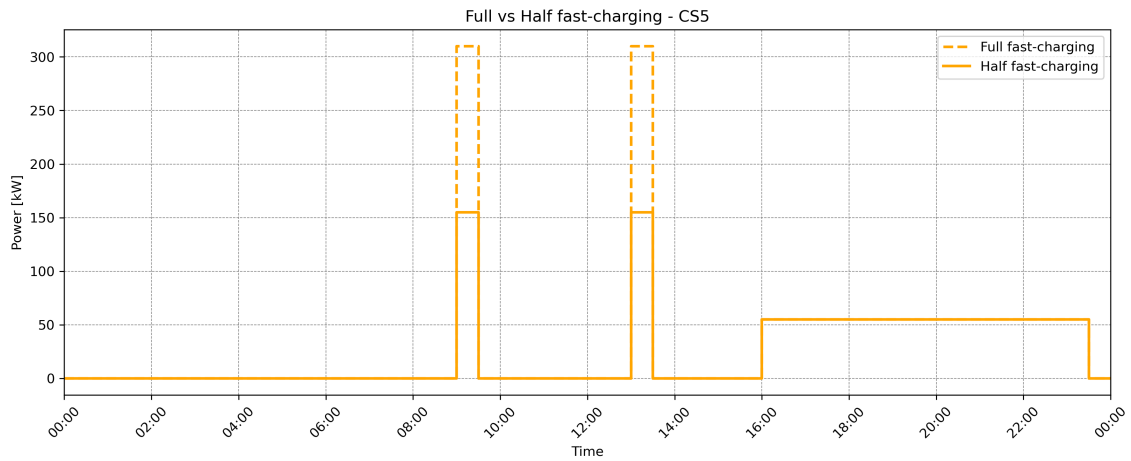


Figure 4.6: Charging profile of construction site scenario 5 (CS5). Dashed lines represent the full fast-charging strategy, while solid lines represent the half fast-charging strategy.

The charging demand peaks at approximately 310 kW during work breaks under the full fast-charging strategy, while the overnight charging demand reaches approximately 55 kW.

4.2.6 CS6: Single-Machine Excavation Project

CS6 represents a small excavation project consisting of a single machine:

- 1×25 t crawler excavator

The charging profile is shown in Figure 4.7.

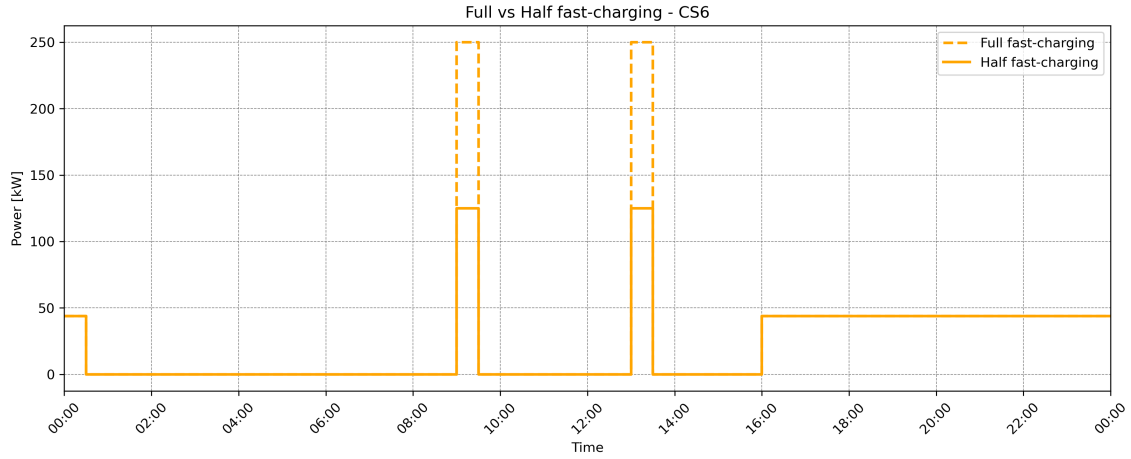


Figure 4.7: Charging profile of construction site scenario 6 (CS6). Dashed lines represent the full fast-charging strategy, while solid lines represent the half fast-charging strategy.

For the full fast-charging strategy, the peak charging demand during work breaks reaches approximately 250 kW, whereas the overnight charging demand remains comparatively low, with a maximum demand of approximately 44 kW.

5

Historical Load from Substations

This chapter describes the methodology used to construct representative historical load profiles and available capacity profiles for distribution substations within the GENAB grid area. The purpose of the methodology is to identify representative substation categories with different load characteristics and estimate how much spare transformer capacity is typically available under varying operational conditions. Since the total number of substations within the study area is too large to analyse individually, a spatial classification methodology was developed to group areas with similar land-use characteristics and expected electricity consumption patterns. Historical load data from representative substations within these categories were then used to construct representative load and available capacity profiles.

Figure 5.1 presents an overview of the methodological workflow applied in this chapter.

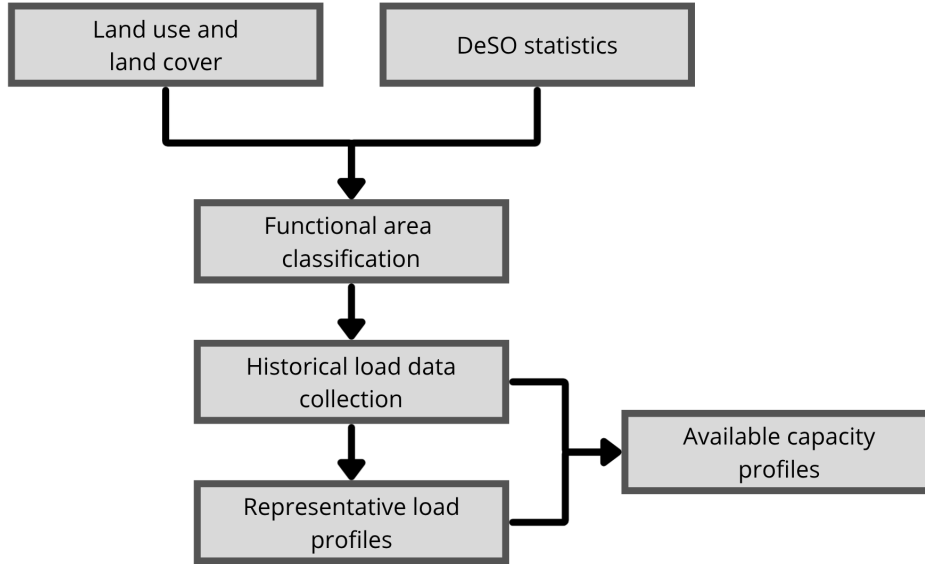


Figure 5.1: Overview of the workflow used to construct representative historical load profiles and available capacity profiles for substations within the study area.

The workflow begins with spatial land-use and land-cover data from the European Urban Atlas together with DeSO-based statistical data. These datasets were combined in order to classify the study area into broader functional area categories representing different expected electricity consumption characteristics. Based on

this classification, representative substations were identified and historical load data were collected for each analysed zone and transformer size category. The historical load data were then processed in Python to construct representative load profiles for the selected substations. In addition, representative available capacity profiles were calculated by comparing the historical load levels with the installed transformer capacities. The representative profiles presented in this chapter are primarily used to visualise and analyse general load behaviour, seasonal variation, and differences between substation categories.

The resulting profiles form one of the main inputs to the overall study. In Chapter 6, the representative load and available capacity profiles developed here are combined with the charging load profiles constructed in Chapter 4 in order to evaluate how electrified construction sites may influence local grid loading and the risk of exceeding available substation capacity. However, for the exceedance analysis, all available historical weekday observations were included for each analysed zone and transformer size category.

5.1 Spatial Classification of the Study Area for Substation Selection

As an initial step to gather data from substations, the study area was spatially classified into distinct zones based on functionality. The motivation for this step was that the total number of available substations was too large to include. A spatial pre-classification was therefore developed to identify areas with potentially similar load characteristics, thus enabling a more informed and systematic selection of substations. Rather than treating all substations as equivalent, the objective was to group the grid area into broader area types that could be expected to exhibit different consumption patterns, for example industrial zones or residential areas.

The workflow combined spatial land-use data from the European Urban Atlas, building statistics linked to DeSO, and the polygon defining GENAB grid area. The complete procedure consisted of three main stages: (i) extraction of relevant Urban Atlas classes within the study area, (ii) divide industrial/commercial land using DeSO-based building information, and (iii) aggregation into four broader functional classes. Each stage is described below.

5.1.1 Extraction of Relevant Urban Atlas Classes Within the GENAB Area

The first step consisted of isolating the parts of the Urban Atlas that were relevant for the intended classification. The Urban Atlas dataset for Gothenburg was read into Python together with the polygon dataset describing the GENAB grid area. Since the analysis aimed to distinguish between different urban environments that may be associated with different electricity demand patterns, only a limited number of Urban Atlas classes were retained. These classes were:

- continuous urban fabric (class 11100),
- discontinuous dense urban fabric (class 11210),
- discontinuous medium density urban fabric (class 11220),
- discontinuous low density urban fabric (class 11230),
- discontinuous very low density urban fabric (class 11240), and
- industrial/commercial units (class 12100).

These classes were selected because they capture two key dimensions of interest for substation screening. First, the urban fabric classes reflect different degrees of density and built intensity, which may be linked to differences in building composition and load concentration. Second, the industrial/commercial class represents areas whose load characteristics may differ from areas which are mainly residential. The selected Urban Atlas classes were intersected with the GENAB grid area polygon. This produced a new layer containing only the relevant land-use polygons located inside the study area.

5.1.2 Subdivision of Urban Atlas Class 12100 using DeSO-Based Building Information

The Urban Atlas class 12100 identifies industrial, commercial, public, military, and private units as one combined land-use category, meaning this class is still too broad for the purpose. From the perspective of electricity demand, a large industrial site may be expected to differ considerably from commercial or service-oriented areas. A second classification step was therefore introduced to subdivide the 12100 polygons into more functionally meaningful classes. This subdivision was based on DeSO polygons and a building statistics table obtained from Statistics Sweden. The DeSO dataset was read as a geospatial layer, while the building statistics table was imported from an Excel file. From this file, only building categories relevant to the intended functional distinction were retained. Specifically, rows associated with *industry*, *business/activity*, and *societal function* were selected. The rationale was that these categories provide the dominant non-residential built areas in each DeSO area. For each row, three separate variables were created:

- `industry_val`, representing building area associated with industrial buildings,
- `commercial_val`, representing building area associated with business/activity

buildings, and

- `society_val`, representing building area associated with societal-function buildings.

These variables were then aggregated by DeSO code so that one summary row was obtained for each DeSO area. On the basis of the aggregated values, each DeSO polygon was assigned a dominant class. If industrial building area was largest, the DeSO area was classified as *Industry*. If either business/activity area or societal-function area was largest, it was classified as *Commercial*. If no category dominated, or if two or more categories shared the largest value, the area was classified as *Mixed*. This rule-based procedure transformed the building statistics into a spatially explicit functional classification. The classified DeSO polygons were then intersected with the Urban Atlas polygons belonging to class 12100 inside the GENAB area. As a result, the originally broad 12100 category was spatially split into three more informative classes: *Industry*, *Commercial*, and *Mixed*. This step was important because it replaced a heterogeneous land-use class with a more differentiated representation of potentially distinct demand environments.

5.1.3 Aggregation into Four Broader Functional Classes

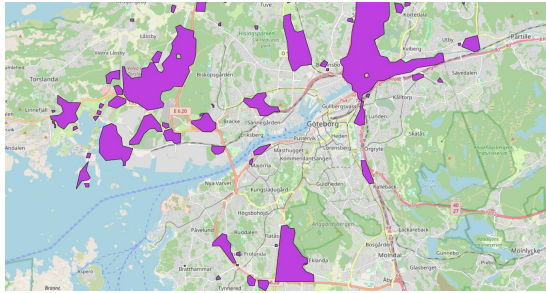
For the final area definition, the eight-class layer was aggregated into four broader functional classes. This aggregation was introduced to create a classification that is both interpretable and practically useful for selecting representative substations. A highly detailed class structure may be informative, but it is less suitable when the objective is to identify broader zones with potentially similar load profiles.

The aggregation was performed through a rule-based mapping:

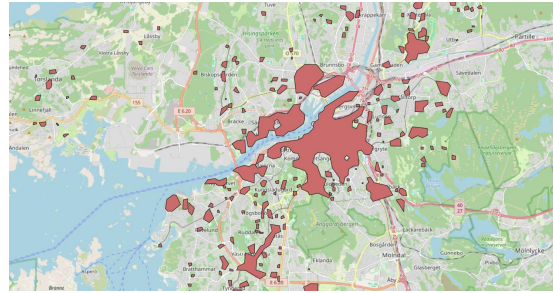
- *Industry* remained *Industry*,
- *Commercial*, *Mixed industrial/commercial*, and *Continuous urban fabric* were grouped into *Central mixed/commercial core*,
- *Discontinuous dense urban fabric* and *Discontinuous medium density urban fabric* were grouped into *Residential medium-high density*, and
- *Discontinuous low density urban fabric* and *Discontinuous very low density urban fabric* were grouped into *Residential low density*.

This grouping reflects an interpretation of the urban structure. The *Central mixed/commercial core* class was intended to capture the most central and functionally mixed parts of the urban area, where residential, commercial, institutional, and dense built-up functions are likely to coexist. The two residential classes were differentiated by density in order to separate more compact urban neighbourhoods from lower-density suburban or rural residential zones. The *Industry* class was kept separate because industrial areas may exhibit distinct electricity demand levels, operating hours, and customer composition.

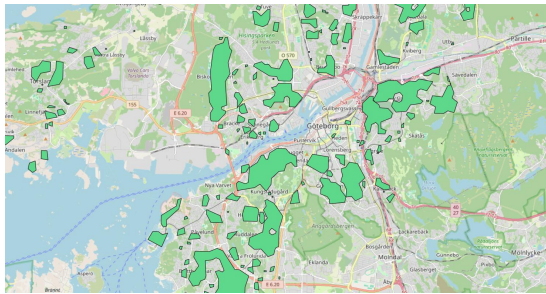
The final outcome of the classification procedure is illustrated in Figure 5.2, zoomed in over central Gothenburg, which shows the distribution of the four functional area types. Each class is presented separately to highlight its spatial extent and structure within the study area.



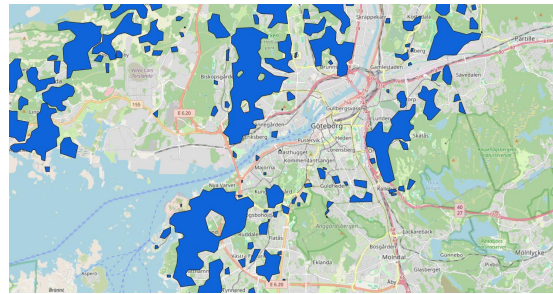
(a) Industry



(b) Mixed/Commercial



(c) Residential medium-high density



(d) Residential low density

Figure 5.2: Final spatial classification of the study area into four functional area types used for substation selection.

As a final step, the resulting layer was reprojected to EPSG:3006 (SWEREF 99 TM), which is appropriate for Swedish spatial data handling, and one shapefile was exported for each class. This could then be used in a GIS environment to determine whether substations lie in the selected areas. The outcome is not intended as a final description of electricity demand in themselves, but as a structured approximation for identifying areas in which substations might exhibit similar load characteristics. In this sense, the classification functioned as a screening and sampling framework. It should also be noted that the functional area categories are not strictly mutually exclusive, and some overlap between zones may occur. This was considered acceptable for the study, since substations located well within the classified areas were selected.

Hereafter, the functional area categories are referred to as industry, commercial, medium residential, and low residential, corresponding to industrial, mixed/commercial, residential medium-high density, and residential low-density areas, respectively.

5.2 Load Profile Construction and Statistical Characterisation

5.2.1 Data Collection

From each zone, as described in Section 5.1.3, data from 50 substations were sampled without applying size-based sorting. The purpose of this approach was to estimate the representative distribution of substation capacities within each zone and thereby identify the most common substation sizes available in the respective areas.

The collected data showed that a limited number of substation capacity categories dominated across all investigated zones. Consequently, the analysis focused on the four most representative substation sizes: 500 kW, 800 kW, 1600 kW, and 2400 kW. These capacities accounted for the majority of the sampled substations and therefore provide a suitable basis for evaluating the charging scenarios presented in this study. The distribution of the sampled substations for each zone is presented in Table 5.1. Substation capacities such as 1000 kW, 1250 kW, 2000 kW, 3200 kW, and 4000 kW were also identified during the sampling process. However, these sizes occurred only in a limited number of cases and were therefore excluded from the analysis in order to maintain a consistent and representative comparison between zones.

Substations rated at 2500 kW were grouped together with the 2400 kW category. From a grid capacity perspective, both substation sizes can be considered functionally comparable for the purpose of evaluating charging demand and hosting capacity for electric construction machinery.

Table 5.1: Distribution of sampled substation sizes across the investigated zones

Zone	500 kW	800 kW	1600 kW	2400 kW
Industrial	3	15	22	7
Commercial	0	12	17	14
Medium-density residential	9	21	15	0
Low-density residential	14	29	5	0

The distribution of substation capacities indicates clear differences between the investigated zones. In the industrial and commercial zones, the analysis primarily focused on substations rated at 800 kW, 1600 kW, and 2400 kW, as these capacities were the most frequently represented within the sampled data. In contrast, the residential zones were predominantly characterized by smaller substation capacities, and the analysis therefore focused on 500 kW, 800 kW, and 1600 kW substations.

The observed distribution further suggests that the spatial division into different zone categories captures meaningful variations in grid infrastructure characteristics.

Industrial and commercial areas generally exhibited larger substation capacities, reflecting higher expected power demands and more robust grid connections, whereas residential areas were dominated by smaller substations associated with lower typical load levels.

5.2.2 Load Profiles and Available Capacity

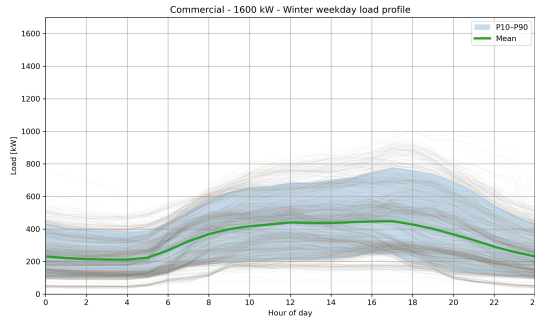
This section presents the constructed weekday load profiles and corresponding available capacity profiles for the analysed substations. The profiles are grouped by zone, transformer size, and season in order to compare how electricity demand and remaining transformer capacity vary between different parts of the distribution grid. The processing and analysis of the historical load data were performed in Python.

For each zone and transformer size category defined earlier, all non-weekday observations were first removed, leaving only weekdays (Monday–Friday) in the dataset. To represent two seasonal extreme conditions, only weekdays from January and July were selected, corresponding to winter and summer conditions, respectively. For each analysed case, such as industrial 800 kW substations during summer conditions, all weekday profiles from the selected month were included in the analysis. The hourly mean load profile was then calculated based on all included weekdays within the corresponding category.

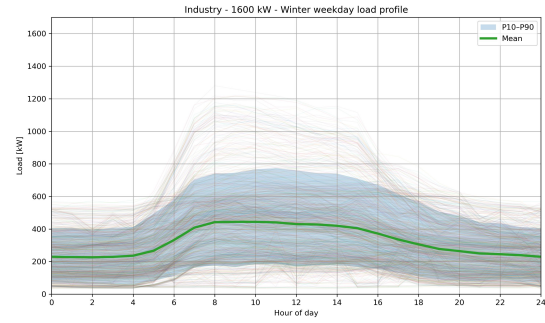
The seasonal weekday profiles presented in this section were constructed primarily to analyse and visualise the general load characteristics of the different substation categories, including typical load levels, daily variation, seasonal differences, and the spread between individual weekdays. The January and July subsets were therefore used as representative examples of winter and summer conditions rather than as the complete dataset used throughout the study. For the exceedance analysis presented later in the thesis, all available weekdays within the analysed dataset were included for each zone and transformer size category. The exceedance calculations are based on the full set of historical weekday observations rather than only the January and July subsets used for profile visualisation.

Comparison Between Zones

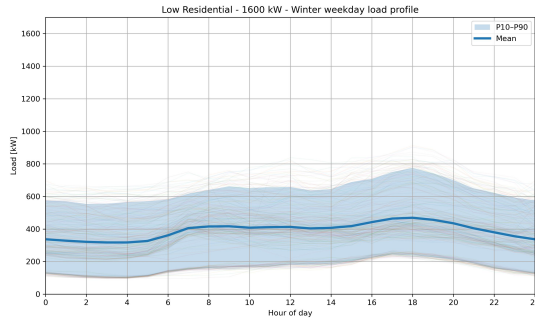
As mentioned in section 3.2.3, load profiles differ depending on the nearby buildings connected to the grid. In figure 5.3 four representative winter weekday load profiles are shown, one for each zone. The winter weekday is represented by weekdays in January. A summer weekday is represented by weekdays in July, of which load profiles for every scenario can be seen in appendix A.3



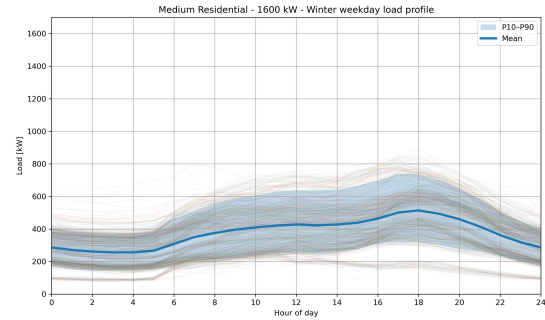
(a) Commercial, 1600 kW, winter



(b) Industry, 1600 kW, winter



(c) Low residential, 1600 kW, winter



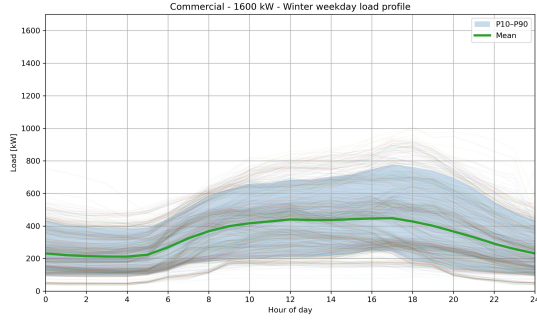
(d) Medium residential, 1600 kW, winter

Figure 5.3: Representative winter weekday load profiles for the analysed zone types. Thin background lines show individual weekdays, the bold line shows the mean profile, and the shaded band shows the P10–P90 interval.

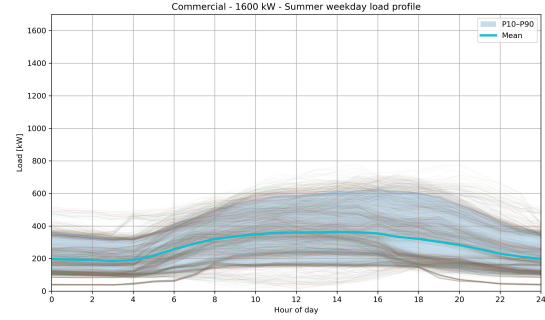
Commercial substations show an increase in demand during daytime working hours, with load rising in the morning and decreasing during the evening. This reflects the presence of offices, retail, services, and other daytime activities. Industrial substations also show a daytime-oriented profile, but the curve is flatter and more stable during operating hours, indicating more continuous loads from industrial processes or logistics activities. Residential areas instead show a stronger evening peak. This is especially visible in medium residential areas, where demand increases after working hours when occupants return home. Low residential areas show similar behaviour but generally with lower and flatter demand.

Seasonal Variation

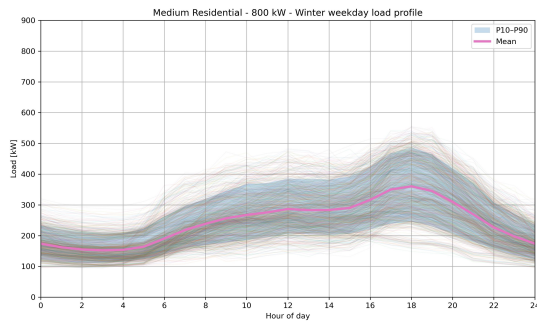
Load profiles also differs based on season, as mentioned in section 3.2.2. Seasonal differences are most visible when comparing winter and summer profiles for the same zone and transformer size. Figure 5.4 shows this comparison for commercial and medium residential substations.



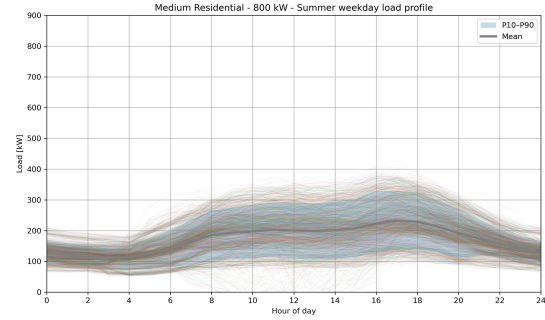
(a) Commercial, 1600 kW, winter



(b) Commercial, 1600 kW, summer



(c) Medium residential, 800 kW, winter



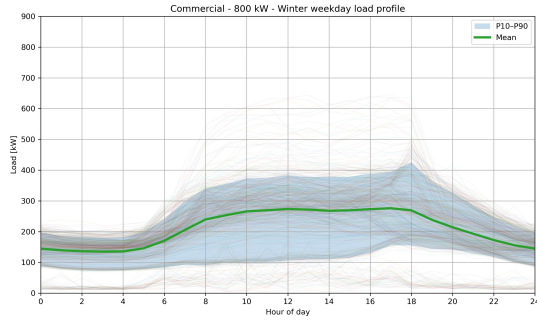
(d) Medium residential, 800 kW, summer

Figure 5.4: Seasonal comparison of weekday load profiles for commercial and medium residential substations. Winter profiles generally show higher demand, while summer profiles are lower and often flatter.

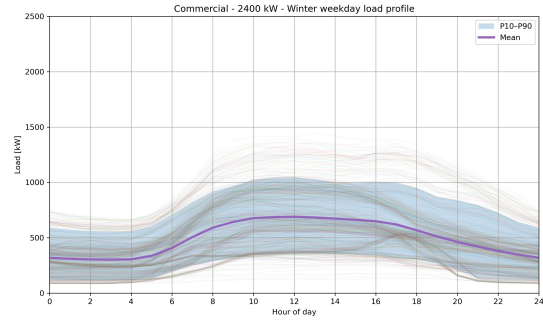
For commercial substations, the overall profile shape remains similar between seasons, but winter demand is generally higher. The load increases during the morning, remains elevated during working hours, and decreases during the evening. The summer profile is typically lower, indicating reduced heating-related demand. For residential substations, the seasonal difference is more pronounced. Winter profiles show a stronger evening peak, which is consistent with heating demand, lighting, cooking, and household activity after occupants return home. Summer profiles are generally flatter and may show relatively lower evening demand.

Effect of Substation Size

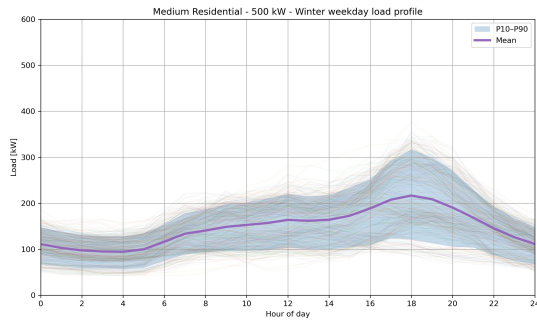
Transformer size affects both the magnitude of the load and the variability of the profile. Larger transformers generally supply a larger number of customers or larger connected loads. As a result, the mean load is higher in absolute terms. However, larger transformer groups also tend to show smoother profiles due to aggregation effects. Individual variations from single customers become less visible when more loads are combined. Figure 5.5 compares different transformer sizes within the same zone.



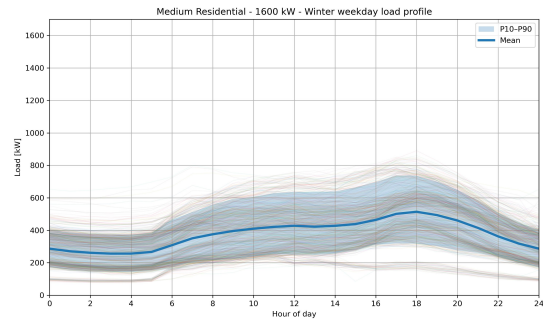
(a) Commercial, 800 kW, winter



(b) Commercial, 2400 kW, winter



(c) Medium residential, 500 kW, winter



(d) Medium residential, 1600 kW, winter

Figure 5.5: Comparison of weekday load profiles for different transformer sizes. Larger transformer groups show higher absolute load but generally smoother aggregate behaviour.

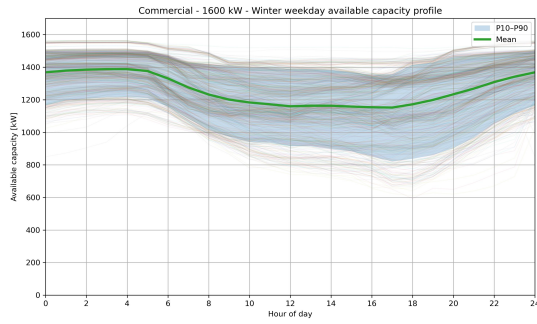
Both the commercial and medium residential profiles show that the general daytime pattern is preserved across transformer sizes, but the absolute load increases with rating.

Available Capacity Profiles

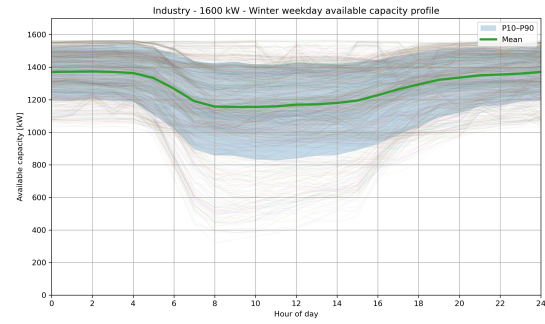
The available capacity profiles show the remaining substation capacity throughout the day. Available capacity is defined as the difference between the substation max capacity and the measured load:

$$P_{\text{available}}(t) = P_{\text{max}} - P_{\text{load}}(t) \quad (5.1)$$

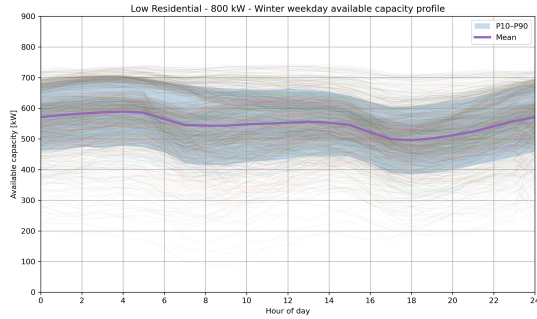
P_{max} is the substation max capacity and $P_{\text{load}}(t)$ is the hourly load at time t . The available capacity profile is therefore the inverse of the load profile. Figure 5.6 shows representative available capacity profiles for all zone types. The figure highlights that available capacity is not constant throughout the day. Instead, it depends strongly on zone type, season, and transformer size.



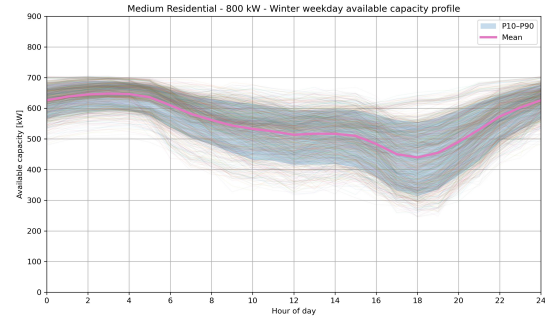
(a) Commercial, 1600 kW, winter



(b) Industry, 1600 kW, winter



(c) Low residential, 800 kW, winter



(d) Medium residential, 800 kW, winter

Figure 5.6: Representative winter weekday available capacity profiles for the analysed zone types. The lowest available capacity occurs during the highest load periods.

When load increases, available capacity decreases, and vice versa. Since available capacity is calculated from the load, the available capacity profile follows the opposite shape of the load profile. For commercial and industrial zones, the lowest available capacity generally occurs during working hours when demand is highest. For residential zones, the lowest available capacity often occurs in the evening, especially during winter.

6

Results

6.1 Charging Demand in Relation to Available Substation Capacity: CS1–CS6

This section evaluates the exceedance rate, defined as the percentage of analysed weekdays during which the combined historical load and construction-site charging demand exceed the available substation capacity. The analysis is performed for charging scenarios CS1–CS6 and divided into industrial, commercial, medium residential, and low residential areas. For each category, the full charging demand is compared with a reduced charging-power strategy, represented by 50% charging power. In addition, exceedance rates for the night-charging scenarios are presented.

For the exceedance analysis, an exceedance was registered if the combined historical load and charging demand exceeded the available substation capacity during any analysed charging period within a weekday. Consequently, if the available capacity was exceeded during either the first charging break, the second charging break, or both, the entire weekday was counted as one exceedance day. The same principle was applied to the night-charging scenarios, where a weekday was counted as an exceedance day if the available capacity was exceeded at any point during the analysed night-charging period. The analysis therefore evaluates the frequency of exceedance events in terms of the number of affected weekdays, rather than the duration of exceedance within individual days. In other words, the exceedance rate represents the percentage of weekdays containing at least one exceedance, independent of how long the exceedance lasted during that day.

6.1.1 Comparison Between Full and Half Charging

This section compares the results from the full fast-charging with those obtained under the half fast-charging in order to evaluate how reduced charging power influences the risk of exceeding available substation capacity. It should be noted that different transformer sizes were analysed for industrial/commercial areas and residential areas due to differences in the available substation configurations, as discussed in Section 5.2.1. For industrial and commercial areas, the analysed transformer sizes were 800 kW, 1600 kW, and 2400 kW, whereas the residential areas were analysed using 500 kW, 800 kW, and 1600 kW substations. Consequently, no 500 kW substations were included in the industrial and commercial categories, and no 2400 kW substations were available within the residential categories.

Industry

Figure 6.1 compare the exceedance rates in industrial areas. Full fast-charging results in high exceedance rates for 800 kW substations in CS1–CS4, while CS5 and CS6 show close to 0% exceedance. In contrast, 1600 kW substations are mainly affected in CS1 and CS2, although some exceedance can also be observed in CS3 and CS4. The 2400 kW substations only show noticeable exceedance in CS1.

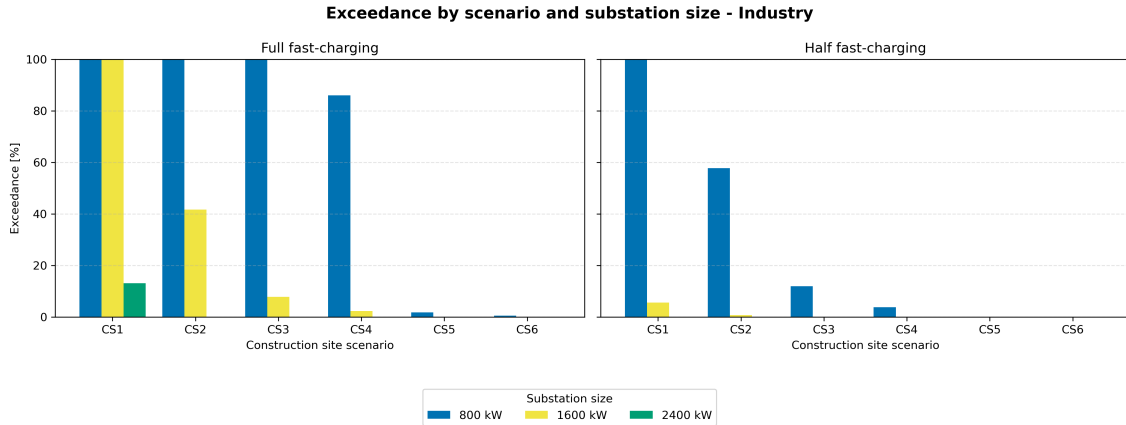


Figure 6.1: Exceedance rates for industrial areas by charging scenario, substation size, and charging strategy.

With half fast-charging, the exceedance rate decreases for all substation sizes, except for the 800 kW substations, where the exceedance rate remains at 100% for CS1. For CS2, the 800 kW substations remain strongly constrained even under reduced charging power, while CS3 and CS4 still show exceedance to some extent. For the 2400 kW substations, the exceedance rate drops to 0%, whereas some exceedance can still be observed for CS1 in the 1600 kW substations. This indicates that reducing the fast-charging power by 50% increases the possibility of charging multiple machines simultaneously without exceeding the available substation capacity.

Commercial

Figure 6.2 compare the exceedance rates for the full and half-charging in commercial areas. Full fast-charging results in high exceedance rates for 800 kW substations in CS1–CS4, while CS5 and CS6 show close to 0% exceedance. In contrast, 1600 kW substations are mainly affected in CS1 and CS2, although some exceedance can also be observed in CS3. The 2400 kW substations only show noticeable exceedance in CS1.

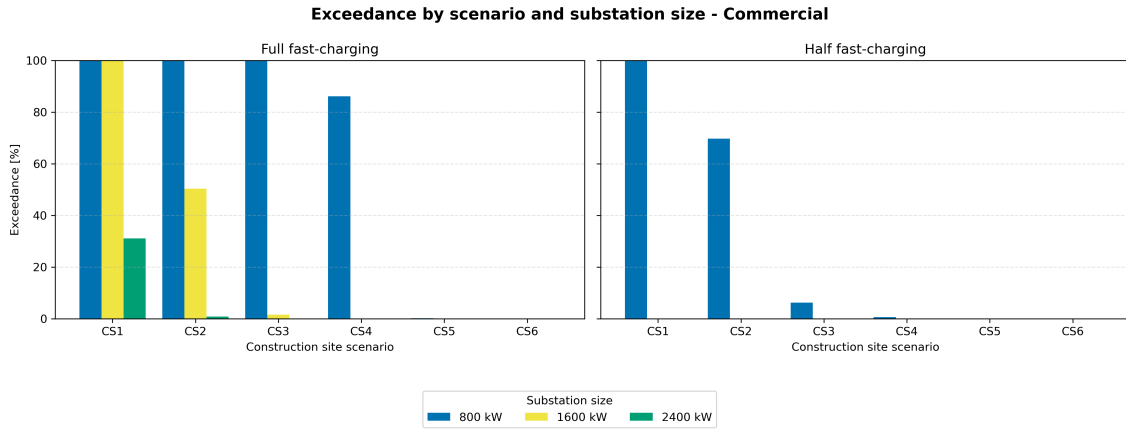


Figure 6.2: Exceedance rates for commercial areas by charging scenario, substation size, and charging strategy.

With half fast-charging, the exceedance rate decreases for all substation sizes, except for the 800 kW substations, where the exceedance rate remains at 100% for CS1. For CS2, the 800 kW substations remain strongly constrained even under reduced charging power, while CS3 still show exceedance to some extent. For the 1600 kW and 2400 kW substations, the exceedance rate drops to 0%. This indicates that reducing the fast-charging power by 50% increases the possibility of charging multiple machines simultaneously without exceeding the available substation capacity.

Medium residential

Figure 6.3 compare the exceedance rates for the full and half-charging in medium residential areas. Full fast-charging results in high exceedance rates for 500 kW substations in CS1–CS4, while CS5 shows some exceedance and CS6 shows 0% exceedance. A similar trend can be observed for the 800 kW substations, where CS1–CS4 exhibit high exceedance rates, whereas CS5 and CS6 show 0% exceedance. In contrast, the 1600 kW substations are mainly affected in CS1 and CS2, while CS3–CS6 exhibit 0% exceedance.

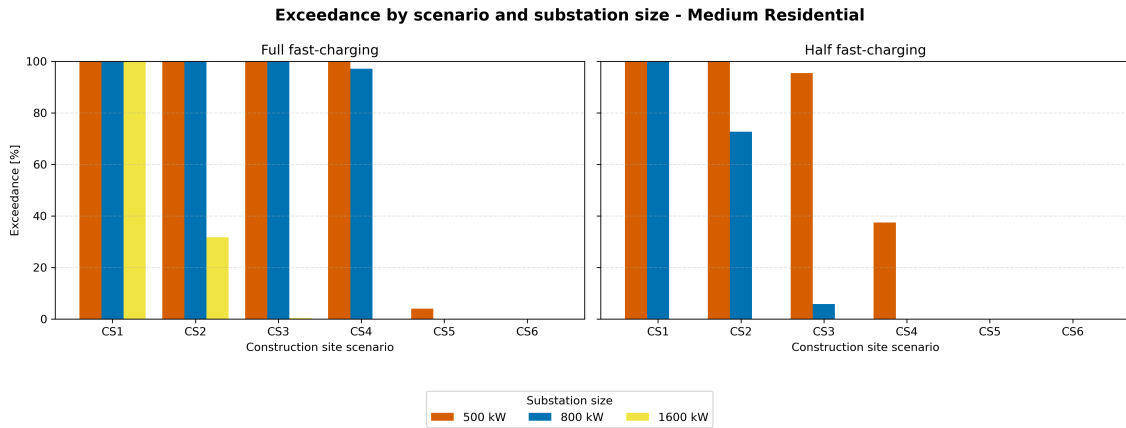


Figure 6.3: Exceedance rates for medium residential areas by charging scenario, substation size, and charging strategy.

With half fast-charging, the exceedance rate for the 500 kW substations remains high for CS1–CS3, although a small decrease can be observed for CS3. CS4 shows a larger reduction, lowering the exceedance rate to below 40%. For the 800 kW substations, the exceedance rate remains high for CS1 and CS2, although CS2 shows a slight reduction compared to full fast-charging. In contrast, CS3 decreases from approximately 100% exceedance to almost no exceedance under half charging. For the 1600 kW substations, no exceedance remains under half fast-charging.

Low residential

Figure 6.4 compare the exceedance rates for the full and half-charging strategies in low residential areas. Full fast-charging results in high exceedance rates for 500 kW substations in CS1–CS4, while CS5 and CS6 shows some exceedance. A similar trend can be observed for the 800 kW substations, where CS1–CS4 exhibit high exceedance rates, whereas CS5 and CS6 show 0% exceedance. In contrast, the 1600 kW substations are mainly affected in CS1 and CS2, while CS3–CS6 exhibit 0% exceedance.

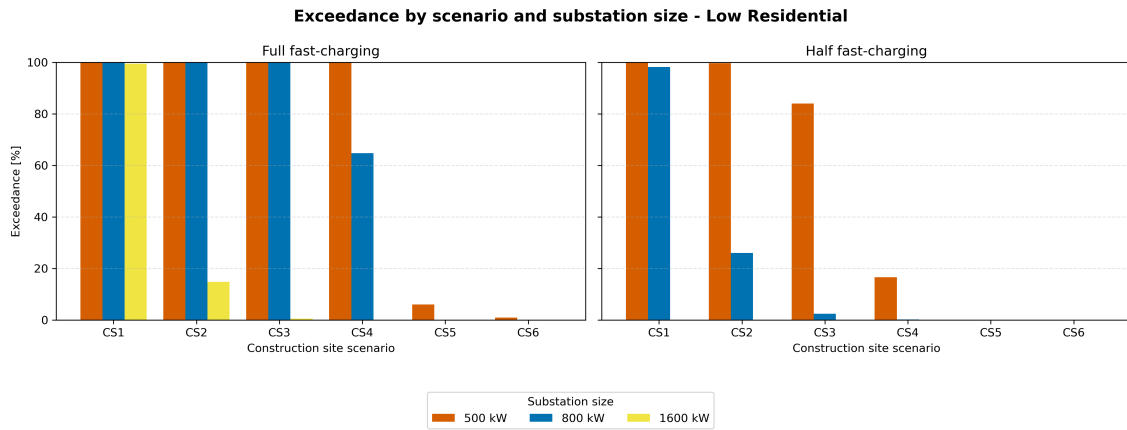


Figure 6.4: Exceedance rates for low residential areas by charging scenario, substation size, and charging strategy.

With half fast-charging, the exceedance rate for the 500 kW substations remains high for CS1–CS3, although a small decrease can be observed for CS3. CS4 shows a larger reduction, lowering the exceedance rate to below 20%. For the 800 kW substations, the exceedance rate remains high for CS1, while CS2 shows a substantial reduction compared to full fast-charging. In contrast, CS3 decreases from approximately 100% exceedance to almost no exceedance under half charging. For the 1600 kW substations, no exceedance remains under the half fast-charging strategy.

Overview

Overall, reducing the fast-charging power by 50% significantly decreases the exceedance rates across all analysed zones and substation categories. The reduction is particularly effective for the larger substations, where the exceedance rates in many cases decrease to close to or exactly 0%. However, the results also show that

the smallest substations remain strongly constrained in the larger construction-site scenarios, especially CS1 and CS2, even under the reduced charging-power strategy. The results therefore demonstrate that reduced charging power can substantially improve the possibility of charging multiple machines simultaneously without exceeding the available substation capacity, although additional measures may still be required for smaller substations and high-demand construction scenarios.

6.1.2 Comparison Between Zones

Figures 6.5 and 6.6 compare the average exceedance rates between zones for 800 kW and 1600 kW substations, which are present in all four zones. The heatmaps provide a compact overview of how the same charging scenarios affect different types of grid areas.

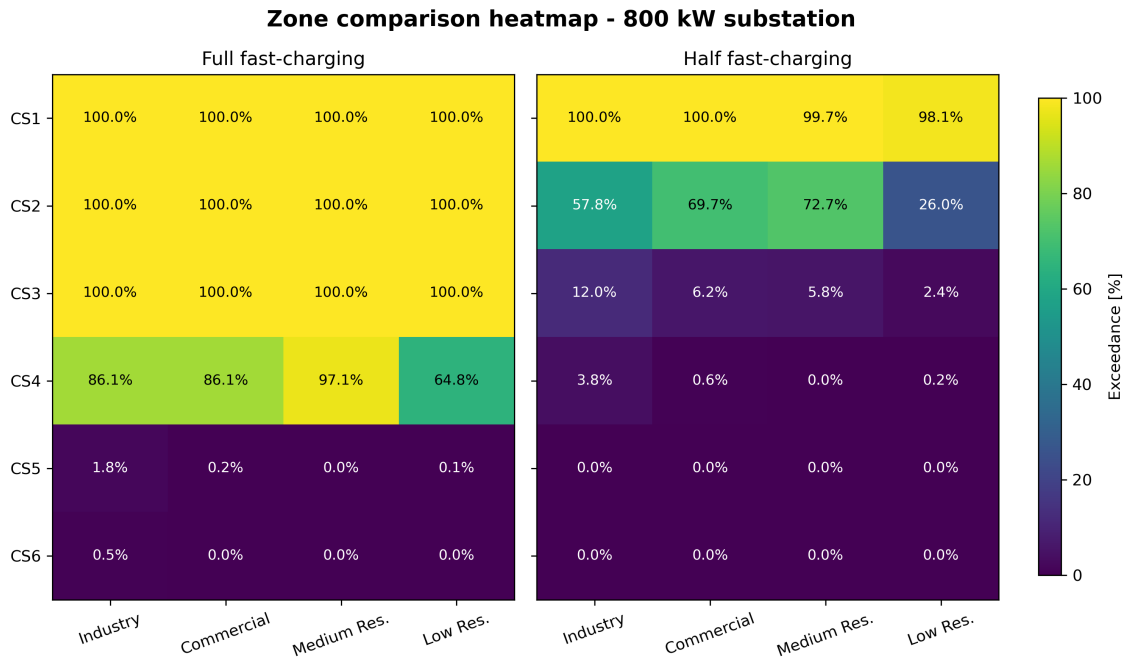


Figure 6.5: Comparison of exceedance rates across zones for 800 kW substations under full and half charging.

For the 800 kW substations, full fast-charging leads to high exceedance rates in CS1–CS3 across all analysed zones. One particularly interesting result can be observed in CS4, where the medium residential areas exhibit the highest exceedance rates, while the low residential areas show the lowest exceedance rates. Overall, the exceedance rates remain relatively high, indicating that 800 kW substations generally have limited spare hosting capacity for construction-site charging demand. For CS5, the medium residential substations show no exceedance, while the remaining zones still exhibit a small exceedance rate. A similar pattern can be observed under the half fast-charging strategy. In CS1, industrial and commercial areas show 100% exceedance, followed by medium residential and low residential areas with 99.7% and 98.1%, respectively. However, in CS2, the medium residential areas instead exhibit

the highest exceedance rate at 72.7%, followed by commercial areas at 69.7%, industrial areas at 57.8%, and low residential areas at 26%.

For CS3 under half fast-charging, the ranking changes again, with industrial areas showing the highest exceedance rate at 12%, followed by commercial areas at 6.2%, medium residential areas at 5.8%, and low residential areas at 2.4%. These results indicate that the different functional area categories respond differently to reductions in charging power. One possible explanation is that the medium residential substations exhibit more homogeneous load characteristics compared to the other zones, resulting in smaller variations between individual substations within the category.

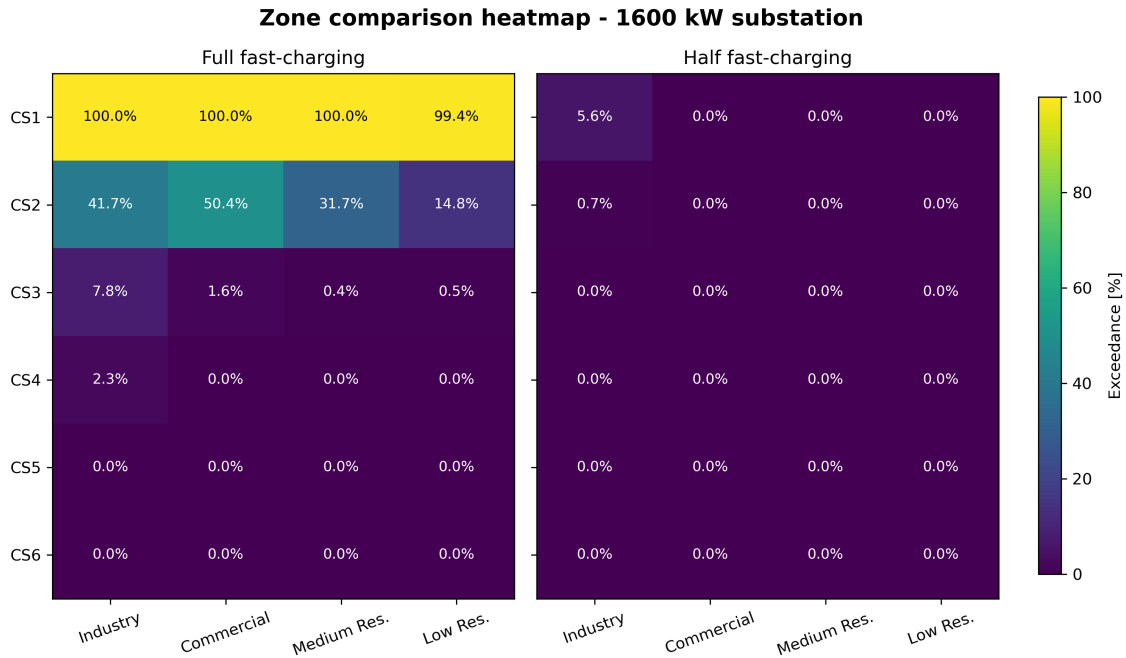


Figure 6.6: Comparison of exceedance rates across zones for 1600 kW substations under full and half charging.

For the 1600 kW substations, the exceedance rates are considerably lower compared to the 800 kW substations. Under the full fast-charging strategy, the exceedance rate is close to 100% for all analysed zones in CS1. CS2 still exhibits considerable exceedance, although the exceedance rates are generally below 50% for all zones. In contrast to the results for the 800 kW substations, the medium residential areas do not exhibit higher exceedance rates than the industrial or commercial areas for the 1600 kW substations. Industrial substations also tend to exhibit exceedance in the smaller machine configurations, such as CS3 and CS4, as well as under the half fast-charging strategy for CS1. This indicates that industrial substations may experience higher simultaneous loading conditions in certain scenarios despite the larger transformer capacity.

Overall, these results indicate that the relationship between charging demand and available substation capacity is strongly dependent on both transformer size and the underlying load characteristics of the surrounding area. The consistently high exceedance rates for the 800 kW substations suggest that smaller substations generally have limited spare hosting capacity for simultaneous fast-charging of multiple construction machines, particularly in the larger construction-site scenarios. At the same time, the varying ranking between zones demonstrates that exceedance risk is not solely determined by transformer size, but also by the temporal characteristics and variability of the historical load profiles within each zone. The results further indicate that reducing charging power by 50% can significantly lower exceedance rates, although the effectiveness of this mitigation strategy varies between both scenarios and functional area categories. In some cases, such as CS3 for the 800 kW substations, the reduction in charging power is sufficient to nearly eliminate exceedance. However, for larger construction-site scenarios such as CS1 and CS2, substantial exceedance remains even under half fast-charging, indicating that reduced charging power alone may not be sufficient for smaller substations with limited spare capacity.

The lower exceedance rates observed for the 1600 kW substations imply that larger substations are generally better able to accommodate electrified construction-site charging demand. Nevertheless, the remaining exceedance observed in some industrial substations suggests that high and relatively stable background loads in industrial areas can still create capacity limitations despite the larger transformer sizes. This highlights the importance of considering both transformer capacity and local load characteristics when evaluating the grid impact of electrified construction machinery.

6.1.3 Night Charging

Night charging was evaluated separately in order to investigate the possibility of applying lower charging power during nighttime, which would be required regardless of the daily machine energy use in order to restore the battery state of charge before the next workday. As expected, the exceedance rates for the night-charging scenarios are generally considerably lower than for the fast-charging cases due to the lower total charging demand and the reduced historical background load during nighttime. Nevertheless, some exceedance can still be observed in certain scenarios and substation categories, indicating that even relatively low nighttime charging demand may create capacity limitations for substations with limited spare capacity.

Industry

Night charging has an exceedance of 0.5% in industrial areas. As shown in Table 6.1, only 800 kW substations in CS1 retain a non-zero exceedance rate. All other scenarios and substation sizes remain below capacity.

Table 6.1: Industrial areas – night charging.

Scenario	800 kW	1600 kW	2400 kW
CS1	0.5%	0%	0%
CS2	0%	0%	0%
CS3	0%	0%	0%
CS4	0%	0%	0%
CS5	0%	0%	0%
CS6	0%	0%	0%

This result indicates that industrial substations in most cases have sufficient available capacity during nighttime charging conditions, allowing electrified construction machinery to be charged with relatively limited risk of exceeding the available substation capacity.

Commercial

Commercial substations show a similar pattern to the industrial areas. Table 6.2 shows that exceedance rates are very low under night charging. The only remaining exceedance occurs for 800 kW substations in CS1–CS3, where the exceedance rate remains below 0.5%.

Table 6.2: Commercial areas – night charging.

Scenario	800 kW	1600 kW	2400 kW
CS1	0.4%	0%	0%
CS2	0.1%	0%	0%
CS3	0.1%	0%	0%
CS4	0%	0%	0%
CS5	0%	0%	0%
CS6	0%	0%	0%

Similar to the substations in industrial areas, the results indicate that sufficient available capacity exists during most weekdays, resulting in relatively low exceedance rates for the analysed night-charging scenarios.

Medium residential

Since the medium residential category includes smaller substations (500 kW) in the dataset, the exceedance rates are generally higher compared to the industrial and

commercial areas. However, when comparing the 800 kW substations, the medium residential areas still exhibit lower exceedance rates. This can be observed in Table 6.3.

Table 6.3: Medium residential areas – night charging.

Scenario	500 kW	800 kW	1600 kW
CS1	26.4%	0.2%	0%
CS2	8.3%	0%	0%
CS3	2.3%	0%	0%
CS4	0%	0%	0%
CS5	0%	0%	0%
CS6	0%	0%	0%

For the 500 kW substations, 26.4% of the analysed weekdays exceed the available capacity in CS1, decreasing to 8.3% in CS2 and 2.3% in CS3. These exceedance rates are sufficiently high to indicate that simultaneous nighttime charging of multiple machines may create capacity limitations for smaller substations.

Low residential

Table 6.4 presents the exceedance rates for night charging in low residential areas. Similar to the medium residential category, the low residential dataset also includes 500 kW substations, which contributes to higher exceedance rates compared to the industrial and commercial areas.

Table 6.4: Low residential areas – night charging.

Scenario	500 kW	800 kW	1600 kW
CS1	11.3%	0.1%	0%
CS2	4.4%	0%	0%
CS3	2.1%	0%	0%
CS4	0.2%	0%	0%
CS5	0%	0%	0%
CS6	0%	0%	0%

The 500 kW substations experience an exceedance rate of 11.3% in CS1, decreasing to 4.4% in CS2 and 2.1% in CS3. Similar to the medium residential areas, this indicates that simultaneous nighttime charging of multiple machines may create capacity limitations for the smaller substation sizes.

6.1.4 Seasonal Variation

The previous exceedance analysis was based on the average exceedance rates over the full analysed year. To further investigate how the exceedance varies throughout the year, monthly average exceedance rates were also analysed. The results demonstrate clear seasonal variation in exceedance behaviour between different months.

The monthly averages were calculated separately for each month and transformer size category. However, scenarios and substation categories containing monthly exceedance values equal to 0% or 100% were excluded from this analysis, since these boundary values would otherwise skew the monthly averages and reduce the ability to observe seasonal variation. For example, the 800 kW substations in CS1 were excluded since several months exhibited 100% exceedance. Similarly, scenarios containing months with 0% exceedance were also excluded from the monthly averaging procedure. The motivation for this filtering approach is that exceedance rates capped at 100% do not reflect the magnitude of the overload beyond the exceedance threshold, but only indicate that exceedance occurred during all analysed weekdays. Including such values would therefore mask the relative monthly variation in exceedance behaviour. Consequently, the monthly average analysis was only performed for scenario and substation combinations where all monthly exceedance values remained strictly between 0% and 100%.

This filtering approach made it possible to combine results across different construction-site scenarios and functional area categories, provided that the monthly exceedance rates satisfied the selection criteria. The resulting monthly averages therefore illustrate how exceedance behaviour varies throughout the year for the different transformer sizes independently of specific construction-site scenarios or functional area categories. Figure 6.7 presents representative monthly exceedance plots for the full fast-charging, half fast-charging, and night charging. With full fast-charging, the monthly variation is clearly visible for 800 kW substations, with the highest exceedance rates occurring during winter and late autumn. Half fast-charging reduces the overall exceedance level, but the seasonal dependence remains visible. Night charging produces the largest reduction overall, although the smallest substations still experience elevated exceedance during winter months.

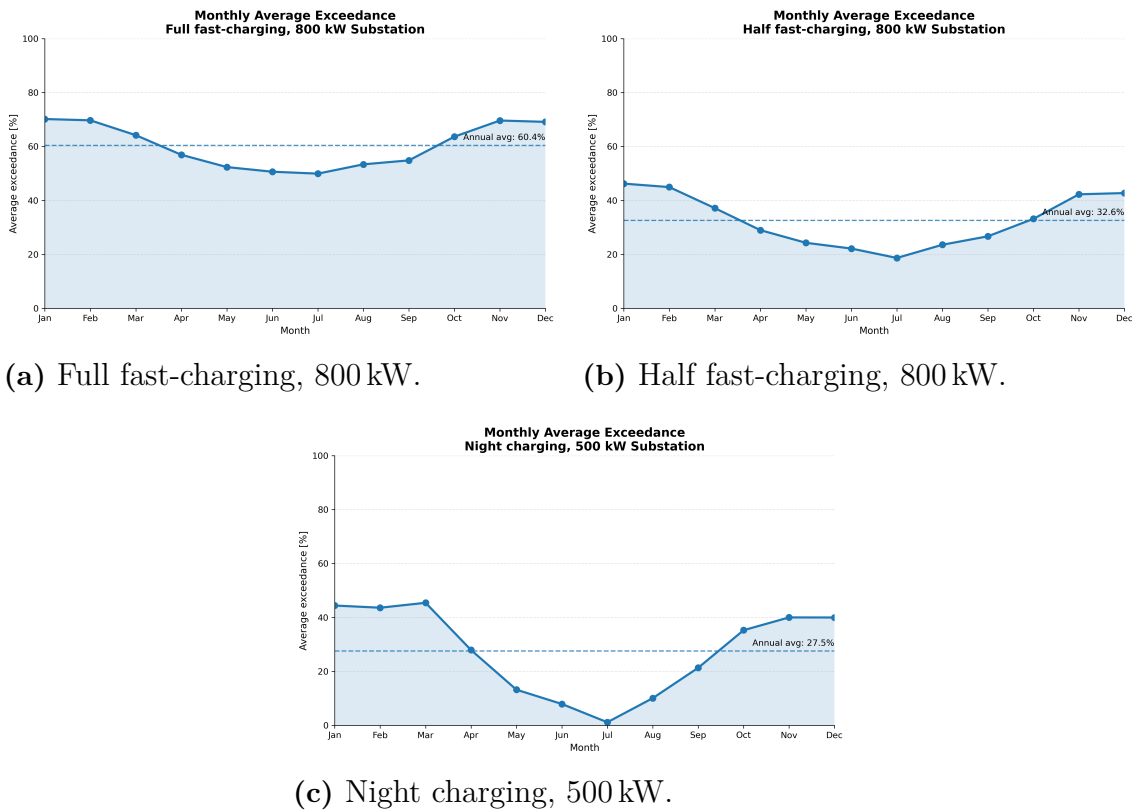


Figure 6.7: Representative monthly average exceedance rates.

The results show that exceedance rates are generally highest during winter months and lowest during summer months. This seasonal pattern reflects variations in historical background demand, linking back to Section 5.2.2. During winter, higher electricity consumption reduces the available transformer capacity, increasing the share of days where charging demand exceeds the transformer rating. During summer, lower background demand results in substantially lower exceedance rates. The seasonal variation is most pronounced for smaller substations during full fast-charging. The results therefore indicate that winter conditions represent the most critical operating period for electrified construction-site charging, particularly in residential areas with limited spare transformer capacity.

Overall, the monthly results demonstrate that exceedance is not constant throughout the year. Instead, the spare hosting capacity of a substation depends strongly on seasonal load conditions, with winter operation representing the most critical period for transformer loading.

7

Discussion

This chapter discusses the results presented in the previous chapters in relation to the research questions, theoretical framework, and previous studies. The discussion focuses on how electrified construction machinery affects substation loading and spare hosting capacity in Gothenburg’s local electricity grid, as well as how different charging powers, seasonal variation, and spatial differences influence exceedance risk. The implications of the findings for future grid planning and electrified construction-site operation are also discussed.

7.1 Impact of Electrified Construction Machinery on the Local Grid

The results demonstrate that electrified construction machinery can create substantial local increases in power demand, particularly during periods of simultaneous fast charging. The exceedance analysis showed that the charging demand from construction sites may exceed the available capacity in multiple substation categories, especially for smaller substations and with full fast-charging. These findings indicate that electrification of construction machinery significantly influences both load amplitude and load profiles within the local distribution grid.

One important finding is that the grid impact is highly localized. The results show that exceedance problems primarily occur in smaller substations with limited spare capacity rather than across the distribution system as a whole. This indicates that electrified construction machinery does not necessarily create a system-wide energy shortage, but instead creates local bottlenecks where charging demand coincides with already highly utilized substations. This behaviour is consistent with the theory of load profiles and peak demand presented in Chapter 3, where transformer loading is primarily determined by short-duration power peaks rather than total energy consumption. The findings also align with previous studies on electrified construction sites. Callanan et al. (2024) emphasized that charging heavy construction machinery may introduce substantial local peak loads, potentially stressing existing distribution infrastructure. Similarly, Bern (2024) highlighted that simultaneous charging events constitute one of the main challenges for electrified construction projects. The present study confirms these findings through a quantitative exceedance analysis using historical transformer load data and realistic construction-site charging profiles.

The results further demonstrate that substation size strongly influences spare hosting capacity. Smaller substations consistently exhibited significantly higher exceedance rates compared to larger substations. Particularly the 500 kW and 800 kW substations showed high sensitivity to charging demand with full fast-charging. In contrast, 1600 kW and 2400 kW substations were capable of accommodating most charging scenarios, especially half fast-charging and night charging. This reflects characteristics of electrical distribution systems. Smaller substations typically operate with lower spare margins and are more sensitive to additional concentrated loads. The results therefore suggest that future electrification of construction machinery will primarily challenge weaker parts of the distribution grid, particularly in residential areas where transformer capacities are smaller and historical load levels are already relatively high during certain periods of the day.

7.2 Differences Between Zones and Substation Categories

The results revealed substantial differences between industrial, commercial, medium residential, and low residential areas. These differences can largely be explained by variations in historical load profiles, transformer capacities, and available spare capacity.

Industrial substations generally showed the highest spare hosting capacity. Even under with full fast-charging, exceedance was mainly limited to smaller substations and the most demanding charging scenarios. With half fast-charging and night charging, exceedance was almost completely removed in industrial areas. This behaviour is consistent with the theoretical load profiles described in Chapter 3, where industrial loads typically exhibit relatively stable demand patterns and higher base loads throughout the day. Because industrial substations are often dimensioned for large continuous loads, they also tend to have higher transformer capacities and more robust infrastructure. Commercial substations exhibited similar behaviour to industrial substations, although slightly higher exceedance rates were observed in some charging scenarios. Commercial load profiles are strongly linked to daytime activity and therefore overlap more closely with construction-site charging demand. However, the relatively large transformer capacities still provide substantial hosting capacity under moderate charging load.

Residential substations were considerably more constrained. Both medium and low residential substations showed high exceedance rates with full fast-charging, particularly for 500 kW and 800 kW substations. This reflects the lower transformer capacities and lower spare margins. Residential load profiles are characterized by strong morning and evening peaks associated with household electricity usage. Construction charging demand occurring during daytime or evening periods therefore creates additional loading during already stressed operating conditions.

The results therefore demonstrate that the impact of electrified construction machinery strongly depends on where construction sites are connected to the grid. This has important implications for future construction-site planning and connection processes. Identical construction projects may produce very different grid impacts depending on local transformer capacity and background load conditions.

7.3 Different Charging Profiles

One of the clearest findings of this study is that charging strategy has a major influence on exceedance behaviour and spare hosting capacity. Full fast-charging consistently produced the highest exceedance rates across all zones. This was expected since the full fast-charging represents uncontrolled high-power charging with strong simultaneity effects, often having higher charging load than the max capacity of the substation. Under this strategy, several substations experienced exceedance rates close to or equal to 100% in the most demanding charging scenarios.

Half fast-charging significantly improved the results across all zones. Particularly for 1600 kW and 2400 kW substations, exceedance was almost completely removed. This demonstrates that charging power reduction may be a highly effective mitigation strategy for electrified construction sites. Importantly, the results indicate that relatively simple charging management measures may substantially reduce transformer loading without requiring immediate grid reinforcement. The effectiveness of charging reduction is closely connected to the simultaneity effects discussed previously. Since transformer loading is driven primarily by short-duration charging peaks, reducing charging power produces disproportionately large reductions in exceedance probability. This indicates that charging optimization strategies may represent one of the most cost-effective approaches for enabling electrified construction machinery within existing grid infrastructure.

Night charging has the lowest exceedance rate. In industrial and commercial areas, night charging almost completely removed exceedance in all charging scenarios. Even residential substations experienced substantial improvements. These results clearly demonstrate that charging timing is one of the most influential factors affecting substation load. The effectiveness of night charging can be explained by historical load profiles. During nighttime periods, background electricity demand is significantly lower, resulting in substantially larger available transformer capacity, as well as lower charging load due to longer charging times. Moving charging demand away from daytime peak-load periods therefore allows the same energy demand to be accommodated with considerably lower overload risk. However, the results also show that night charging alone is insufficient for the weakest residential substations. The 500 kW substations still experienced noticeable exceedance under the most demanding charging scenarios. This demonstrates that some substations may require additional measures such as local battery storage, temporary transformer upgrades, or permanent reinforcement even when charging optimization strategies are applied.

7.4 Seasonal Variation

The seasonal analysis is relevant, since construction sites operates year round, indicating the need for charging during all the months. The analysis demonstrated clear variations in exceedance behaviour throughout the year. Winter months consistently produced the highest exceedance rates, while summer months generally showed substantially lower overload probability. This seasonal variation is directly connected to historical background demand. During winter, electricity consumption increases due to heating demand, lighting, and other seasonal factors. As a result, the available spare substation capacity becomes significantly lower. Construction machinery charging added on top of this already elevated load therefore creates higher exceedance probability.

The results show that seasonal effects are particularly important for smaller substations. The combination of high background demand and construction charging creates very limited operating margins during winter conditions. This indicates that electrified construction machinery may become most problematic precisely during periods when the distribution grid is already under stress. These findings are highly relevant for practical grid planning. Annual average loading conditions may underestimate the true operational challenges associated with electrified construction machinery. Instead, winter peak conditions appear to represent the critical design case for transformer hosting capacity. The results are also consistent with general power-system theory regarding seasonal load variation in colder climates. Sweden's electricity demand is strongly influenced by winter heating requirements, which naturally reduce available grid margins during cold periods. Electrified construction machinery therefore becomes part of a broader electrification challenge affecting multiple sectors simultaneously.

7.5 Comparison with Previous Research

The findings of this thesis generally support and extend previous research on electrified construction sites and charging infrastructure. Previous studies have largely focused on technical feasibility, machine performance, and environmental benefits. For example, Bern (2024) and Hjertström et al. (2021) demonstrated that electrified construction sites are technically feasible and capable of substantially reducing emissions. However, these studies also identified charging infrastructure and grid capacity as important challenges.

The present study contributes by quantitatively analyzing how charging demand affects real transformer loading conditions within an urban distribution grid. Rather than only discussing theoretical charging requirements, this thesis evaluates exceedance behaviour using historical substation load profiles and realistic charging scenarios. The findings also support earlier observations regarding the importance of charging coordination. Käck and Jansson (2024) emphasized that charging infrastructure design and operational planning are critical for reducing grid impact. The

present study confirms this through the strong improvements achieved under half charging and night charging strategies. Furthermore, the results align with studies of electrified transport systems and electric vehicle fast charging, where simultaneity effects and peak-demand management are frequently identified as key challenges. Similar to electric vehicle charging infrastructure, construction-site charging appears to create concentrated high-power peaks that may stress local distribution systems unless charging behaviour is actively managed.

At the same time, this study also highlights characteristics specific to construction machinery. Unlike passenger vehicles, construction machines often operate according to synchronized schedules with common break periods. This creates particularly strong simultaneity effects and concentrated charging peaks. The temporary and mobile nature of construction sites further differentiates construction electrification from many other forms of electrification.

7.6 Methodological Considerations and Uncertainties

Several methodological assumptions and limitations influence the interpretation of the results. One important limitation concerns the charging profiles and machine utilization assumptions. The charging scenarios were developed using interviews, literature, and available machine specifications. Although these profiles are grounded in real data, actual construction projects may differ substantially depending on project type, contractor practices, weather conditions, and machine usage. It also acts as an extreme case, where machines are used full workdays with high workload, which might not be correct all of the time.

Another limitation concerns the use of historical substations load data. Future electricity demand may differ from historical patterns due to broader electrification of transport, heating, and industry, as well as more electricity production from solar. As a result, future available substation capacity may become lower than assumed in this study. The analysis also focuses primarily on transformer loading and does not include detailed modelling of voltage quality or current. High-power charging may influence additional aspects of grid operation beyond simple capacity exceedance.

Despite these limitations, the study provides valuable insight into how electrified construction machinery may influence local distribution grids. The use of historical load profiles combined with realistic charging scenarios allows for a robust evaluation of hosting capacity and overload risk under different operational conditions.

7.7 Implications for Future Grid Planning and Electrified Construction Sites

The results have several important implications for future grid planning and construction-site electrification. First, the findings demonstrate that charging management strategies may substantially reduce the need for immediate grid reinforcement. Both charging power reduction and night charging produced large improvements in spare hosting capacity across all zones. This suggests that operational measures may be highly effective during the early phases of construction-site electrification.

The results also indicate that future grid planning should increasingly consider temporary but high-power construction loads. Historically, construction sites have represented relatively minor electrical loads, through heating and lighting, compared to industrial and residential consumers. Electrification fundamentally changes this relationship by introducing high-power charging demand into temporary construction environments. Lower charging power can also be achieved through changeable batteries for the machines or mobile batteries that charges throughout the day, where machinery can be fast-charged when needed.

At the same time, the findings highlight the importance of local grid analysis. Since hosting capacity varies strongly between substations and zones, generalized assumptions regarding available capacity may be insufficient. Future construction-site planning may therefore require more detailed local capacity assessments prior to project connection.

The result implies that we have enough spare hosting capacity in most substations for up to two larger machines to be able to fast-charge during the day, in some cases three. If it is possible to divide the charging load onto multiple substations close by, it could be possible with an electrified construction site, without upgrading the grid or other measurements such as smart-charging, even for the extreme case with high hourly energy use.

7.8 Future Research

This thesis has investigated how electrified construction machinery may affect the local electricity grid in Gothenburg under different charging and construction site scenarios. While the results provide an indication of how future electrified construction activities can influence substation loading and available grid capacity, several areas remain for further investigation.

One important direction for future research is the development of more detailed and dynamic charging models. In this study, representative charging profiles and simplified charging strategies were used to estimate construction related loads. Future

studies could incorporate real operational data from electrified construction sites, including machine telemetry, battery state-of-charge behaviour, weather conditions, and operator-dependent usage patterns. Such data would improve the accuracy of load forecasts and provide a more detailed understanding of temporal variations in charging demand.

Another relevant area is the investigation of smart charging and coordinated energy management strategies. The present study only considered simplified charging variants such as reduced charging power and night charging. Future research could evaluate optimization-based charging control, where charging schedules are adapted in real time based on electricity prices, grid conditions, local renewable production, or flexibility market signals. This could help reduce simultaneous peak loads and improve utilization of existing grid infrastructure, especially for the night charging.

The interaction between electrified construction sites and local energy systems also deserves further attention. Future studies could investigate the integration of battery energy storage systems, temporary microgrids, mobile charging solutions, and local renewable energy production such as solar photovoltaics. Such systems may reduce the need for grid reinforcement while increasing operational flexibility at construction sites. In addition, future work could extend the geographical and electrical scope of the analysis. This study focused on the local distribution grid in Gothenburg and did not include impacts on the regional or transmission grid. As electrification continues across multiple sectors, cumulative effects from electrified transport, industry, and construction may become increasingly important to study from a broader system perspective.

Finally, as the market for electrified heavy construction machinery continues to develop, future studies should investigate larger and more energy-intensive machines that are currently not widely available commercially. This includes heavy-duty excavators, cranes, and additional transport vehicles, which may create substantially higher charging demands than those included in the present study.

8

Conclusion

This thesis investigated how electrified construction machinery may affect the local electricity grid in Gothenburg through the development of representative charging profiles and a quantitative exceedance analysis based on historical substation load data. The results demonstrate that electrified construction machinery can create substantial local increases in power demand, particularly during periods of simultaneous fast-charging. However, the impact is highly dependent on substation size, surrounding load characteristics, charging power, and seasonal variation.

The exceedance analysis showed that smaller substations, particularly 500 kW and 800 kW, are significantly more sensitive to charging demand compared to larger substations. Full fast-charging frequently resulted in high exceedance rates in the more demanding construction-site scenarios, especially in residential areas with limited spare hosting capacity. In contrast, larger substations such as 1600 kW and 2400 kW were generally capable of accommodating most charging scenarios with considerably lower exceedance rates. The results therefore indicate that electrified construction machinery is more likely to create localized grid constraints rather than system-wide electricity shortages. The study further demonstrated that charging strategy strongly influences exceedance behaviour. Reducing the charging power by 50% substantially lowered exceedance rates across all analysed zones and substation categories. Similarly, night charging proved highly effective due to lower historical background demand during nighttime periods, as well as lower total charging load. In industrial and commercial areas, night charging almost completely removed exceedance for most charging scenarios. Nevertheless, some smaller residential substations still experienced exceedance even during night charging, indicating that reduction of charging power alone may not always be sufficient in weaker parts of the distribution grid.

Further did the result show that when only using one or two construction machines, full fast-charging during the day is possible during most days, even for the smaller substation sizes, indicating that smaller construction projects, typically done within cities, can be done. Looking at the other end, with six construction machines active, problem can occur when charging during the night as well. The results also revealed clear seasonal variation in exceedance behaviour. Winter months consistently produced the highest exceedance rates due to increased historical electricity demand and reduced available transformer capacity. This suggests that winter conditions represent the critical operating case when evaluating hosting capacity for electrified

construction machinery.

Overall, the findings demonstrate that electrified construction machinery can in many cases be integrated into the existing distribution grid without immediate large-scale reinforcement. However, the results also highlight the importance of local grid analysis, since available hosting capacity varies substantially between different substations and functional area categories. Future electrification of construction machinery will therefore require a combination of charging optimization, local capacity assessment, and in some cases targeted grid reinforcement in order to enable large-scale deployment without creating unacceptable local overload conditions.

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A

Appendix

A.1 Machine size classification

Table A.1: Defined machine classes by type and size range used for aggregation.

Machine type	Size class	Number in dataset
Crawler excavators (CEX)	1–2.5 t	11
	2.5–5 t	11
	5–9 t	3
	10–12 t	2
	14–17 t	3
	20–27 t	10
	27–34 t	4
	35–42 t	2
	55 t	1
Wheeled excavators (WEX)	7 t	1
	11 t	1
	17–18 t	4
Wheel loaders (WL)	2–3 t	2
	4–7 t	5
	15–16 t	2
	18–21 t	5
	22–26 t	5
	29 t	1
	35 t	1
Articulated haulers (AH)	59 t	1
	29 t	1
	39–41 t	2
Compactors (C)	1–3 t	3
	17 t	1
	27 t	1

These are the size classes defined for this study, articulated haulers is defined by what weight they can carry, whilst the rest by the machine weight.

A.2 Calculation of Hourly Energy-Use Thresholds

The hourly energy-use thresholds presented in Section 4.1.3 were calculated based on the available battery energy and the charging energy supplied during scheduled work breaks. For the night charging configuration, the daily available energy was assumed to equal 80% of the total battery capacity:

$$E_{\text{daily}} = 0.8 \cdot E_{\text{battery}} \quad (\text{A.1})$$

For the reduced fast-charging configuration, the charging energy supplied during work breaks was added to the usable battery energy:

$$E_{\text{daily}} = 0.8 \cdot E_{\text{battery}} + E_{\text{reduced fast charge}} \quad (\text{A.2})$$

Similarly, for the baseline fast-charging configuration:

$$E_{\text{daily}} = 0.8 \cdot E_{\text{battery}} + E_{\text{baseline fast charge}} \quad (\text{A.3})$$

An operating time of 8 hours per workday was assumed. The average hourly energy-use threshold was therefore calculated as:

$$E_{\text{hourly}} = \frac{E_{\text{daily}}}{8} \quad (\text{A.4})$$

where:

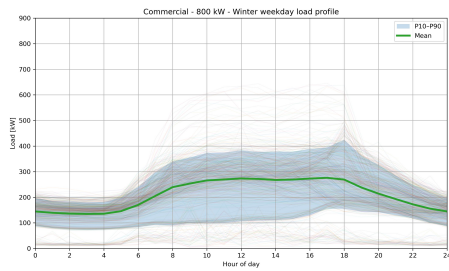
- E_{daily} = daily available energy [kWh]
- E_{battery} = total battery capacity [kWh]
- $E_{\text{reduced fast charge}}$ = energy supplied through reduced fast charging during work breaks [kWh]
- $E_{\text{baseline fast charge}}$ = energy supplied through baseline fast charging during work breaks [kWh]
- E_{hourly} = average hourly energy-use threshold [kWh/h]

The available battery energy before charging is required was assumed to be 80% of the total battery capacity, corresponding to an end-of-day SOC of 20%. For the fast-charging configurations, two 30-minute charging breaks during the workday were assumed, resulting in one hour of total fast charging. Consequently, the charging power directly corresponds to the supplied charging energy during the workday. For example, a charging power of 250 kW corresponds to 250 kWh of supplied charging energy over one hour of charging.

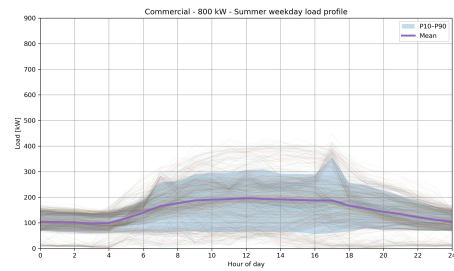
A.3 Additional load and available capacity profiles

This appendix contains the full set of generated weekday load and available capacity profiles. The figures are grouped by zone type. Within each zone, the figures are grouped by transformer size and season.

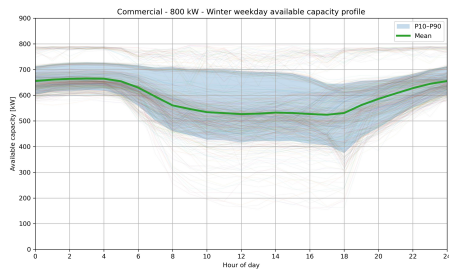
A.3.1 Commercial substations



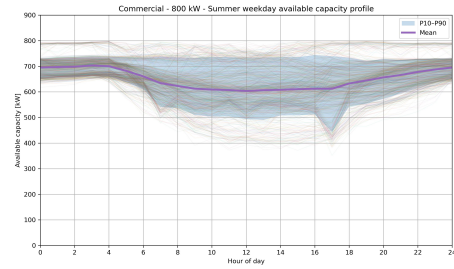
800 kW winter load



800 kW summer load



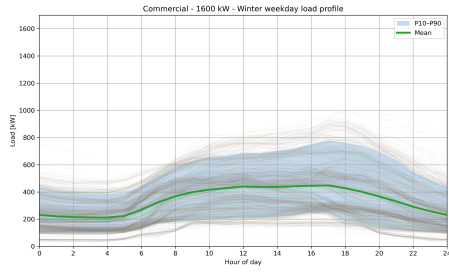
800 kW winter available capacity



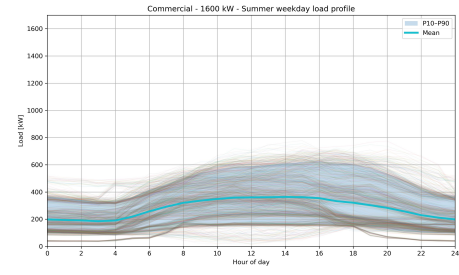
800 kW summer available capacity

Figure A.1: Commercial 800 kW weekday profiles.

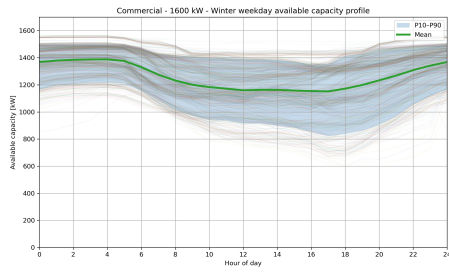
A. Appendix



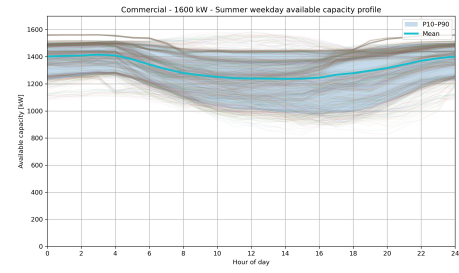
1600 kW winter load



1600 kW summer load

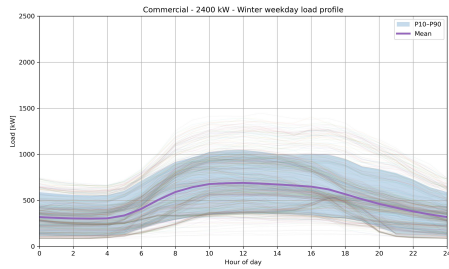


1600 kW winter available capacity

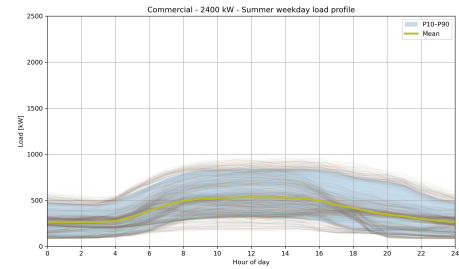


1600 kW summer available capacity

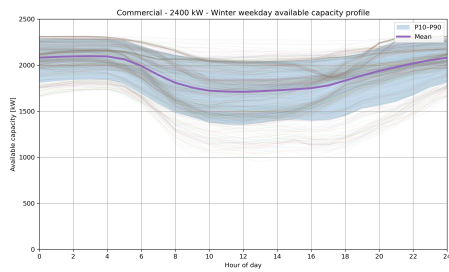
Figure A.2: Commercial 1600 kW weekday profiles.



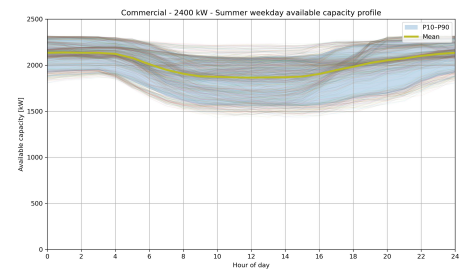
2400 kW winter load



2400 kW summer load



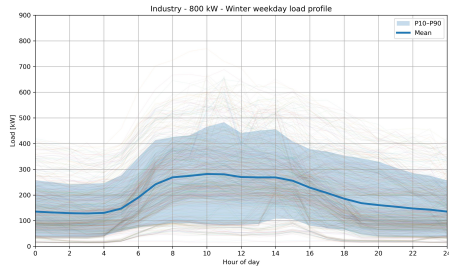
2400 kW winter available capacity



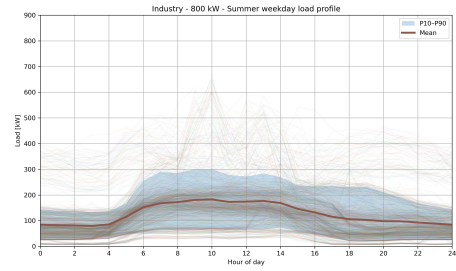
2400 kW summer available capacity

Figure A.3: Commercial 2400 kW weekday profiles.

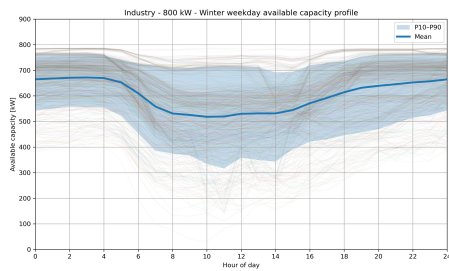
A.3.2 Industrial substations



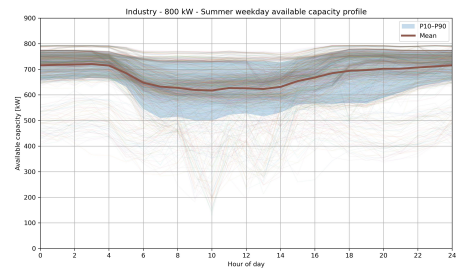
800 kW winter load



800 kW summer load

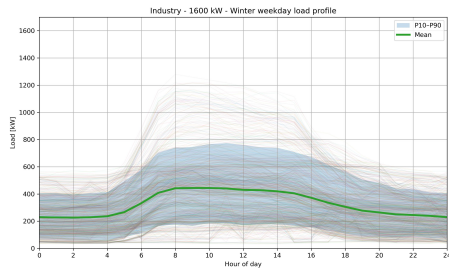


800 kW winter available capacity

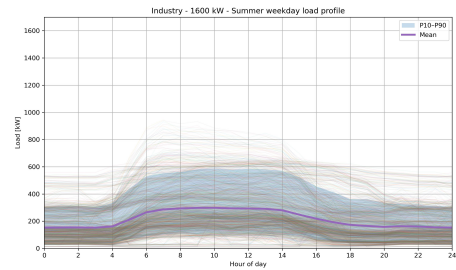


800 kW summer available capacity

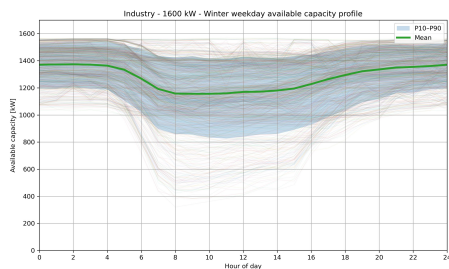
Figure A.4: Industry 800 kW weekday profiles.



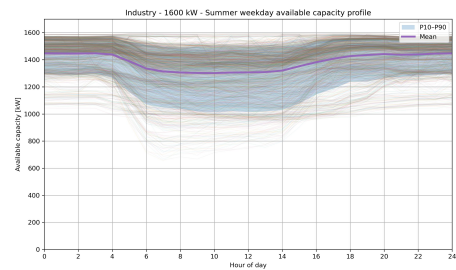
1600 kW winter load



1600 kW summer load



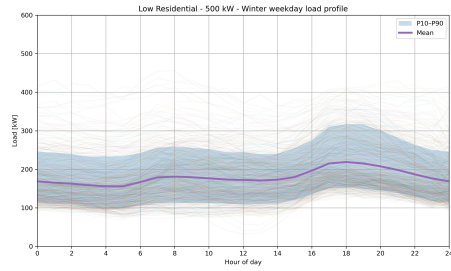
1600 kW winter available capacity



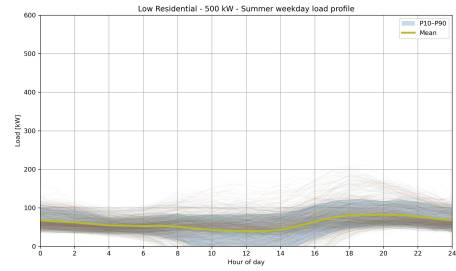
1600 kW summer available capacity

Figure A.5: Industry 1600 kW weekday profiles.

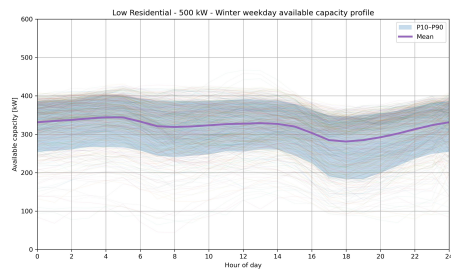
A.3.3 Low residential substations



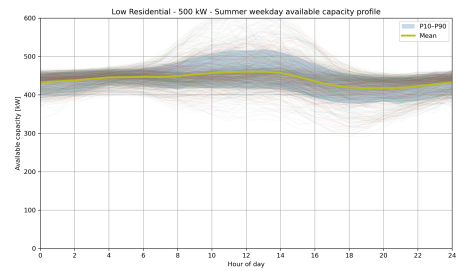
500 kW winter load



500 kW summer load

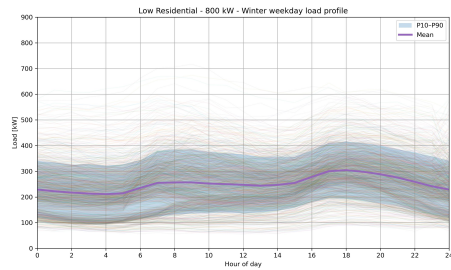


500 kW winter available capacity

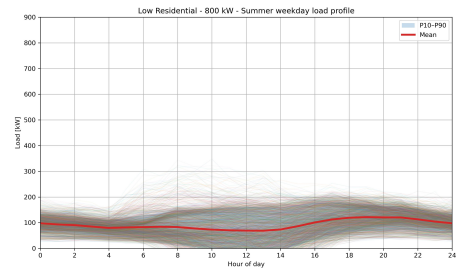


500 kW summer available capacity

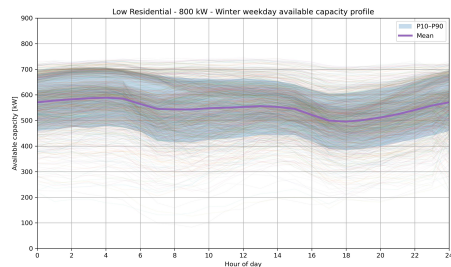
Figure A.6: Low residential 500 kW weekday profiles.



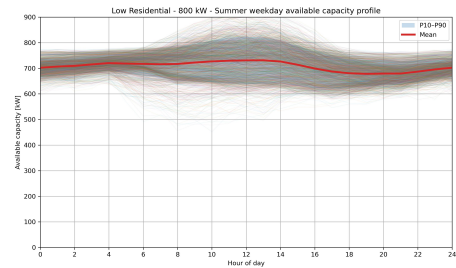
800 kW winter load



800 kW summer load

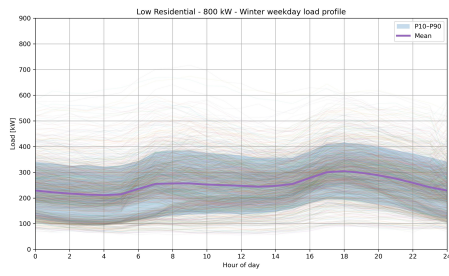


800 kW winter available capacity

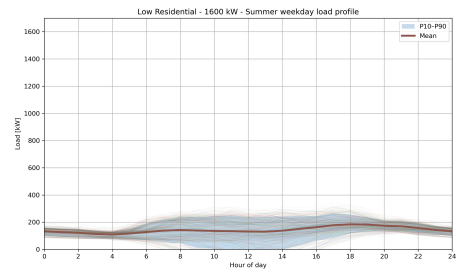


800 kW summer available capacity

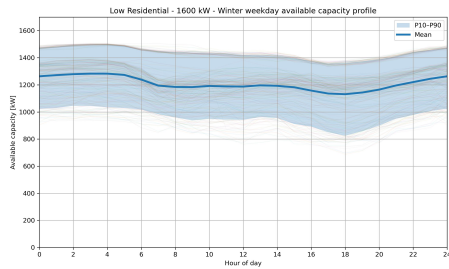
Figure A.7: Low residential 800 kW weekday profiles.



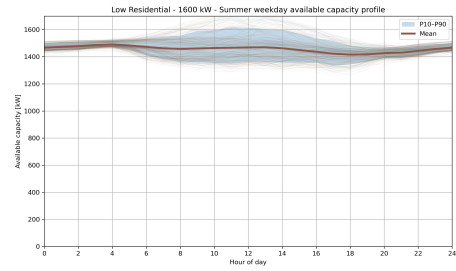
1600 kW winter load



1600 kW summer load



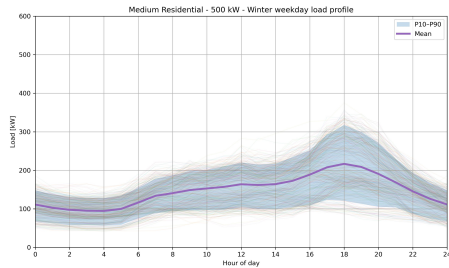
1600 kW winter available capacity



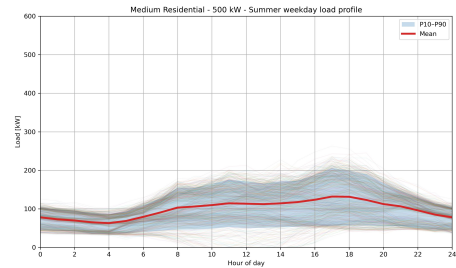
1600 kW summer available capacity

Figure A.8: Low residential 1600 kW weekday profiles.

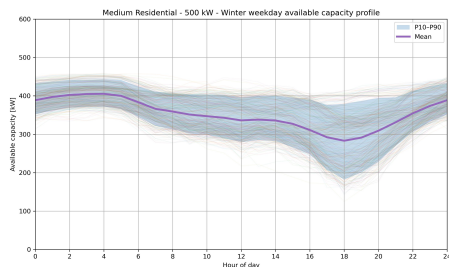
A.3.4 Medium residential substations



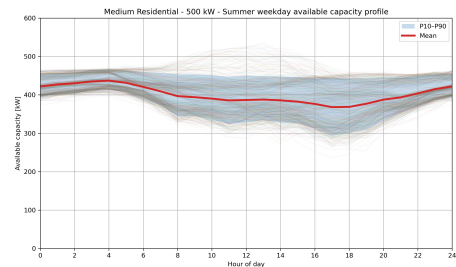
500 kW winter load



500 kW summer load



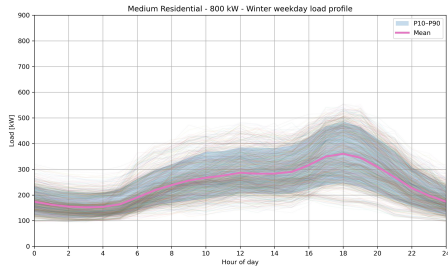
500 kW winter available capacity



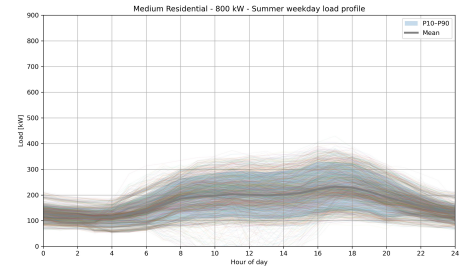
500 kW summer available capacity

Figure A.9: Medium residential 500 kW weekday profiles.

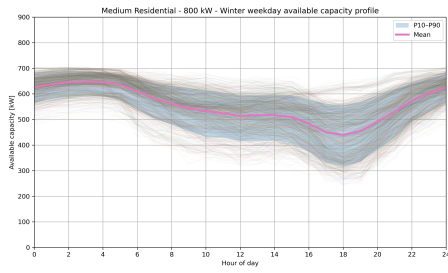
A. Appendix



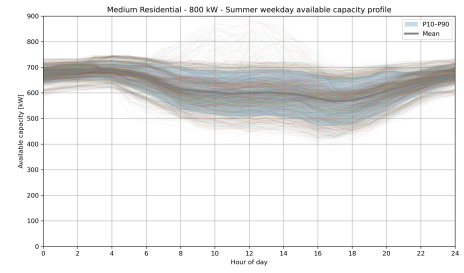
800 kW winter load



800 kW summer load

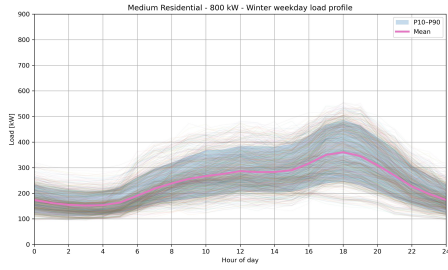


800 kW winter available capacity

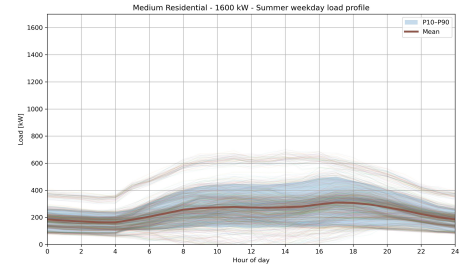


800 kW summer available capacity

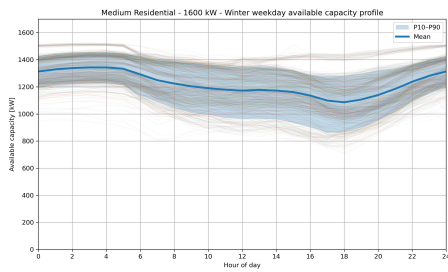
Figure A.10: Medium residential 800 kW weekday profiles.



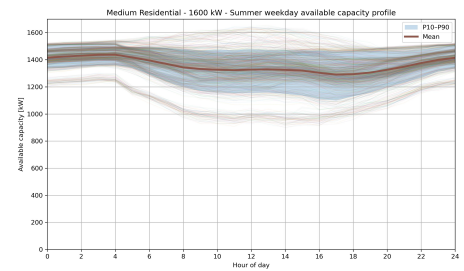
1600 kW winter load



1600 kW summer load



1600 kW winter available capacity



1600 kW summer available capacity

Figure A.11: Medium residential 1600 kW weekday profiles.

A.4 Additional monthly exceedance results

This appendix presents additional monthly average exceedance plots for charging scenarios CS1–CS6. The monthly averages were calculated separately for each month and substation size. Invalid values above 100% or below 0% were excluded from the averaging process. The figures complement the seasonal analysis presented in the main text and further illustrate how exceedance probability varies throughout the year for different charging strategies and transformer sizes, showing similar traits and results.

A.4.1 Full fast-charging

Figures A.12 and A.13 show the monthly average exceedance rates for full fast-charging with 1600 kW and 2400 kW substations. The seasonal trend observed in the main text is also visible here. Winter months generally show the highest exceedance rates, while summer months exhibit substantially lower values. The larger substations experience lower overall exceedance rates, although seasonal dependence remains visible in the most demanding charging scenarios.

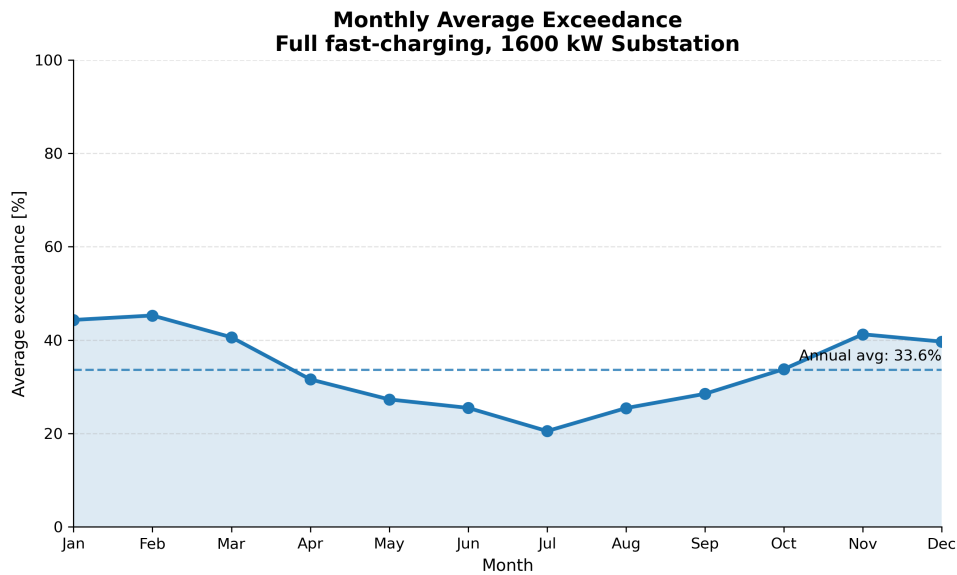


Figure A.12: Monthly average exceedance rates for full fast-charging with 1600 kW substations.

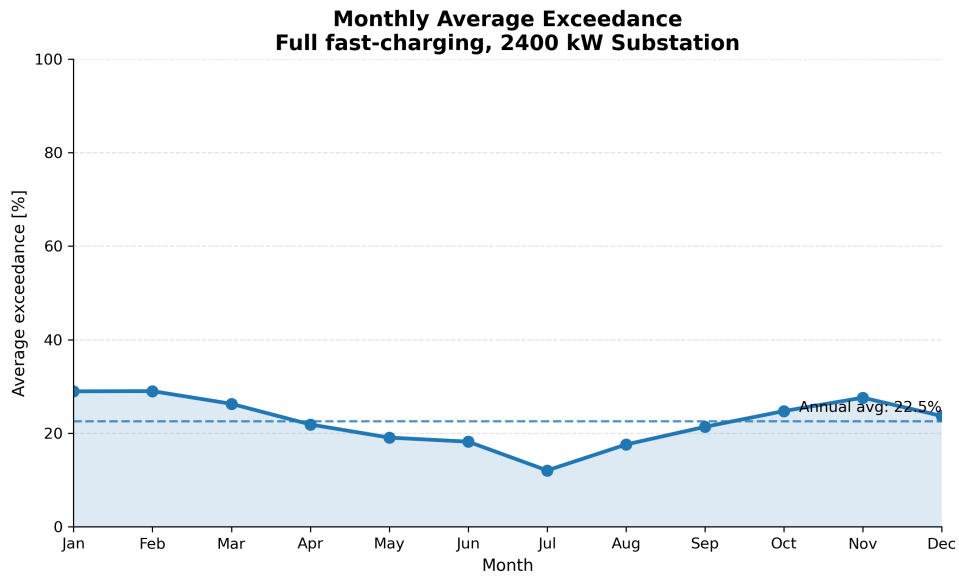


Figure A.13: Monthly average exceedance rates for full fast-charging with 2400 kW substations.

A.4.2 Half fast-charging

Figures A.14 and A.15 present the monthly average exceedance rates for half fast-charging with 500 kW and 1600 kW substations. The results show that reducing the charging power substantially lowers the exceedance probability throughout the year. However, the smallest substations continue to show relatively high exceedance during winter months, indicating that charging power reduction alone may not fully eliminate overload risk in heavily constrained residential areas. For 1600 kW substations, exceedance rates remain comparatively low throughout the year, confirming that larger substations benefit strongly from charging power reduction.

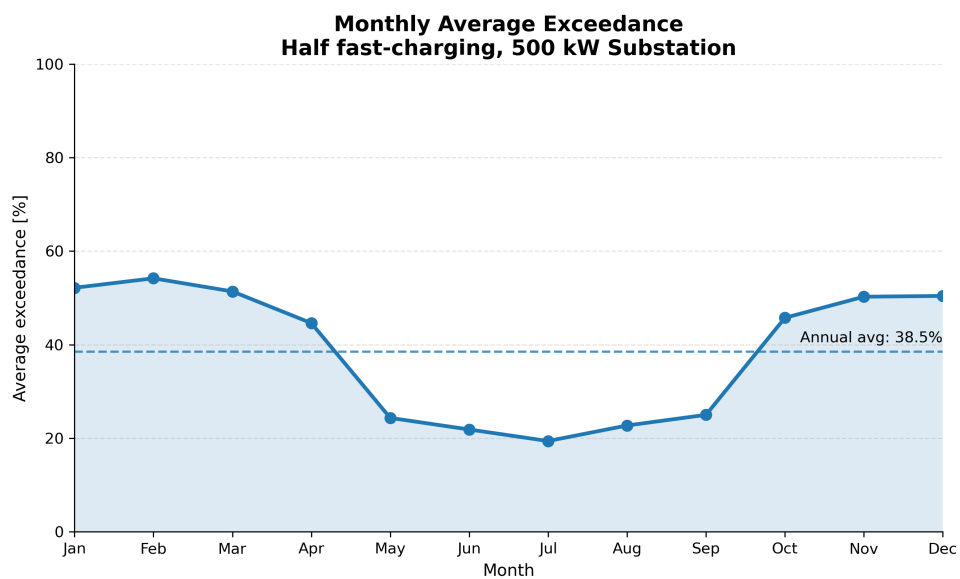


Figure A.14: Monthly average exceedance rates for half fast-charging with 500 kW substations.

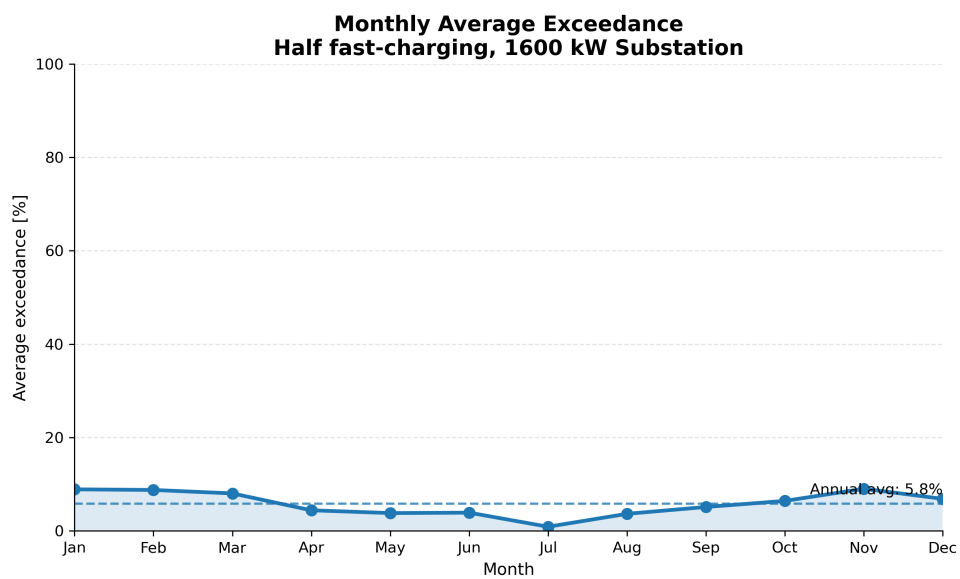


Figure A.15: Monthly average exceedance rates for half fast-charging with 1600 kW substations.

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