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Industrial Electrical Engineering and Automation

Smart Charging and Ancillary Services in the Malmö region

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Abstract

To meet Sweden's national environmental goal of 70% emissions reduction by 2030 compared to 2010 from domestic transport, electrification is considered key. However, as more chargeable vehicles are integrated into the market, shortage of capacity for charging infrastructure may arise. To remedy this, flexibility within charging infrastructure is proposed. The aim for this thesis is to estimate the progress of electrification in Sweden, as well as evaluate the potential and need for different types of flexibility concerning electric vehicle charging. A MATLAB model for a future scenario for electrification of transport is developed to assess the future need and potential for various strategies of smart charging solutions. Results indicate that a 90% reduction in peak power consumption, compared to the base case, may be obtained using solutions such as scheduling and signals from flexibility markets. Also as part of the thesis, a smart charging demonstration project performed by E.ON and Parkering Malmö is evaluated in terms of delivered power reduction and ease of operation. Assessment shows that reduction in power did take place, with varying impact. Influenced by the number of charging sessions meeting conditions for participation, relative reduction varies between 14% and 82%. The manual nature of the evaluation performed in this thesis might not be desirable for future development of the project and may induce some inaccuracy. A more automatic method using the VPP control software is proposed, but may require further studies for verification.

Preface

This thesis the the final work of my 5.5 years of study in Lund. During the course of this last autumn I have learned many things about planning, research, and business development. I would like to thank everyone who has helped me along the way. My supervisors at Lunds Tekniska Högskola, Professor Mats Alaküla and PhD student Alice Jansson, thank you for getting up early mornings to listen to me ramble about MATLAB code and other things. I greatly appreciate your support throughout this journey. To my supervisor Peder Berne at E.ON Energy Infrastructure, thank you for your invaluable support and introductions to both new concepts and new people. To all the people at E.ON and elsewhere I have met discussing flexibility and electrification, thank you for inspiring me. To my friends and family, thank you for always being there even when days are slow and mood is low. I hope you enjoy the read.

Philip Johansson

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1 Introduction

1.1 Background

In the Paris agreement, struck in December 2015, the countries of the world agreed to limit the increase in average global temperature to well below 2 °C, and to work towards keeping it at 1.5 °C [1]. The latest report from the Intergovernmental Panel on Climate Change (IPCC) not only states that its unequivocal humans are influencing the climate of the planet [2], but it also shows that if emissions continue to rise at the present rate, the goal of 1.5 °C will be passed within ten years [3].

Sweden has as part of its overarching environmental goals committed to reducing emissions from domestic transport by 70% by 2030 compared to levels in 2010 [4]. In 2019, emissions from domestic transport totaled 16.428 million tonnes carbondioxide equivalents (CO_2eq). To meet Swedens environmental goals, emissions from domestic transport must then by 2030 be only 6.162 million tonnes CO_2eq [5]. To reach this goal, a shift away from usage of fossil fuels towards renewable alternatives and electrification is presented as a key strategy [4].

To accommodate this emerging type of transport (i.e electric-, chargeable vehicles), there needs to be considerable expansion of charging infrastructure. At the same time, concerns are being raised with respect to lack of grid capacity [6]. In a report prepared by WSP on behalf of the Swedish Environmental Protection Agency (Swedish EPA, Naturvårdsverket) challenges involving grid capacities are identified as main obstacles in expanding charging infrastructure [7].

Flexibility (or smart charging in regards to charging infrastructure) could have the possibility of alleviating some of the challenges of fast adoption of chargeable vehicles, and the issue of grid capacity in general. The last few years has seen the rise of capacity markets, in which grid operators and grid customers can cooperate and engage in trade with capacity [8]. Within the EU-project "Concepts, planning, demonstration and replication of Local User-friendly Energy communities" (CLUE), project partners Parkering Malmö and E.ON have performed a demonstration of flexibility and smart charging of vehicles in two parking garages in Malmö, Sweden. Questions remain however as to what use and value actually was created in the demo, if any grid capacity was freed, and what the future potential for the project is [9].

1.2 Purpose and Goals

The general purpose of this thesis is to evaluate the need for and the potential of different kinds of flexibility connected to charging infrastructure. Work on the thesis builds on two main guiding problem statements:

1. The present and the future of electrification of transport in Sweden
    - How far has electrification of transport come in Sweden?
    - How is flexibility defined with respect to electricity?
    - What does a future scenario for electrification of transport look like in terms of energy and power demands, with and without flexibility?
2. Evaluation of smart charging pilot project by E.ON and Parkering Malmö
    - What value has been created by the use of flexibility for different actors?
    - What is the main business case for using flexibility?

- What is the potential for developing and scaling the project in the future?

1.3 Involved parties

This thesis was carried out by Philip Johansson (ph7886jo-s@student.lu.se) in the fall semester of 2021, at the division of Industrial Electrical Engineering and Automation (IEA) at the faculty of Engineering at Lund University, in collaboration with E.ON. The main supervisor for this thesis was professor Mats Alaküla (mats.alakula@iea.lth.se), with help from assistant supervisor Alice Jansson (alice.jansson@iea.lth.se). The supervisor on behalf of E.ON Energy Infrastructure was Peder Berne (peder.berne@eon.se).

1.4 Disposition

The report starts with a literature study of electrification and charging infrastructure in Sweden. Flexibility in general is then explored, followed by a deep dive into the concept of smart charging. In section 3, the method of setting up a future scenario for the municipalty of Malmö and evaluating the potential for flexibility is detailed. Also covered in this section is the method for evaluating the results from the Parkering Malmö smart charging demonstration.

In section 4 results from simulating the future scenario using various parameters are shown, along with results from evaluating the Parkering Malmö smart charging demonstration. The results are then discussed and compared in section 5. Lastly, the report ends with a brief summary and some conclusions that might be drawn.

2 Theory

This chapter starts off with describing the state of electrification of transport in Sweden and Malmö. Three future scenarios for 2030 from various actors are then presented. The general concept of flexibility is then explored, along with flexibility markets and their function. The chapter then finishes with a deep dive into flexibility connected to charging infrastructure, i.e Smart Charging.

2.1 Electrification in Sweden/Malmö

2.1.1 Electrification of transport

The total energy consumption of road transport in Sweden 2019 was roughly 83 TWh. Of this, 3.5% was electricity, and 19.9% was from different biofuels, which is a shift from 2.7% and 5.1% respectively in 2010 [10]. This consumption resulted in emissions from domestic transport totalling 16.428 million tonnes CO_2eq in 2019. 61.4% of this originated from cars, while heavy- and light trucks accounted for 19.6% and 9.2% respectively. The last 9.8% is constituted of a mix of maritime, aviation, buses, military, motorcycles, and rail. While total emissions from domestic transport have decreased by 20% from 20.540 million tonnes CO_2eq in 2010, the more impressive decrease in emissions has been done by buses which has seen a 83.8% decrease in the same period. Since only 4% of buses in Sweden are chargeable, it is probable that this is due to the increased utilization of biofuels by buses, rather than through electrification [5][11][12].

In reaching the goal of 70% reduced emissions from domestic transport in 2030 compared to 2010, electrification is seen as a key strategy [4]. Electrification of vehicles is usually done by swapping the internal combustion engine for an electric motor, and the gasoline- or dieseltank for a chargeable battery. This is referred to as a battery electric vehicle (BEV). Hybridization is also possible, where both types work together. Hybrid electric vehicles (HEV) can be both chargeable and non-chargeable. A HEV which can be charged from some sort of charging station is called a plug-in HEV (PHEV). Most often a PHEV will have a smaller battery compared to a BEV. BEVs and PHEVs will be the main areas of consideration in this report.

2.1.2 Vehicle-fleet today

As of October 2021 there are 285 865 chargeable vehicles in Sweden. Roughly 96% of these are passenger cars, with a small amount of trucks, motor cycles, and buses. This means 5% of the cars in Sweden are chargeable, with 4% for buses. Below in figure 1 is shown the change in the number of chargeable vehicles by month since 2014 [12].

Within the municipality of Malmö, the number of chargeable vehicles is 10 068, of which 57.2% is PHEVs, and 39.8% is BEVs. 7.9% of the cars in the municipality are chargeable (above the national share). The yearly change in chargeable vehicles in Malmö is shown below in figure 2.

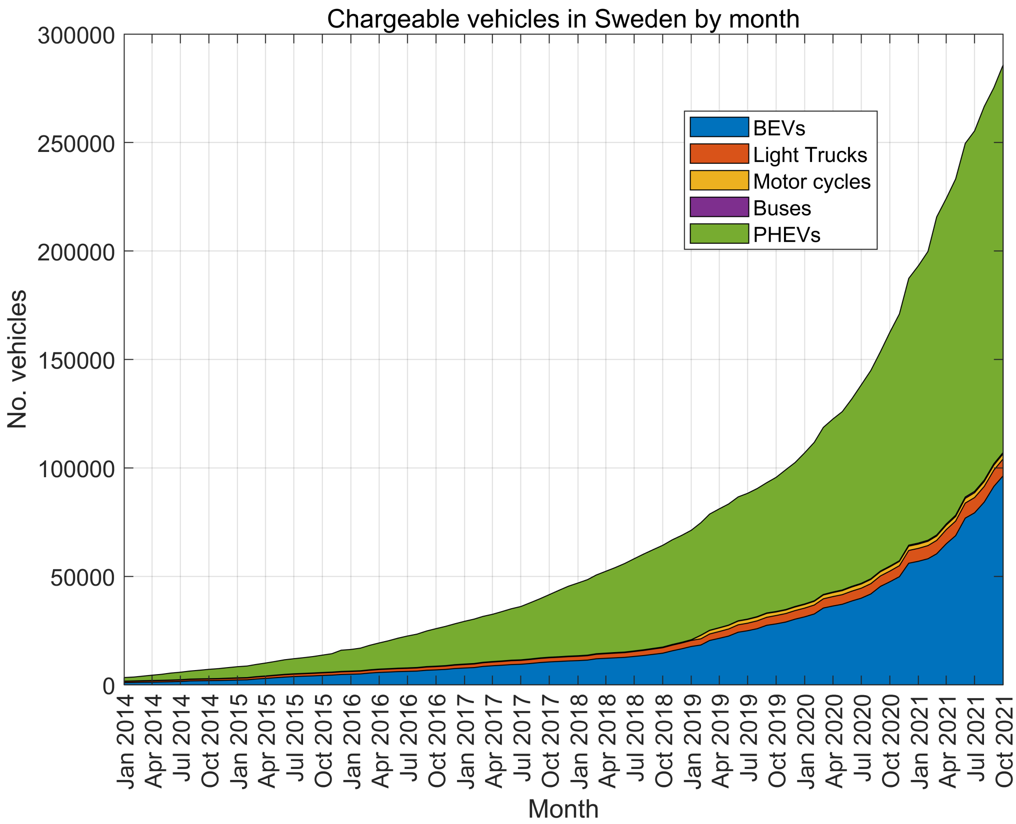

Figure 1: *Chargeable vehicles in Sweden by type and month*

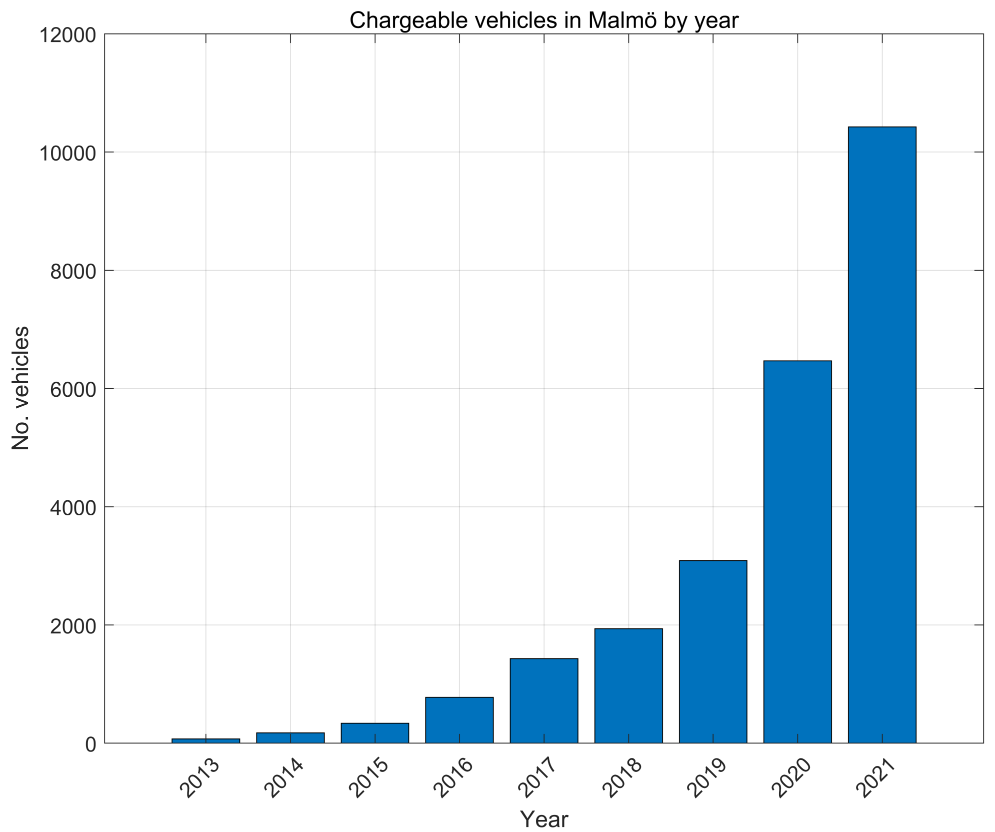

Figure 2: *Chargeable vehicles in Malmö by year*

2.1.3 Vehicle-fleet in the future

In their report titled *"Elbilsläget 2018"*, Power Circle presents a prognosis for the growth of chargeable vehicles in Sweden towards 2045 [13]. The share of chargeable vehicles in new car sales is estimated to dominate the market after 2025. The sale of PHEVs is expected to peak in 2025 at 38%, after which the sales of BEVs take over and increasingly have a larger and larger share of total car sales, until it levels out just over 90% after 2030. The number of active chargeable vehicles expected by 2030 is just over 2.5 million. This is roughly 50% of the active cars in Sweden 2020 [14]. For 2021 the prognosis predicts 257 601 chargeable vehicles, which as of October 2021 already has been exceeded by approximately 11%, with three months of the year to go.

The Swedish Transport Administration (Trafikverket) presents their nine scenarios for reaching the 2030 emission reduction goals in the report *"Scenarier för att nå klimatmålet för inrikes transporter"* [15]. Throughout the scenarios, most variance is found in terms of taxation of fuels and usage of biofuels, although some variance is also found in the share of electrification. Below in table 1 is shown the share of electrification for cars 2030 in the scenarios meeting the emission goals (scenario A is excluded since it does not meet emission targets). For all scenarios a 10% share of electrification of trucks is used.

Table 1: *Share of electrification of cars in scenarios for reaching 2030 targets by The Swedish Transport Administration.*

Scenario	B	C1	C2	C3	C4	D1	D2	D3
Share of electrification	27%	32%	28%	32%	36%	27%	32%	30%

The Stockholm Chamber of Commerce published their report on scenarios for chargeable vehicles in October 2020 [16]. They put forth three scenarios with varied assumed pace of growth of the share of electrified vehicles. Two with linear growth (at different speeds), and one with exponential growth. They then extrapolate the emissions reduction compared to 2018 levels. Below in table 2 is shown the respective scenarios of electrification and the corresponding reduction in emissions.

Table 2: *Scenarios for electrification and corresponding emissions reduction (2030 compared to 2018) by the Stockholm Chamber of Commerce*

2030 Scenario	Low	Medium	High
Share of cars electrified	28%	50%	65%
Emissions reduction	-40%	-57%	-73%

2.1.4 Charging Infrastructure

Providing charging opportunities is identified by the Swedish Energy Agency (Energimyndigheten) as a foundation for the transition from fossile fuel powered vehicles [17]. Charging an electric vehicle can be done both on public and private charging stations. Examples of common charging locations are charging at home, at a workplace, at a mall, gas station, or at a public parking garage. All these examples can be both public and private, all depending on the charger owner. Both alternating- (AC) and direct current (DC) are used. While AC is by far the most common standard (also in general used for home charging), DC generally provides higher power. Even if higher power is available at a charging point, a vehicle might not be able to utilize it since it has a certain maximum power it can tolerate in its internal charging system. Many PHEVs for instance only allow for 3.7 kW charging [18].

A *charging station* may house several *charging points*. In Sweden as of October 2021, there exists 2598 public charging stations, with a total of 14 051 charging points, including 1529 fast charging points (defined as charging power above 22 kW [17]). Below in figure 3 is shown the monthly change in the number of charging points, per power rating. In table 3 and 4 below is shown the share number of charging points per power rating, AC and DC [12]. Note that no official registration is required to set up a public charging station (unlike with registration of vehicles). The public charging points represented below are those which Power Circle have detected. Thus, there is a possibility that there exists more public charging points than is shown here.

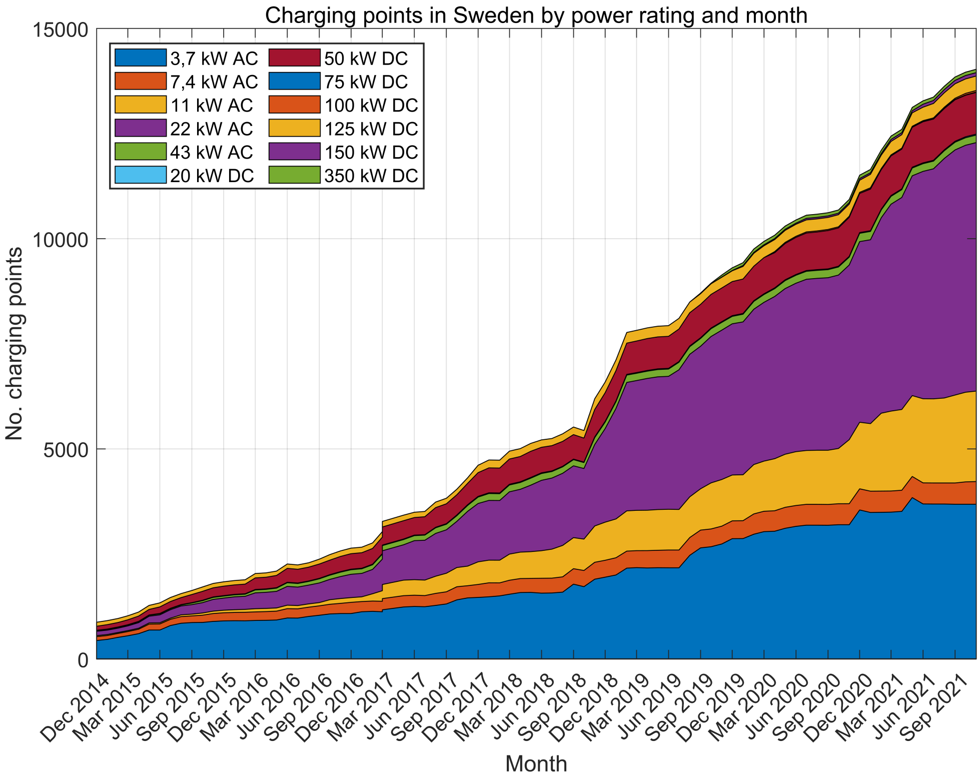

Figure 3: *Public charging points in Sweden by power rating and month*

Table 3: *Share of number of public charging points per power rating, AC, October 2021.*

	AC				
Power	3,7 kW	7,4 kW	11 kW	22 kW	43 kW
Share	26,38%	3,81%	15,28%	42,08%	1,28%

Table 4: *Share of number of public charging points per power rating, DC, October 2021.*

	DC						
Power	20 kW	50 kW	75 kW	100 kW	125 kW	150 kW	350 kW
Share	0,16%	7,07%	0,06%	0,27%	2,46%	0,58%	0,57%

In the municipality of Malmö there are 370 public charge points distributed across 61 charging stations. Comparing Malmö to the country in its entirety, there are 25 chargeable vehicles per public chargepoint, compared to 20 for Sweden as a whole. In figure 4 below is shown the yearly change in the number of public charging points for Malmö.

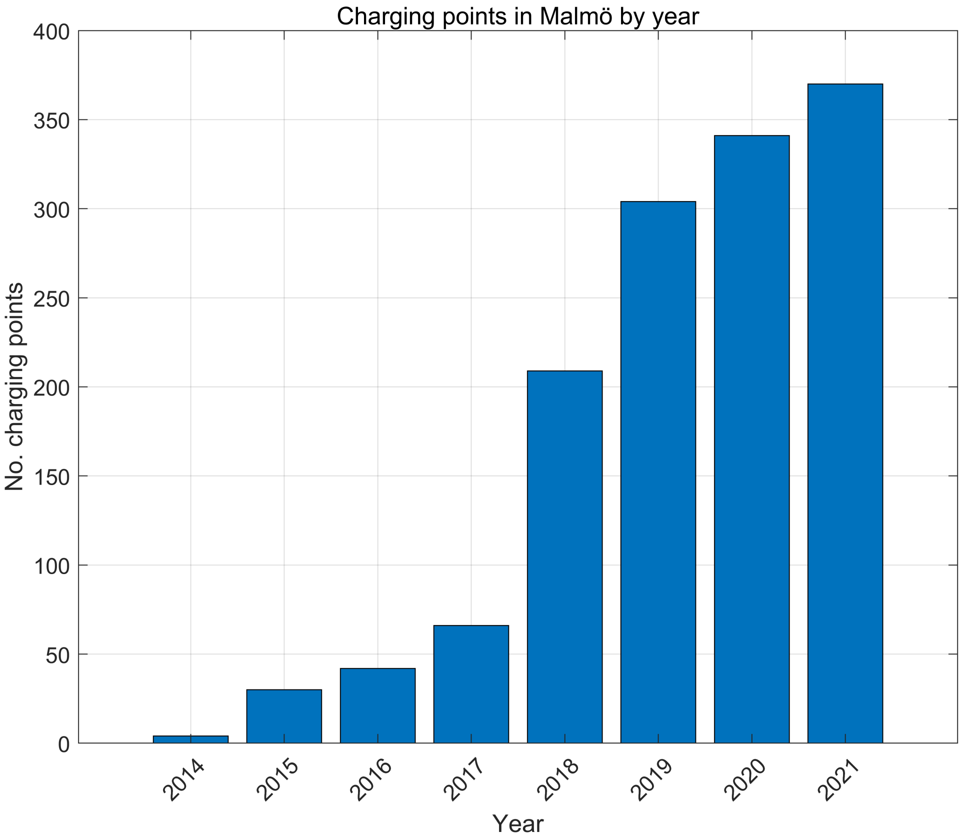

Figure 4: *Public charging points in Malmö by year*

Battery capacity vary between different chargeable vehicles. In general, BEVs will have a larger battery than PHEVs. Below in table 5 and 6 is shown the top five registered BEVs and PHEVs, and their respective battery capacities [19][12].

Table 5: *Battery capacity of the top five BEV models in Sweden.*

BEV Model	Tesla Model 3	Renault Zoe	Kia Niro	Nissan Leaf	Volkswagen ID 3
Bat Capacity	75 kWh	52 kWh	64 kWh	62 kWh	58 kWh

Table 6: *Battery capacity of the top five PHEV models in Sweden.*

PHEV Model	Volkswagen Passat	Volvo V60	Volvo XC60	Mitsu. Outlander	Kia Niro
Bat Capacity	13 kWh	11 kWh	10 kWh	14 kWh	9 kWh

The average battery capacity from this data are for BEVs 62.2 kWh, and for PHEVs 11.4 kWh. The total battery capacity summed across all chargeable vehicles in Sweden is 6895 MWh.

2.1.4.1 Charging services

In building, maintaining, and operating charging infrastructure there may be several actors involved. Including but not limited to: distribution system operators (DSOs, in charge of the local grid), charge point manufacturers, landowners or owners of a charging station, charge point operators (CPOs, responsible for running and maintaining a charge point), E-mobility service providers (EMSPs, providers of payment services or other connected services), and aggregators (collects a larger number charge points for smart use in flexibility services) [20].

Power Circle present some potential business models available when operating or owning a charging point in their report about smart charging [8]. *Energy based* rates are based directly on the amount of energy (kWh) transferred to the vehicle. Both fixed and flexible (perhaps linked to the current cost of electricity) rates are possible. With *time based* rates, a customer is charged proportionally to the time they use the charging point (might be used for instance at fast chargers along highways where you want to maximize charge point availability for new vehicles coming in). In a *lump sum* system the charging customer is allowed unlimited access to the charger in exchange for some regular fee (perhaps monthly).

2.1.4.2 Other types of charging

Although charging is usually done when the vehicle is parked (stationary charging), technology is now being developed allowing for charging while the vehicle is moving. The transfer of power to the vehicle comes via a pickup from powered rails or lines placed on-, in the road or suspended above via poles. In some cases magnetic fields are used through inductive plates beneath the road. These various systems are commonly known as electric road systems (ERS) [21].

Another way of utilizing an electric motor is by pairing it with a hydrogen tank and a fuel cell. The fuel cell converts hydrogen to electricity through a chemical reaction in which the only byproduct is water. This powers the motor and/or charges the battery. The main benefit of this technology is that it allows for faster fuelling (i.e charging), since the hydrogen is loaded onto the vehicle the same way you would with gasoline or diesel vehicle. It may also make the vehicles dry mass lighter, since hydrogen is more energy dense as a storage medium than lithium-ion batteries, and only a small battery needs to be used [22].

2.2 Flexibility

2.2.1 Shortage of electricity

Shortage of electricity has become a source of debate in Sweden in recent years, although some confusion often arises as to which type of shortage is best adressed, and how [23][24]. Shortage of electricity can be divided into three sub categories: shortage of energy, shortage of power, and shortage of grid capacity.

Shortage of energy occurs when a system consumes more electric energy than it produces, in a given time frame. Although Sweden does import energy on occasion, yearly exports are greater. Since Sweden has been a yearly net exporter of electric energy since 2011 [25] , there is currently no yearly shortage of energy in Sweden.

Shortage of power is the term used when production can not keep up with consumption, from second to second. In order for the grid to function, there needs to be constant balance between the supply and demand of electric power. In situations where this is not the case, the most common example being perhaps when the wind stops blowing, there could be large scale, long lasting blackouts. As more intermittent sources of electricity such as solar and wind are introduced to replace dispatchable sources such as fossile gas and nuclear, the risk of shortage of power is increased.

Even if there is enough production in the system to match consumption, it is not a given that the grid has the capacity to transfer power to where it is needed most. Local shortages of power can therefore arise as a consequence of **Shortage of capacity**. Shortage of capacity may exist both on a large scale, and on a small scale. On a large scale there may be bottlenecks in the transmission grid, responsible for connecting northern Sweden, where lots of hydro- and wind power are located, to the south where most of the consumption takes place (and plannable power sources such as the Barsebäck nuclear power plant and the natural gas fired Öresundsverket have been decommissioned). On the smaller scale, it is possible to imagine scenarios where an industry might not be able to expand their operation, or high power electric vehicle chargers can not be installed as fast as desired, due to lack of capacity in the local grid [26].

2.2.2 Flexibility strategies

Flexibility can be defined as the act of moving demand or production in time. Variation management strategies, another name for flexibility, can be divided into three sub categories.

Shifting involves storing electricity and then moving it in time for output back on the grid. Examples of these are stationary batteries or pumped hydropower. Shifting from a consumer perspective also includes moving ones consumption from a time when demand is high, to a time when demand is low (for instance charging an electric vehicle at low peak hours of the day).

Absorbing strategies are deployed when production is higher than demand. Demand may then be increased to meet production (for instance with electric vehicle charging, hydrogen-, or synthetic fuel production), or production decreased (lowering output from hydropower or windpower for example).

Complementing strategies are the opposite of absorbing. When demand outweighs production, one may either increase production (most common is increasing output from hydropower or activating gas-fired power plants), or reduce demand. Reducing demand is most often done by consumers, who might be incentivised to do so by responding to signals such as from electricity price or power tariffs (overlaps with shifting strategies). In system emergencies, the Transmission System Operator (TSO) in Sweden Svenska Kraftnät have deals with large industries to limit their consumption so that grid stability may be maintained. As a last resort Svenska Kraftnät may also create deliberate rotating blackouts [27][28]. Svenska Kraftnät also manages markets for reserve power, which can be activated in case of high demand.

2.2.3 Load balancing within properties

For a property, the fuse capacity sets what peak power the property is able to use. A higher capacity fuse is most often connected to higher costs [29] , but a problem might also arise where the DSO is not able to increase the property fuse capacity on a time scale relevant to the property owner because of shortage of capacity further upstream in the grid. Solutions enabling flexibility may then be deployed to allow for higher total energy consumption while keeping fuse capacity at the same level. One name for such solutions is *local balancing.*

For instance, power limiters (also known as load guards) may be used to distribute available capacity among electric vehicle chargers connected to the property's internal grid. At the same time, some sort of local energy production (solar cells are common) might be present. A control system could be able to steer demand in such a way that the self produced energy is utilized according to the desires of the property owner. Stationary storage, most often in the form of lithium-ion batteries, helps further in this regard. Storing locally produced energy for when it is needed is perhaps the most obvious use case, but the battery may also act as a buffer between the property and the grid. When demand on the property is low, or price signals from the grid are low enough, the battery may be charged using the remaining available power from the grid. Then, when demand of the property increases, or price signals from the grid is high enough, the battery can be discharged to satisfy demand [30].

2.2.3.1 Booster-battery

Another way to utilize storage when grid capacity is lacking is as a booster. An example of this could be for electric vehicle fast chargers. While no vehicles are using the charging point, a battery is charged using available grid power. Then when a vehicle desires to charge its battery, it may do so with the combined power available from the grid and the now charged battery. If the vehicle in question allows for it, higher power (faster) charging can be achieved as a result without increasing the fuse capacity of the property [31].

2.2.4 Flexibility Markets

2.2.4.1 TSO ancillary services

Svenska Kraftnät is the TSO in Sweden which means they are responsible for system- and frequency stability in the national grid. Matching demand with sufficient production is primarily handled by the market (day-ahead and intraday) but the final balancing is the responsibility of Svenska Kraftnät. They do so by procuring ancillary services from different producers (and large consumers with the ability to regulate their power usage). Since these services need to be plannable by nature, intermittent power sources like solar and wind are not the most suitable. Most often hydro power plants are utilized, but regular condensing power plants are also used. Although not available on markets in Sweden today, system services such as reactive power management and handling of grid inertia could be possible areas of interest for market development.

There are four main categories of ancillary services available for tendering [32]:

- **FFR (Fast Frequency Reserve):** Deals with fast and deep variations in frequency. Is procured yearly. Often used in times of low rotational energy (for instance when nuclear power is on revision)
- **FCR (Frequency Containment Reserve):** Stabilises frequency in case of deviations. Automatic activation in the frequency range the reserve is tasked with. Is procured in advance for each moment of the day. FCR is in turn split up into three parts, FCR-N (Normal, both up and down), FCR-D Up (Up regulation in case of disturbances), FCR-D Down (Down regulation in case of disturbances).
- **aFRR (automatic Frequency Restoration Reserve):** Automatic activation tasked with restoring frequency to 50 Hz in case of deviations.
- **mFRR (manual Frequency Restoration Reserve):** Relieves the automatic services. Activated on SvK request. Service specifically targeting smaller actors and assets not typically active on these markets.

2.2.4.2 CoordiNET

CoordiNET is an EU-financed project meant to demonstrate how TSOs, DSOs, and end consumers can cooperate and coordinate to solve problems relating to shortage of capacity in grid operations. Three countries are taking part, Sweden, Greece, and Spain. For Sweden, four regions have participated in capacity market demonstrations, Skåne (Malmö), Uppland, Jämtland/Västernorrland, and Gotland. Malmö and Uppland are facing city development limitations when increased power requests can not be met due to limitations in the grid both on a local level and national level. In Jämtland/Västernorrland, grid capacity is putting constraints on production by hydropower and windpower in the area. Since Gotland is an island, its mainland HVDC connector cable is of great importance. However, limitations in the mainland connector is currently limiting and interfering with wind power expansion [33][34].

The main application is for grid operators to make deals with larger end consumers or producers on local digital marketplaces. In case of strained grid capacity, a grid operator may ask a large industry to cut down on consumption, or they may ask a power plant to increase production temporarily, in exchange for the current market rate.

CoordiNET was first demonstrated at small scale in the winter of 2019/2020, but was continued and scaled up for the winter of 2020/2021 (will also continue winter 2021/2022). Evaluation of the project might lead to demonstrations being offered as permanent solutions.

2.2.4.3 Switch

Switch is a capacity market platform devoloped by E.ON as an implementation of CoordiNET. On the platform, grid operators may create local markets in which they are the responsible DSO, and consumers can provide flexibility within that market (becoming Flexibility Service Providers, FSPs) [30].

A typical process using the platform can be summarized into three parts:

- A grid operator identifies through prognosis and predictions that consumption in the grid will exceed some limiting threshold value.
- A flexibility service provider (most often consumers) makes an offer to lower their consumption a certain amount during the time period in question (a producing FSP might increase production instead). This bid can then be accepted by the grid operator.
- Flexibility is delivered which reduces strain on the grid. Delivered flexibility is validated before payment is transferred.

The market is open winter time, that is between the first of November until the 31st of March (winter is usually associated with higher power loads, mainly due to cold weather). Time periods in which flexibility can be provided are on weekdays between 07 - 20. The smallest amount of flexibility which may be participated with is 100 kW, and above that in steps of 100 kW. Other conditions for being allowed to participate may be presented, such as how often the FSP must have flexibility available.

To prepare for the next winter several steps are taken. In the first quarter, basic analysis of flexibility needs are done. The need is then communicated to relevant parties. Tendering is completed in the third quarter, after which training and setup for the coming season is performed according to needs.

Compensation provided to FSPs can be divided into two main parts, one movable part and one fixed. The fixed part is given for flexibility to be available a certain share of the time. The variable compensation is based on the amount of flexibility that has been delivered

(MWh or kWh). Settlement usually takes place the day before (on the day-ahead-market), but may also take place on the day of delivery (intra-day).

Different deals may also be available [30]:

1. **Seasonal availability:** Bids are sent in the entire season.
    - Bids are sent in daily by FSPs.
    - Bids are usually settled on the day-ahead-market.
    - FSPs send selling bids 9.00 at the latest the day before, buyers settles the bid before 10:30 the same day.
    - Fixed compensation based on how much potential flexibility can be provided.
    - Movable compensation based on delivered flexibility.
2. **Weekly availability:** Bids are requested thursday the week before by the grid operator.
    - After requests from the grid operator is receieved, FSPs answer with bids on friday for the whole coming week.
    - Bids are settled ongoingly by the grid operator if the need exists (usually on day-ahead-market).
    - Fixed compensation based on how much potential flexibility can be provided.
    - Movable compensation based on delivered flexibility.
3. **Free bids:** Bids are sent in freely by FSPs before 9.00 the day before.
    - Bids are settled by grid operators before 10:30 the day before, if the need exists.
    - Only movable compensation for delivered flexibility.

2.2.4.4 Validating flexibility

For flexibility markets to function in a satisfactory way, there needs to be some way for the market DSO to validate that the agreed upon volume of flexibility has been delivered. Baselining is one such way, where one asks the question what consumption would have looked like without flexibility participation. Calculating this baseline may be done in several different ways:

Larger industries with high power intensity may need to plan their consumption anyways, since they might be reliant on the price of electricity or the availability of some other resource. This *consumption plan* may then be used as a baseline. However, this method is only applicable for very large users, and might be sensitive to gamification. For instance, an industry might internally plan to reduce production anyway because of some factor, but still claim that the reduction in power usage is due to flexibility participation, and thus receive compensation.

Another method is the *meter-before-meter-after* technique. Measurements of power consumption are made in the moments before and the moments after a certain flexibility period. A straight line between the two points is then used as the baseline, and compared with the actual consumption to evaluate delivered flexibility.

There is also the possibility of using the historical data generated from a FSP to set the baseline automatically. As time progresses, the model which create the baseline can be dynamically updated to provide better validation [30].

2.2.4.5 Aggregation

While larger industries and energy production facilities may participate in flexibility markets with relative ease, smaller scale operations face some hurdles. Individual assets such as chargers, heat pumps, and residential energy storage will not on their own meet the volume requirements to participate in flexibility- and frequency markets.

Possibilities then arise for new or present entities to act as *aggregators* of many assets, and as middlemen between consumers and the relevant markets. Such actors may be large parking space operators, charging point operators, energy systems solutions companies, property owners, or new companies operating solely with the aim of aggregating flexibility assets for market participation [30]. One example of such a company is Swedish tech startup Krafthem, which was approved for supplying flexibility to Svenska Kraftnäts FCR service, using aggregated vehicle chargers, heatpumps, batteries, and renewable end production [35]. The Svenska Kraftnät ancillary service mFRR specifically targets smaller size actors and assets, and may thus also be a potential alternative for smaller size aggregators of flexibility assets not able to comply with higher requirement services such as FCR [32].

2.2.4.6 CLUE Demo Parkering Malmö

In the Parkering Malmö flexibility demonstration within the CLUE project, smart charging connected to the flexibility market Switch has been tested. During predefined hours most associated with high grid load (8:30-10:30 in the morning, and 17:00-19:00 in the evening), load reduction was executed with electric vehicle chargers in parking garages operated by Parkering Malmö. Three different sets of conditions for which chargers were eligible for load reduction were tested [30]:

1. **Use Case 1 (UC1), Site based:** All active charging sessions within time period eligible for reduction.

2. **Use Case 2 (UC2), Session based:** Reduction allowed if charging session has been active for at least 1 hour, and has transferred at least 2 kWh to customer.

3. **Use Case 3 (UC3), Customer based:** Condition for reduction based on previous data for individual customers. Reduction is allowed if a customer has been parked for 75% of their average charging time, or if they have managed to charge 75% of their average charging energy.

The signals controlling the system is sent by the Virtual Power-Plant software (VPP) developed by E.ON, in which the user may tweak different parameters such as active time period or the conditional variables in the use cases. Chargers meeting the conditions for the use case being tested (within the relevant time periods) are put in a control group called reduced. Chargers not meeting conditions are put in a group called blocked. The system works with 15 minute resolution, and updates which chargers belong to which group with each tick.

Also updated is what current may flow through each group. Rather than controlling the current of each charger individually, a total current for all chargers in a group is set. This allows for a load balance system present in the facilities to act within that current ceiling to optimize power flows within each site. Current ceiling assignment is not the same for the two groups. For the blocked group, current is set according to equation 1 below,

Removed for secrecy. Contact E.ON for further details. (1)

where $i_{blocked}$ is the ceiling current for the group, $i_{nominal}$ is the total nominal current for all chargers, $N_{blocked}$ is the number of chargers in the blocked group, and N is the total number of chargers.

For the reduced group, the current ceiling is set according to equation 2 below,

Removed for secrecy. Contact E.ON for further details. (2)

where z is the reduction factor, $N_{reduced\_new}$ is the number of new chargers eligible for reduction, $N_{reduced\_old}$ is the number of chargers which participated in the previous time slot, p_n is the sampled power of charger n, and F is a conversion constant from power to current. Chargers are divided into new and old to avoid concurrent reduction of the same chargers. Note that 6 Amperes current (corresponding to approximately 1.38 kW single phase) is the minimum charging current possible to charge vehicles with. Any reduction which would make current drop below these level was blocked.

During the winter of 2020/2021, two sets of tests were performed. In November and December of 2020, a handful of chargers (in *P-Huset Anna* and *P-Huset Hyllie* using all use cases were tested (two weeks for each use case starting with use case 3). Preliminary evaluation consisted of comparing main meter reading from the tested time period with a reference period. No data allowing for individual evaluation of each charger are available for this period. Data logs from the VPP system for the time period are available, containing assigned total current for each group.

In March of 2021 additional tests were made, with 78 charging points participating (across multiple parking garages). This time only use case 1 and 2 were evaluated, since use case 3 in an initial analysis was deemed to have too small reduction potential. Data from this testing period includes 15 minute values for each charger, enabling individual assessment. Preliminary evaluation on summed data across all chargers was performed by E.ON Energy Networks. No individual charger assessment was thus made. One goal of this thesis has been to make such an evaluation.

2.3 Smart Charging

Smart charging of electric vehicles is a wide term encompassing many different types of behaviours and uses of technology. Although the central theme is most often the ability to charge in such a way which optimizes energy and power usage from a certain point of view, that point of view may vary. In an attempt to quantify and standardize different aspects of smart charging, Power Circle defines five levels of smartness, each with its own solutions and optimization strategies [8]:

2.3.1 Level 0

Level 0 is defined as the base case, and is also known as *dumb charging* or *direct charging*. The vehicle uses the maximum power available and charges until battery is either full, or the session is aborted. If many vehicle owners behave in the same way around the same time of day (as is often the case when returning home from work for example), this level may result in the highest aggregated peak powers, which in turn puts high demand on the grid. Optimization on this level targets the speed of charging, which may be desirable for instance next to gas stations, or along highways.

2.3.2 Level 1

Level 1 focuses on user comfort and digital services. On this level the user may through smart apps schedule their charging and plan ahead for when they want to use the vehicle again. For example, a user requires 10 kWh and plans to use their vehicle 5 hours later. Instead of charging with 10 kW power for 1 hour, level 1 services allow for charging with 2 kW for 5 hours, thus decreasing peak power load from the grid. Lower power charging also has the added benefit of potentially being better for the long term health of the EV battery [36].

Since the price of electricity tends to be higher in the day, scheduling charging to occur at night may also provide useful incentives for the user. This can be considered a *shifting* strategy (explained in section 2.2.2). While not directly connected to the charging of the vehicle, apps communicating through charging stations and a users smartphone may also allow services like booking and opportunities for users to know whether a certain charging point is available or busy. Even though user comfort is the main target of optimization on this level, lower peak power may also be possible as a side effect.

2.3.3 Level 2

On **level 2** lies solutions connected optimization in terms of conditions for a certain property or facility. Load guards and load distributors can share the available power from the grid among vehicle chargers. More charging points can then be used safely without concerns for fuse blowouts, or the need for costly fuse upgrades, which is the main source of incentives for these types of solutions.

Further solutions such as local production and storage (as described in section 2.2.3 on local balancing) may add further incentives, for instance maximizing self consumption of locally produced energy through storage and charging, which often is cheaper than buying electricity from the grid [37]. While optimization on this level concerns the property, it indirectly also helps the grid since no installation of upgrades may be necessary. It can then also be said that the higher fee associated with fuse upgrades, is an indirect incentive signal from the DSO, which most often is the concern of the next level.

2.3.4 Level 3

Level 3 factors in external signals into smart charging. Different types of dynamic price signals can be used by DSOs to incentivize charging when beneficial for the grid, for instance in high demand hours or cold winter days. The price of electricity, albeit not controlled by DSOs, is one such external signal. If connected services are used by electric vehicle users or charge point operators, level 1 strategies may be used to optimize charging based on spot price (for instance at night). Charging point operators may also choose to enter into bilateral deals with DSOs, allowing DSOs to reduce power available to concerned chargers under certain conditions.

Since the spot price of electricity is the same in same electricity price area, local grid challenges might not be captured by such optimization alone. Power tariffs are then another type of price signal that DSOs can use. In times of strained grid load, additional fees per unit of power used by consumers would then be payed, incentivizing low power usage and for charging to occur at hours with low tariffs. Such tariffs may be based on real time data according to grid load, using predetermined time periods, or a combination of the two.

This type of tariff have been implemented by Göteborg Energi, for their grid customers. Göteborg Energi splits the grid fee into two parts. The first one is the regular, fixed fee, which have been lowered to compensate for the addition of the power tariff. The second part is the new power tariff, in which customers pay a monthly fee based on the average of the three highest hours of power usage (power measured in one hour averages) [38].

2.3.5 Level 4

The final stage of optimization is **level 4**, where multiple levels can be optimized for simultaneously, and several different price signals may be taken into consideration. In this stage aggregation of many chargers is key. Aggregation allows for participation by electric vehicle charging in flexibility markets such as Switch/CoordiNET and other markets for ancillary services with Svenska Kraftnät. Both increasing charge power (an *absorbtion* strategy) and decreasing charge power (a *complementing* strategy) can provide such services. The CLUE smart charging demonstration project (described in section 2.2.4.6) is a test of a level 4 solution on top of level 2 solutions (local load balancing systems).

Another level 4 strategy with which electric vehicles may offer services is by reversing power-flow and instead providing power from the battery to the grid. This is called Vehicle-2-grid (V2G). One example of this is to use the vehicle battery as a home battery (and with other level 2 solutions). While smart charging in general moves charging in time or reduces charging power, V2G turn chargeable vehicles into energy producing assets, which also may participate in various markets for flexibility. Again aggregation is key to participation because of volume requirements in relevant markets. With 60% of cars chargeable and with access to V2G capabilities, half of the total power demand in Sweden could potentially be covered. [39]

3 Method

3.1 Future scenario

An aim for this thesis is to set out a future scenario for electrification in Sweden in 2030, and evaluate what power demands large scale electrification puts on the grid, with and without different flexibility solutions.

For this purpose, a MATLAB model is developed. Transport data and surveys is used to model energy usage by vehicles. This consumption data is then fed into different models for charging, examining different parameters and behaviours, resulting in peak power values. Details of the model, assumptions, limitations, and algorithms are detailed in the subsections below.

3.1.1 Initial assumptions and limitations

At today's 5% chargeable vehicles, shortage of capacity is already an issue. An interesting scenario to evaluate is then what demands would be put on grid operations if the environmental goal for transport emissions reduction in Sweden is met. As described in section 1.1, a 70% reduction in carbon emissions compared to levels in 2010 is targeted. The scenarios developed by The Stockholm Chamber of Commerce (detailed in section 2.1.3) is used to calculate a corresponding degree of electrification for 70% emissions reduction (compared to 2010 levels, 2018 used in source scenarios). With 55% chargeable cars, the target is met.

Hourly time resolution is used throughout the model. The geographic area is limited to the municipality of Malmö. In Malmö, the intensity of cars is assumed to stay relatively constant at 350 cars per 1000 residents [40]. Using the prognostisized 377 231 residents in Malmö by 2030, the number of cars is assumed to be 132 030 [41]. Assuming 55% electrification, the number of chargeable vehicles is then 72617.

The share of BEV and PHEVs respectively is assumed to be 65% and 35%, based on the 2030 prognosis by Power Circle (section 2.1.3). BEVs is assumed to have a battery capacity of 100 kWh, with 15 kWh for PHEVs [42]. The energy consumption per unit length traveled is assumed to be 2 kWh/mile (10 km) [43].

3.1.2 Consumption modelling

Travel data from the transport survey conducted by Region Skåne 2018 is used to model consumption [44]. Since the geographic location of interest is the municipality of Malmö, only travels with a destination in Malmö are included. This means for example, a commuter from a neighbouring municipality which works in Malmö is included on his or her way to work, but not on their way home. This is done so that only charging taking place in Malmö is modelled. Only travel by car is considered.

Three data sets are used. One for weekdays, one for Saturdays, and one for Sundays. The data sets includes data on probabilities that a certain type of journey will take place a certain hour, and their respective median lengths. Below in table 7 is shown the different types of journeys and their respective median lengths.

For every vehicle, a predetermined number of hours may be modelled. The travel data is translated into a probability distribution. Meaning, each hour the vehicle in question has a certain probability of performing a certain type of journey. When a journey is selected, the distance is calculated from a normal distribution, with the mean equal to the median distance in table 7, and standard deviation 2 km. The distance is then converted

Table 7: *Journey types and their median lengths from the 2018 travel survey.*

Journey Type	Median Length (km) Weekday	Median Length (km) Saturday	Median Length (km) Sunday
To residence	8	8	10
To workplace	16	10	13
Shopping	4	5	5
Give lift	5	6	10
Leisure/relatives	8	8	18
Exercise/Outdoors	6	7	5
Worktravels	10	28	7
Healthcare	6	8	3
To school	20	15	2
Other	7	5	5

to energy consumption (with 0.2 kWh/km as described above in section 3.1.1), which is then assigned to that hour. Only one journey may be taken each hour, and all journeys were assumed to be completed the hour in which they started.

3.1.3 Charging

In order to get the full potential of smart charging, charging is assumed to be available at each hour the vehicle is parked, i.e whenever consumption is zero. Different charging algorithms corresponding to levels of smart charging defined in section 2.3 is used.

For **level 0**, each vehicle is assigned a charging power, based on either the real distribution (see table 3, only AC charging is considered) or a certain variable power for all. When consumption is zero, and the battery lower than 100% of its capacity, charging is assumed to occur. The assigned power is used every hour until the battery was full. The charging hours and the power used that hour is stored in a vector for that specific vehicle.

The key assumption in **level 1** charging is that charging is now able to be scheduled, taking into account for how long the vehicle can be charged (hours until next consumption), and the expected next consumption (amount of energy). Two new parameters is introduced, *style*, and *limit*.

The *style* parameter sets the type of scheduling available to vehicle users. In the "standard" style, the energy needed (until battery is full) and hours available (until next consumption) is calculated. Those hours are then assigned the average power needed, i.e energy needed/hours available. If that average power is below 1.38 kW (minimum level of power for vehicle charging), the power is set to 1.38 kW for the hours required with that new power. The "planned" style operates mostly similar to the standard style, but the energy needed is instead the energy of the next consumption

The *limit* parameter sets at what battery level the user wants to charge their vehicle. Thus, charging will not take place until the battery decreases below that level. A limit of 1 means that charging will happen as soon as the battery level is below 100%. A limit of 0.5 means that charging only may happen after 50% of the battery has been consumed. During initial testing of the model, a variable tracking the number of times a vehicle reached 0% battery capacity was used. In some cases when utilizing the limit-parameter, 0% on the battery was reached approximately 3000 instances. Upon further examination, such low battery levels were only reached by PHEVs. To remedy this, the limit parameter is set constant to 1.0 for all PHEVs.

Since the model covers all chargeable vehicles in the municipality of Malmö and does not consider individual properties, **level 2** is not applicable. Neither is **level 3**, since no price data (most often associated with level 3) is used in the model.

Level 4 smart charging focuses on adapting charging to grid capacity requirements. This is implemented in such a way to mimic the Parkering Malmö tests (see section 2.2.4.6). This flexibility system is assumed to be active on weekdays between 9.00-11.00 in the mornings, and 17.00-19.00 in the evenings. In those time periods charging power is reduced with 50% according to either use case 1 or use case 2 (set by parameter *flex*). In addition, this system is implemented on top of both **level 0** and **level 1** smart charging algorithms described earlier.

For each level and parameter variant, the charging consumption each hour from all vehicles is summed. Charging consumption from cars are also added with charging from heavy transport (see section 3.1.5 below) to see in which scenarios each segment dominate peak consumption. Additionally, these peak values (all taken on the same Monday) are compared with the regional subscription limit, at 900 MW (Sege and Arrie transmission grid stations combined [30]). This limit governs how much power the regional grid in Malmö may import from the national transmission grid. If the limit is exceeded, the regional DSO (E.ON Energy Networks in this case) may be subject to fees. One may also consider a future case where the operational limits of the transmission grid connections may be exceeded due to high regional grid loads.

3.1.4 Parameters

The main parameters which may be altered before running the model varies with what level of smart charging algorithm is used. In table 8 below is summarised the main parameters, their function, and at what levels they are relevant.

Table 8: *Main charging parameters and their functions*

Parameter name	Relevant Levels	Possible Options	Function
Charging power	0, 0+4	"dist", 3.7, 7.4, 11, 22, 43	Sets constant charging power .
Limit	1, 1+4	0.0 - 1.0	Sets battery threshold .
Style	1, 1+4	"standard", "planned"	Sets scheduling solution. Detailed in 3.1.3
Flex	0+4, 1+4	"UC1", "UC2"	Sets flexibility conditions. Detailed in 2.2.4.6

3.1.5 Heavy transport

A small model is also developed for trucks/heavy transport. The share of chargeable trucks in 2030 is assumed to be 30% [42]. The number of trucks registered in Malmö is 13 708, out of which 11 792 are light trucks (weight less than 3.5 tonnes), and 1916 are heavy trucks (weight more than 3,5 tonnes) [45]. The number of trucks 2030 is assumed to be the same as today.

Data from a previous report by the thesis author in collaboration with a logistics company on typical drive cycles is used to generalize consumption behaviour for all trucks. Below in tables 9 and 10 is shown the assumed distribution and number of trucks (with 30% assumption) by typical daily distance driven and energy consumed, for light and heavy trucks respectively.

Table 9: *Distribution of light trucks and their energy consumption*

Assumed distance	50 km	100 km	150 km	200 km	250 km	300 km
Daily energy consumption	17 kWh	33 kWh	48 kWh	64 kWh	79 kWh	95 kWh
Share of vehicles	6.7%	16.7%	10%	13.3%	33.3%	20%
Number of vehicles	237	590	354	470	1178	707

Table 10: *Distribution of heavy trucks and their energy consumption*

Assumed distance	75 km	150 km	225 km	300 km
Daily energy consumption	53 kWh	130 kWh	205 kWh	282 kWh
Share of vehicles	57.6%	16.9%	15.3%	10.2%
Number of vehicles	331	97	88	59

A consumption vector for each truck is created. Consumption on Saturdays and Sundays is assumed to be zero. Using a normal distribution, a departure and arrival time (from/at a home terminal) is assigned for each vehicle. The battery capacity of a certain truck is assumed to be equal to its daily energy consumption, thus trucks are assumed to be BEVs.

Charging is assumed to to take place at the home terminal between arrival and departure. This is implemented with a similar algorithm as for smart charging with cars at level 1. The charging power for each hour is stored in a vector and then summed across all vehicles to get the total power for each modelled hour.

3.2 Case study - CLUE Demo Parkering Malmö

The second key aim for this thesis is to evaluate the tests performed by E.ON and Parkering Malmö for the CLUE Demonstration project. Since no deep dive analysis of data from the tests had been done thus far, a key goal for this thesis is to evaluate generated data on a deeper level, both in terms of technical aspects (such as power and energy usage), but also what value has been created for different actors. Potential improvement possibilities and obstacles for future continuation or evolution of the project connected to the thesis aims are also considered.

3.2.1 Autumn 2020

For the tests performed in November and December, individual data for every charger is not available. Saved logs from the test control software VPP, containing $i_{blocked}$ and $i_{reduced}$

for each time slot, were instead used in the evaluation. Since the reduction factor was set at 0.5 (50%) throughout the tests, the values for $i_{reduced}$ should be equal to the *amount* of reduced current. While this may provide a straightforward method for evaluation, it fails to take into account the load balancing system, which operates below the upper current limit of $i_{reduced}$, and includes chargers in the blocked group. No data or logs of the actions of the load balancing system are available for cross referencing. Thus, in order to use $i_{reduced}$ for this assessment purpose, additional tests are likely required.

3.2.2 Spring 2021

For the tests in March the opposite data is available. While logs from the tests control software VPP does not exist, data logs from the chargers control system does exist. The data consists of meter readings (in Watt hours, Wh) for each of the 78 chargers and every relevant time slot.

Meter readings are converted into an average power used during the time slot in question. Then, for each period the tests were performed and for each charger, power readings are analyzed to evaluate if any reduction in power has occurred. If such a reduction is deemed to have taken place, notes are taken as to the estimated average magnitude of the reduction, its duration, and comments on the function of the present use case (it should be noted that mainly use case 2 was used in the March tests). Notes are also taken of charging sessions commencing during the testing periods. This is done so that this analysis may be compared with previously made analyses which only had access to the aggregated data with all chargers summed.

4 Results

4.1 Future scenario

4.1.1 Cars

In order to meet environmental goals, 55% of cars need to be chargeable by 2030. For Malmö, 55% means approximately 72 617 chargeable cars (see section 3.1 for details). The modelled total energy consumption for all 72 617 chargeable vehicles (cars) by hour (for a representative week), is shown below in figure 5. To be clear, this is energy usage by vehicles and should not be confused with energy consumption from charging. For figure 5 and other figures presenting results from the future scenario, the same full week is shown, with hour 2520 representing midnight on Monday.

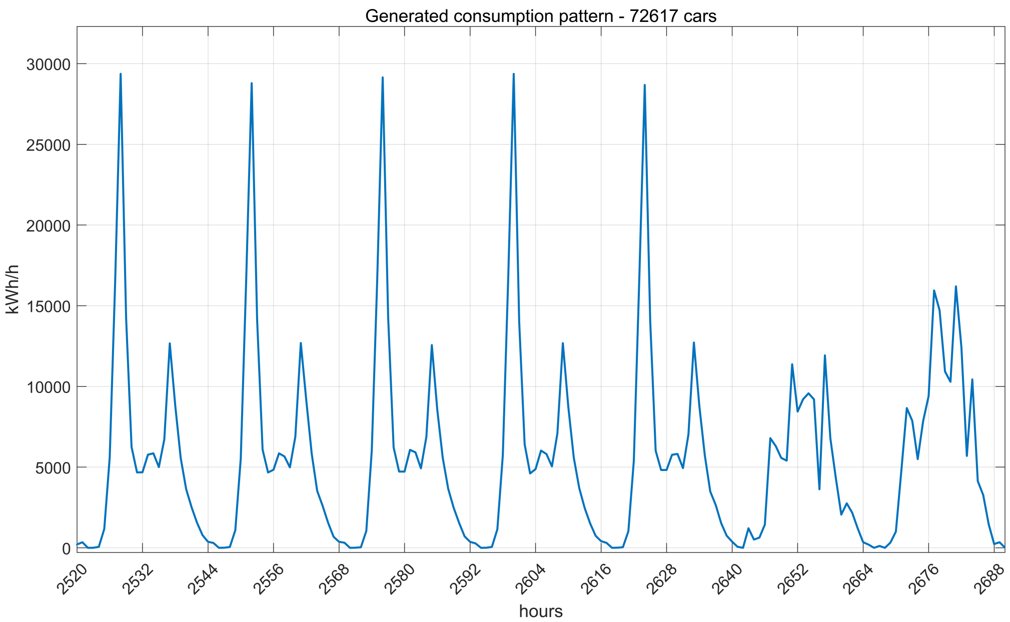

Figure 5: *Generated total energy consumption by 72617 vehicles by hour*

4.1.1.1 Charging

In appendix A, in figures 9 to 29, is shown detailed graphs of the hourly charging energy consumption when various levels of smart charging with different parameter values are applied (see section 3.1 for details). In each figure two time scales are visualized. To the left is shown hourly consumption during a 7-day week. To right is shown the the same data during the Monday of that same week.

Results from all above tested variants with associated parameters are summarized in table 11 below, for easy comparison of peak consumption values for each variant. Also in table 11, peak values when adding charging of light and heavy trucks are shown, along with a relative comparison of peak values and the regional grid subscription limit at 900 MW. Table 11 is then visualized in figure 6, which shows the data in a bar-style graph. For each variant, three bars are shown. The blue bar represents the standard levels 0 and 1 without using level 4 flexibility. The green bar represents usage of level 4 flexibility (when used with level 0 and 1 respectively) and charging when using use case 1 (see section 2.2.4.6), while the orange bar shows level 4 charging with use case 2.

Table 11: *Results from the various smart charging algorithms*

Charging Level	Power	Style	Limit	Flex	Peak Power	Peak relative to 900 MW limit	Peak Power + trucks
0	Distr.	N/A	N/A	None	143 MW	15.8 %	143 MW
0	3.7 kW	N/A	N/A	None	39 MW	4.3 %	44 MW
0	22 kW	N/A	N/A	None	218 MW	24.2 %	218 MW
1	N/A	Standard	1.0	None	20 MW	2.2 %	30 MW
1	N/A	Standard	0.5	None	13 MW	1.4 %	27 MW
1	N/A	Planned	1.0	None	14 MW	1.6 %	32 MW
1	N/A	Planned	0.5	None	14 MW	1.6 %	32 MW
4+0	Distr.	N/A	N/A	UC1	72 MW	8 %	80 MW
4+0	Distr.	N/A	N/A	UC2	143 MW	15.8 %	143 MW
4+0	3.7 kW	N/A	N/A	UC1	24 MW	2.7 %	43 MW
4+0	3.7 kW	N/A	N/A	UC2	37 MW	4.1 %	44 MW
4+0	22 kW	N/A	N/A	UC1	109 MW	12.1 %	109 MW
4+0	22 kW	N/A	N/A	UC2	218 MW	24.2 %	218 MW
4+1	N/A	Standard	1.0	UC1	19 MW	2.1%	29 MW
4+1	N/A	Standard	1.0	UC2	20 MW	2.2 %	30 MW
4+1	N/A	Standard	0.5	UC1	11 MW	1.2 %	28 MW
4+1	N/A	Standard	0.5	UC2	12 MW	1.3 %	28 MW
4+1	N/A	Planned	1.0	UC1	14 MW	1.6 %	33 MW
4+1	N/A	Planned	1.0	UC2	14 MW	1.6 %	33 MW
4+1	N/A	Planned	0.5	UC1	14 MW	1.6 %	33 MW
4+1	N/A	Planned	0.5	UC2	14 MW	1.6 %	33 MW

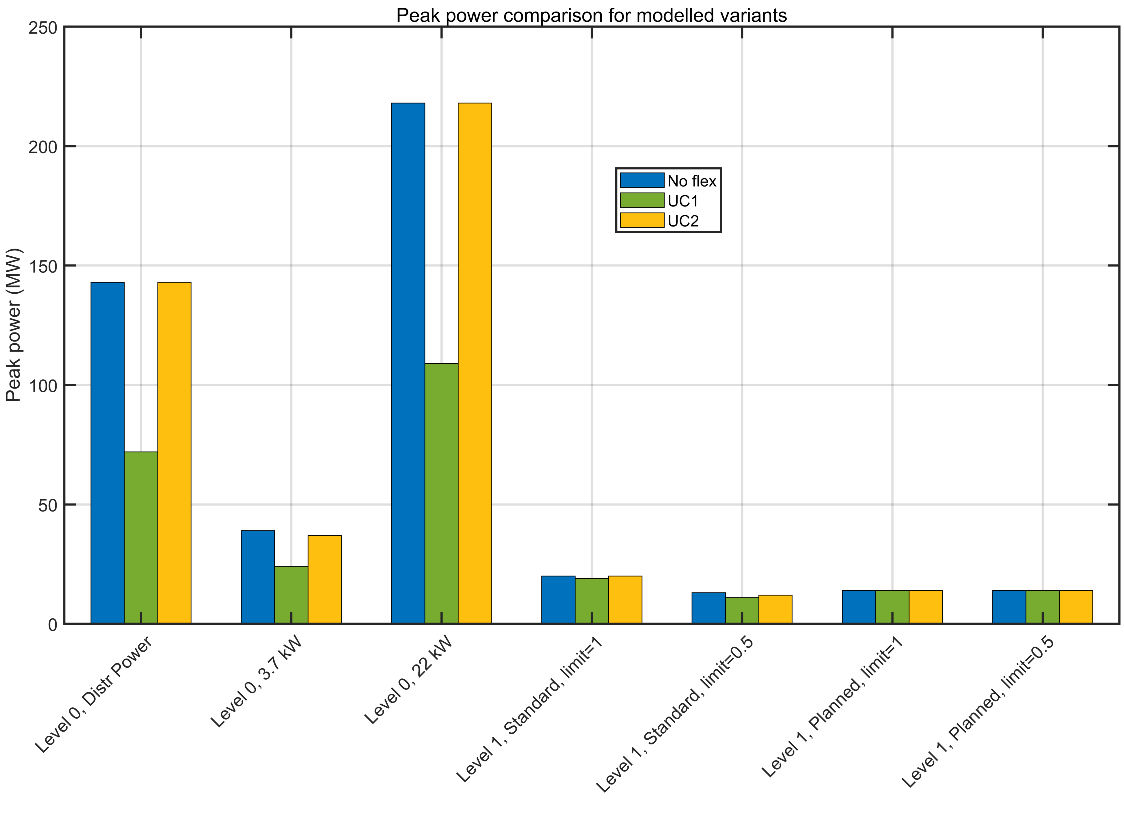

Figure 6: *Results from the various smart charging algorithms in a bar-style graph*

4.1.2 Heavy transport

For 30% market penetration of chargeable light and heavy trucks, the total charging energy consumption by hour is shown below in figure 7.

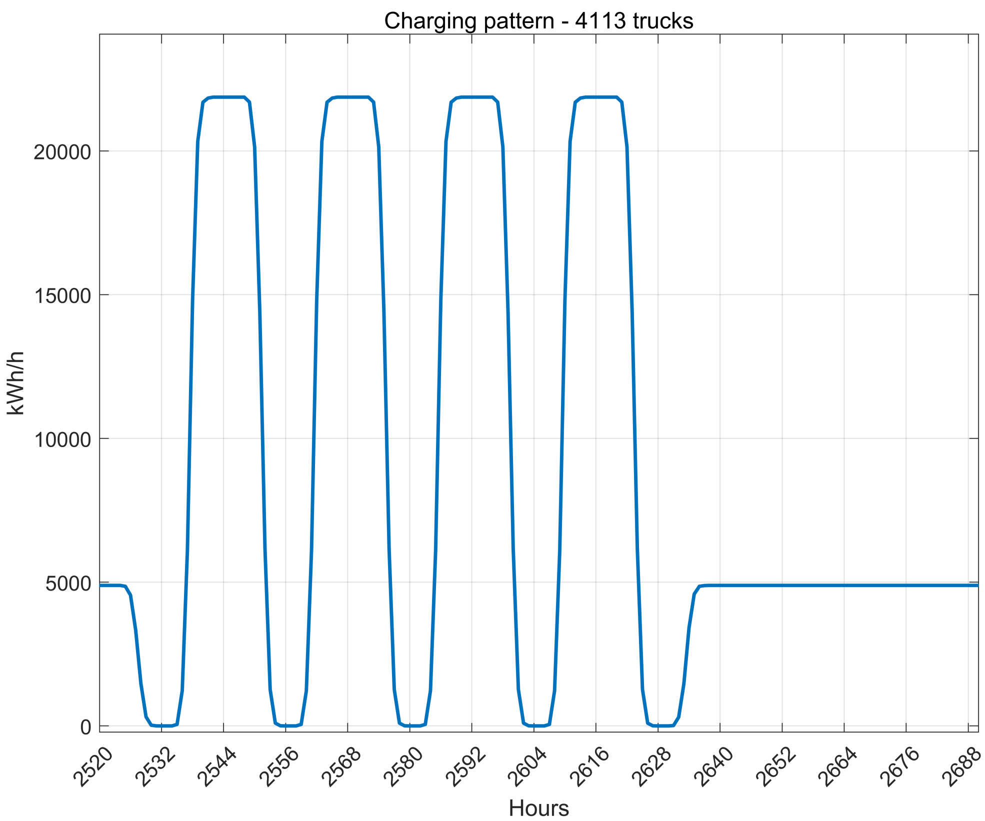

Figure 7: *Charging consumption of light and heavy trucks*

4.2 Case study Parkering Malmö

Below in table 12 is shown the evaluation of the smart charging tests in March 2020. Each test is marked with date and time, as well as the total charging power in the time slot before the tests execution. Reduced power, reduced relative power, and added power (from charging sessions with start time within the tests time slot) is shown together with the previously performed analysis, which used aggregated power across all chargers. To illustrate typical charger behaviour during reduction periods, figure 8 shows the average power (each time slot, 15 minutes) during the testing period 23 March 9-11 for chargers with ID: 2988, 2983, and 2991. Also in the figure is marked the testing period in which reduction of charging power may occur. Note that because of control software operating using Finnish time, time markers are shifted by one hour backwards.

Table 12: *Results of smart charging test evaluation for March 2021*

Date	Time	Ongoing Power	Reduction factor z	Reduced Power	Reduced Power (%)	Added Power	Reduction Initial analysis
22 March	9-11	79 kW	50 %	18.5 kW	23.4 %	16.5 kW	N/A
22 March	17-19	N/A	50 %	27 kW	N/A	27.5 kW	2 kW
23 March	9-11	92 kW	50 %	37 kW	40.2 %	6.4 kW	14 kW
23 March	17-19	29 kW	50 %	4 kW	13.8 %	21.3 kW	-1 kW
24 March	9-11	N/A	50 %	29 kW	N/A	12.5 kW	17 kW
24 March	18-19	29 kW	50 %	6 kW	20.7 %	17.2 kW	2 kW
25 March	9-11	87 kW	35 %	36 kW	41.4 %	13.2 kW	12 kW
25 March	17-19	40 kW	50 %	16 kW	40.0 %	13.8 kW	14 kW
26 March	9-11	65 kW	54 %	37.5 kW	57.7 %	16.4 kW	21 kW
26 March	17-19	32 kW	60 %	26.2 kW	81.9 %	8.7 kW	8 kW
29 March	17-19	14 kW	70 %	2 kW	14.3 %	32.4 kW	N/A
30 March	9-11	78 kW	39 %	34 kW	43.5 %	25.8 kW	N/A
30 March	17-19	N/A	N/A	8 kW	N/A	19.4 kW	N/A

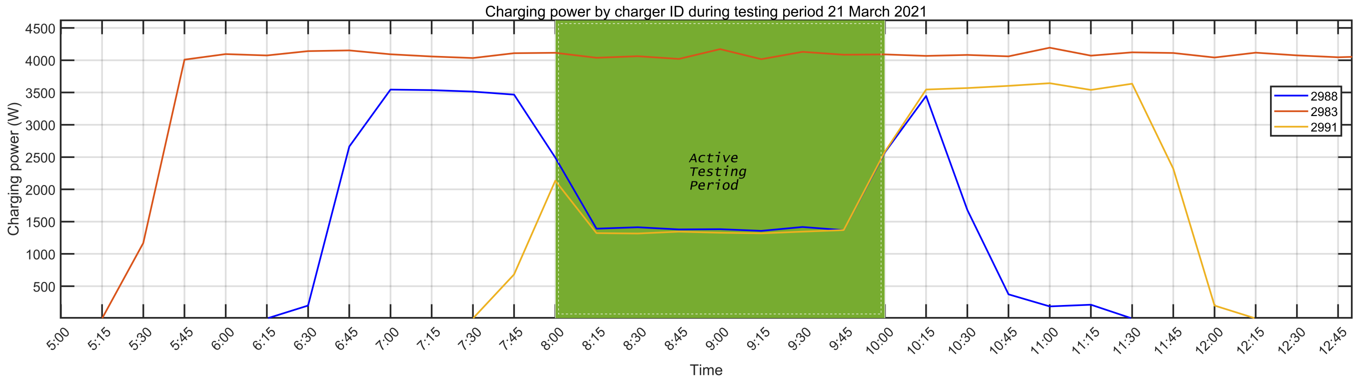

Figure 8: *Charging power for chargers ID: 2988, 2983, 2991, during testing period 23 March 2021 9-11*

5 Discussion

5.1 Future scenario

5.1.1 Level 0 and Level 1

Looking at level 0 results in table 11, it is clear that lowering charging power can have great impact, even if no smart or flexible solutions are used. Worst case scenario is achieved when all vehicles only have access to 22 kW chargers, with a peak of 218 MW. An 82% reduction in peak power (to 39 MW) is possible just by lowering constant charging power to 3.7 kW. This is somewhat expected since assigned charging power also is lowered by approximately 82%, and similar behaviour at similar times is expected for level 0. It is likely in many cases that 3.7 kW for one hour is all that is needed, since the level 0 algorithm infers vehicle charging occurs as soon as the battery level falls below 100%, which it will do regardless of journey length.

Comparing with the real distribution of chargers in level 0 (peak at 143 MW, we will consider this as the base case), level 1 charging (using scheduling and planning) also contributes some impressive reductions in peak power, approximately 90% for all variants.

Using the standard style, i.e when using all available charging time to fully charge the battery, peak power varies with what limit is used, with 20 MW for limit = 1, and 13 MW for limit = 0.5. When using limit = 0.5, charging may only occur after battery level has dropped below 50% capacity. Since cars will reach this threshold at different times because of the individually modelled driving pattern, not all cars will have to charge at the same time. This should result in lower peak power, which indeed it does.

Using the planned style, the battery is no longer charged to 100% when possible or desired. The total charging energy for one session is instead dependent on how long the next trip is (i.e how much energy is required), which means that the limit parameter will have little to no effect. This is because as soon as all cars have gone below the set limit, they will thereon after charge only what they need, independent of the actual value of limit. The results verify this, as both options with limit = 1 and limit = 0.5 gives a peak power of 14 MW.

5.1.2 Level 4

The best case scenario is found when using level 4 charging combined with level 1 (standard style, limit = 0.5, with UC1) for a peak power of 11 MW, a 92% reduction compared to the base case. However, the effectiveness of using level 4 charging is not given. For starters, only level 4 charging using UC1 (see section 2.2.4.6) conditions seem provide relevant reduction.

When combined with level 0 charging, UC1 conditions result in an approximate 50% peak power reduction. This is true when using the real charging distribution (see table 3) and when using 22 kW, but not for 3.7 kW which only resulted in a 38% reduction. This is somewhat unexpected since all power should be lowered with 50% no matter what the numerical values. But when comparing figure 10 (level 0 with 3.7 kW) with figure 18, (level 4+0 with 3.7 kW and UC1) both which can be found in appendix A, possible answers arise. Since lower power is used, more time may be needed to fully charge some vehicles, possibly resulting in hours where the 50% power reduction is counteracted with a higher number of active charging sessions. The reason this does not appear for the base case and the 22 kW case might be that when 50% power reduction is performed, power is still high enough to finish the charging session in fewer hours (or perhaps as soon as the first hour).

Effects of UC1 diminish greatly when combining level 4 charging with level 1 charging, although some reduction in peak power may still be observed. The reason for this might be that level 1 charging in many cases already utilizes power close to the limit of 1.38 kW (6 A), which is the lower internal limit for vehicle charging. In such cases, further power reductions will not be possible as they are capped at this lower limit.

Using UC2 in this model has little to no effect at all. Reduction in power using these conditions only occurs for two combinations with level 4, level 0 charging with 3.7 kW, and level 1 charging with standard style and limit = 0.5. Although there is some reduction, it is in the range of 5-8%. The ineffectiveness of UC2 across all variants is probably because of the the time condition. For reduction with UC2 to occur, the charging session of concerned vehicles must have been going on for at least one hour (and have acquired at least 2 kWh of energy but it is not likely this is the main constraint). This has two main consequences. First, in many cases charging sessions might be finished after only one hour (especially with regards to level 0 using higher power), which means reduction will not take place. Secondly, since vehicles are allowed to use full power that first hour before the reduction kicks in, the main peak will still be unaffected, if it is centered around that first hour.

5.1.3 Levels comparison

While level 4 charging solutions such as grid signals may indeed help lower peak powers for vehicle charging, the greatest effect comes with the introduction of level 1 charging solutions, such as scheduling and planning. Solutions implementing these strategies are easy to imagine. For example, when plugging in a vehicle for charging, an app on the users smartphone connected to the charging solution may ask when a user wants to use the vehicle again, and how far the next expected journey will be. Such a system may also be integrated into the vehicle itself for increased usability for customers with no smartphone access.

Implementing features such as the limit parameter is perhaps less of a technical challenge, and more of an educational one. Training vehicle users in how to optimally use and charge their vehicle might be an important factor in the transition to chargeable vehicles. In some ways such training already exists. When using a regular gas driven vehicle, fuelling is only needed when the level of gas is low enough. For BEVs especially, much of the same behaviour seems to be beneficial in terms of reducing peak power, except charging can not be completed as fast as regular fuelling. The incentive for consumers to lower their overall charging power also already exists in some ways. Lower power means less stress on the battery, prolonging its life and performance in the long term. If charging is mainly done at home, it may also avoid unnecessary fuse upgrades (which would mean higher monthly costs), especially when combined with level 2 solutions such as load guards, and level 3 solutions such as electricity spot price signals.

The assumption that all vehicle users are behaving and charging in an optimal manner to help relieve grid peaks the way they are doing for level 1 may however be unrealistic, and some nontrivial amount of level 0 charging behavior might still occur. The potential for level 4 charging solutions to reduce peaks will then still be substantial, if enough assets can be aggregated to allow market participation.

5.1.4 Heavy transport

Optimization of charging of light and heavy trucks is a somewhat less complex problem, assuming all trucks return to the same home terminal each night. Since operation of many trucks is largely the same day to day, a consistent peak power of approximately 22 MW is present during weekday nights, and a longer peak at 5 MW during weekends. When cars are mainly utilizing level 0 charging, they dominate the peak power, since they often charge mostly right after arriving for work or when arriving home, while trucks mainly charge during nights. However, as cars utilize more and more level 1 and level 4 solutions (many times shifting charging into the night hours), peaks will increasingly be dominated by truck charging. The total peak (together with cars) will in most of the evaluated scenarios settle at around 30 MW, which would be 3.3% of of the 900 MW subscription limit.

Due to the plannable nature of truck operation, level 2 charging solutions such as local production and storage are easily deployed to avoid large fuse upgrades. For freight terminals and other similar industrial building, local production might be especially interesting, since roofs of such buildings often are flat, and located in non shaded areas, all key enablers for solar cells.

Once these types operations have been cost optimized using level 1 and level 2 (or even level 3 solutions, planning charging for when lowest price of electricity is available) solutions, there might be little room left for inclusion of level 4 solutions. In the case where trucks charge their required daily energy each night, no further reductions in power are possible. However, if grid operators favor a higher peak at certain hours, charging could potentially be stopped entirely for hours which are critical for the grid. Higher powered charging during non critical hours could then be used to compensate energy needs, but only if local infrastructure allows for it.

5.1.5 Possible model improvements

There are several aspects to consider when evaluating the accuracy of the developed model. Hourly resolution was chosen for its simplicity and data availability. However, vehicles or people do not operate on a hourly basis. The model does not for instance have any way of discerning whether a charging session started or ended in the middle of a certain hour. Using higher time resolution would probably more accurately represent vehicle behaviour and their charging needs. It is possible that this would result in lower peak power for some variants. Going all the way down to second by second would have produced very high resolution, but might have resulted in diminishing returns comparing to minute by minute resolution. This was however never considered, since the base of the model, the travel survey by Region Skåne for 2018, uses hourly resolution [44]. Any minute resolution based behaviour would then have been pure guesswork.

The use of the travel survey may also influence results. To estimate charging needs from cars in the municipality of Malmö, all journeys with a destination in Malmö are included. This means work commuters are included when going to Malmö, but not when going home. This is probably the main reason for the very high usage peak present in the mornings (see figure 5). However, since travel data is extrapolated into probabilities, there are vehicles representing commuters that still have a non-zero chance of being included in the "home-journey"-set in the afternoons. In reality, this is not possible. It is possible that this is counteracted by the opposite type of work commuters, i.e the ones living in Malmö but working in another municipality. Thus, this consideration might not be a substantial issue contributing to model inaccuracies. Additionally, the model assumes regional travel patterns to be constant (i.e the same 2018 and 2030). It is possible that car usage will change substantially, for instance with increase usage of community car pools, biking, public transport, or flexible work-hours. In such scenarios, it is possible charging infrastructure demands will be lower that what is presented in this report.

Assumed charging behaviour may also be a source of inaccuracy. For starters, users are assumed to have the possibility and desire to charge their vehicles whenever parked, which might not be realistic. This is done so that potential for smart charging could be evaluated without regards to chargepoint availability, which would have added considerable complexity. Some users might for instance only have access to their home charger, while others might rely upon public charging stations. Some data on user proclivity to start charging their vehicle certain hours could probably be used to increase model accuracy, perhaps shifting the main peak to afternoons if users are more inclined to charge their vehicles at night.

Using level 1 smart charging solutions, lowering the limit parameter to 0.5 does decrease peak power. Further lowering of this parameter could possibly give even lower peak power. Additionally, a variant which is not tested but might be interesting is using a limit parameter for level 0 charging. Users would then wait until a certain battery capacity is left, and then fully charge their vehicle with the maximum power available to them. This variant, along with additional testing of different values for parameters were ultimately omitted due to time constraints. Along with testing of additional parameters and behaviours (such as operating according to price signals), introduction of V2G solutions and their impact on grid operations could be focus points in future work. Additionally, applying this type of model for level 2 (property optimization) or level 3 (for instance optimizing for cost of charging each vehicle, perhaps with real world data) charging solutions could also be interesting.

5.2 Case study Parkering Malmö

5.2.1 Main evaluation

The results from evaluating the Parkering Malmö smart charging tests in March show that reduction of peak power did occur. When looking at reduced power and added power, the expectation is that the difference between the two would equal the results from the initial analysis (which used the total aggregated data). In some instances this expectation holds more true than in others. For example, the ”24 March 9-11”-test shows a reduction of 29 kW, and an addition of charging sessions corresponding to 12.5 kW. One would then expect the difference between them, approximately 17 kW, to equal the results from the initial analysis, which indeed it does. But there are also cases where this is less accurate, as with the ”24 March 18-19” -test. The discrepancy in these comparisons is possibly best explained by the manual nature of the way the evaluations are performed. If a more automated way of evaluating reduced power had been available, then this discrepancy might not exist.

Evaluating delivered flexibility is key for capacity markets such as Switch to operate with success. Using aggregated data to analyse the total reduction in power is however not the best way of evaluating power reductions for flexibility market purposes. The only column that really matters is the reduced power, since it represents how much higher the power would be if flexibility of this sort was not utilized. But the way the evaluation is done for this thesis (manually for every charger) is probably not an optimal or time efficient solution, especially if the project is to be expanded with more chargers included. Using the $i_{reduced}$ variable available for every time slot through the control system VPP could provide an easy and fairly automated way of evaluating power reduction. Additionally, running VPP in a ”read-only” mode allows for the flexibility potential to be displayed in real time, for each time slot. Deploying this feature to interested charging infrastructure entities would be a way for them to evaluate their flexibility potential as new FSPs (flexibility service providers). The accuracy of VPP, through its $i_{reduced}$ variable, to provide such a service could likely be evaluated if VPP logs and individual charger logs are available for the same testing period.

Another way to better evaluate similar projects in the future would be to change the way VPP operates. Instead of setting a current ceiling $i_{reduced}$ for all chargers combined, VPP could perhaps control each charger individually. This could allow for very easy validation of flexibility delivery since each charger is tracked and controlled individually, thus avoiding the issue of the load balancing system having control beneath the current ceiling presently implemented.

Figure 8 shows three examples of charger behaviour during reduction periods. The blue curve, representing charger 2988, shows a common and typical behaviour. Nominal charging is carried out at roughly 3.5 kW for about 1.5 hours. By the time the reduction period is active, charger 2988 has been put into the *reduced* group of chargers, since the UC2 conditions have been fulfilled (see section 2.2.4.6 for details). After the reduction period, charging power ascends to its nominal state briefly, before reducing again at the end of the charging session. Whilst doing the manual evaluation, the rise back up to nominal power is recognized as a key identifier that reduction have taken place.

The yellow curve in figure 8, representing charger 2991, displays similar behaviour. However, this charging session commences much closer to the start of the reduction period. At the start of the reduction period it displays the same reduction as the blue charger (number 2988), but it should not, according to UC2 conditions. The charging session was not active for at least one hour before it was reduced, which is the time condition. The condition requiring 2 kWh to have been transferred might have been met, since power values are averaged over the previous 15 minutes. This type of early activation was common throughout the tests. One explanation could be that a mistake in the code makes it so that both conditions are not required to be eligible for reduction. Additional evaluation could aim to investigate this. Another topic for additional evaluation are examples like charger 2983 (represented by the red curve in figure 8), where reduction according to UC2 conditions clearly should have taken place, yet no such reduction seems to have executed.

5.2.2 Incentives and obstacles

Participating with grid flexibility on markets such as Switch includes some challenges for charging infrastructure actors. As previously mentioned, the ability to accurately evaluate delivered flexibility is key. Control systems such as VPP can potentially be deployed to help FSPs within charging infrastructure with this.

Predictability is another issue. Typical FSPs such as large industries have a predictable and easy way of knowing and planning how much power and energy they will consume an upcoming day. For charging infrastructure FSPs, it is much more difficult knowing how much reduction is possible, since it is hard to know for certain how many cars will need to charge an upcoming day (although intra-day is also possible on Switch). While this is certainly true for individual chargers, it is possible that if enough chargers are aggregated, standard patterns in behaviour will emerge. Actors like Parkering Malmö are well suited to operate as such aggregators, controlling a large amount of parking spaces which could be potential charging points. Easier predictability of available flexibility resources may potentially increase the desirability for charging infrastructure assets to participate in flexibility markets.

Not only flexibility markets such as Switch are suitable for smart charging participation. The market for ancillary services provided through Svenska Kraftnät is also a possible option. Participation here instead targets the stability of the national grid, instead of local capacity issues. However, no practical difference (except for specific participation requirements and possible administration) exists for FSPs, since in both cases temporary reduction of power is what is delivered. Already there are companies like Krafthem providing this service for the FCR, but the mFRR (see section 2.2.4.1) may also a be a good fit for aggregated flexibility assets.

Different types of rates for charging purposes may incentivize certain behaviours. Often when discussing smart charging, the topic of charging power is often more prioritized over charging energy. The charged energy may be the same independent of how fast said energy is transferred (i.e power). Thus, energy based rates (see section 2.1.4.1) does not have any means incentivize customers in lowering their power usage. If paired with external signals such as electricity price however, they may however incentivize shifting charging to times of low price (perhaps nights). If power reduction is the desired target, time base rates will equally not be beneficial. Time based rates will instead incentivize raising charging power to shorten charging session duration. A lump sum system might be convenient for the customer, it has the possibility of incentivizing customers to use their vehicle as much as possible, in order to lower the price per kilometer, and thus might not be desirable from an energy system optimization standpoint. If charging energy is assumed constant for a certain charging session, power reduction is possible by lengthening the duration of said session. A monetary incentive to do so could be to introduce power based tariffs (higher powered charging equals higher price). The proposed development of the future scenario also considering level 3 solutions (i.e external signals) could evaluate such tariffs.

The smart charging demonstration with Parkering Malmö is an example of a level 4 solution. However, as the future scenario section of this thesis shows, lower levels (i.e level 1) may also be considered to lower grid loads. Already, Parkering Malmö has multiple level 2 solutions installed, such load guards and load balancers. Along with local production and storage, these types of solutions can help not only with lowering of costs such as fuse fees, but also helps the grid indirectly, by lowering capacity requirements. Once a certain capacity has been installed however, level 4 solutions may well be implemented to help the grid when experiencing critical loads.

Also as shown, level 1 solutions can have a huge impact on peak power. Although incentives for customers to use scheduling to to lower peak charging power exists (lower charging power increases battery lifespan), monetary incentives could also possibly be deployed, perhaps as a tariff based on peak power usage. The use of level 4 solutions need not perhaps be permanent features of charging infrastructure, nor completely dismissed, but maybe rather only deployed a few times a year when grid conditions are at their worst. The evaluation done in this thesis show that significant reduction in power can be had using UC2 conditions, and while not evaluated in the same manner, UC1 conditions are likely to be effective as well.

Evaluating what value was created through the use of flexibility in the smart charging demonstration with Parkering Malmö is one of the goals for this thesis. While the technical value in terms of power reduction and operation has been evaluated, assessment of *monetary* value of delivered flexibility, and flexibility in general, was omitted. Such assessment could be the focus point of similar future work.

6 Summary and conclusions

In this thesis electrification of transport and flexibility connected to charging infrastructure for transport purposes is investigated. The number of chargeable vehicles in Sweden is increasing rapidly, especially for cars. While PHEVs have a head start, BEVs are expected to catch up and outpace PHEVs by the second half of the decade. Reaching the national environmental goals of 70% emissions reduction (compared to 2010) for domestic transport by 2030 will require approximately 55% of cars being chargeable. At the same time, some predictions showing 50% chargeable vehicles by 2030, are already being outpaced by growth in chargeable vehicle ownership.

Flexibility, the act of moving consumption or production of energy in time, is a way of dealing with lack of grid capacity. The usage of various kinds of flexibility may allow customers to increase their temporary power usage, expand their business, or utilize local production without having to strain the grid. To accommodate new partnerships and cooperation between grid operators and customers, marketplaces for grid capacity have been developed. Additionally, markets for ancillary services, for instance helping with grid frequency stability, are available through the Swedish TSO Svenska Kraftnät.

Smart charging is the name for flexibility within charging infrastructure. Most often, smart charging includes lowering charging speed (i.e charging power) by reacting to some external signal. Different levels of smart charging can be defined, with level 0 being the default case when charging is done at the highest speed possible, whenever possible. With increasing levels, integration of different strategies, technologies, and solutions, is expanded. Some such solutions are digital services enabling scheduling (level 1), local production and storage of energy (level 2), electricity price signal adaptation (level 3), and participation in flexibility markets (level 4).

In order to evaluate the potential of and need for flexibility in charging infrastructure, a future scenario for 2030 is developed in MATLAB. Assuming 55% chargeable vehicles by 2030 (which reaches environmental goals), vehicle usage and charging behaviour is modelled. Results show that various strategies corresponding to different combinations of smart charging levels produce different peak powers. In the worst case, peak power from vehicle charging reaches upwards of 200 MW (level 0, using 22 kW chargers). In the best case, peak power only reaches 11 MW (level 4+1, utilizing scheduling, and market style flexibility). While most of the charging is done with level 0, the potential for level 4 type market flexibility is substantial, but as level 1 solutions are adopted (such as scheduling, i.e allowing the vehicle to charge the full time parked), the impact of level 4 solutions are diminished. Only utilizing level 1 style solutions, a 90% reduction in peak power consumption is achieved.

As part of the thesis, a smart charging demonstration project performed by E.ON and Parkering Malmö, is evaluated in terms of power reduction and ease of operation. Assessment shows that reduction in power did take place, with varying effect. Influenced by the number of charging sessions meeting conditions for participation, relative reduction varies between 14% and 82%. As more chargers are included into the system through aggregation, more predictability and less variable results may arise. The manual nature of the evaluation performed in this thesis induces some inaccuracy, which could be mitigated by introducing some sort of automated assessment system. One such solution could potentially be to use the control system software VPP developed by E.ON, although further assessment of the accuracy of this method is likely required.

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A Graphs from Future scenario modelling

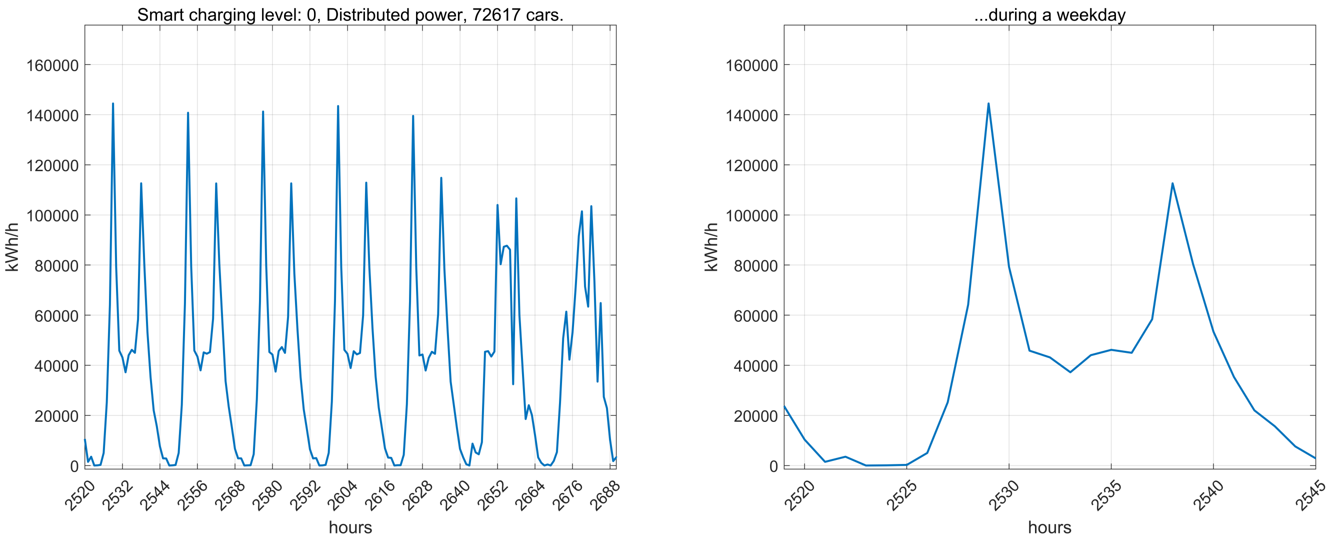

Figure 9: *Level 0 charging with distributed charging power*

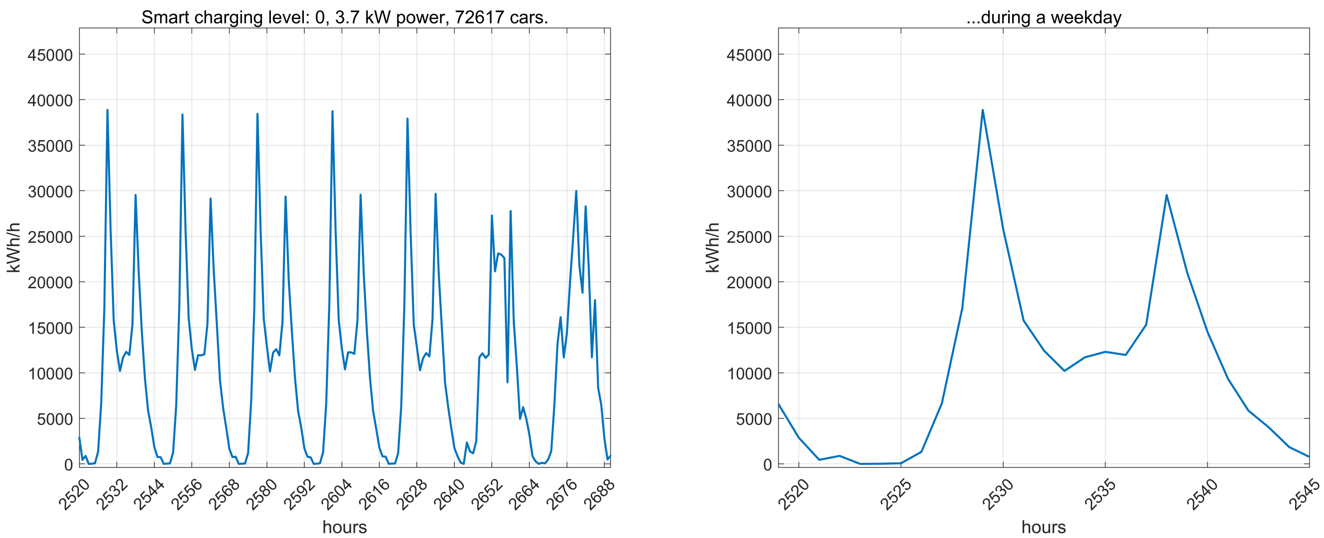

Figure 10: *Level 0 charging with 3.7 kW charging power*

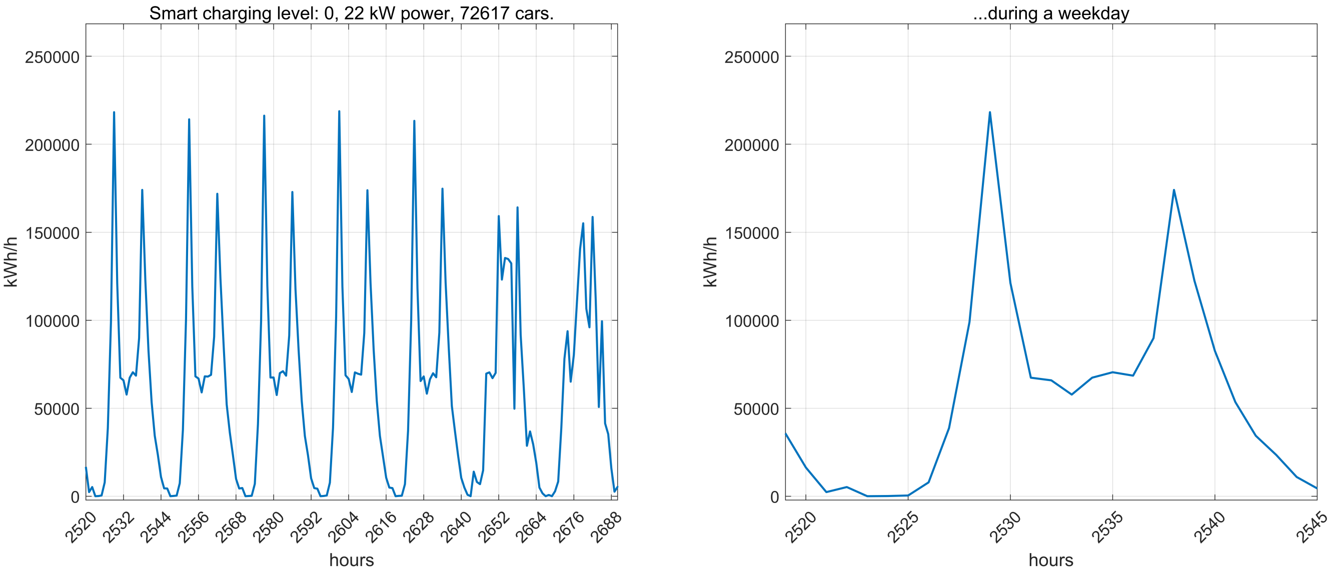

Figure 11: *Level 0 charging with 22 kW charging power*

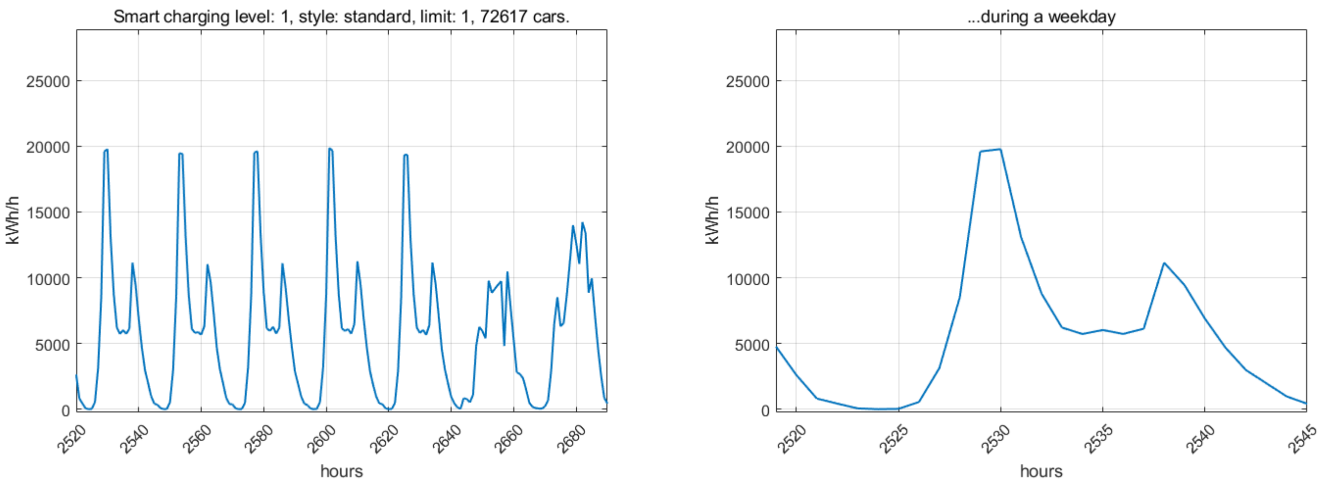

Figure 12: *Level 1 charging with standard style and limit = 1*

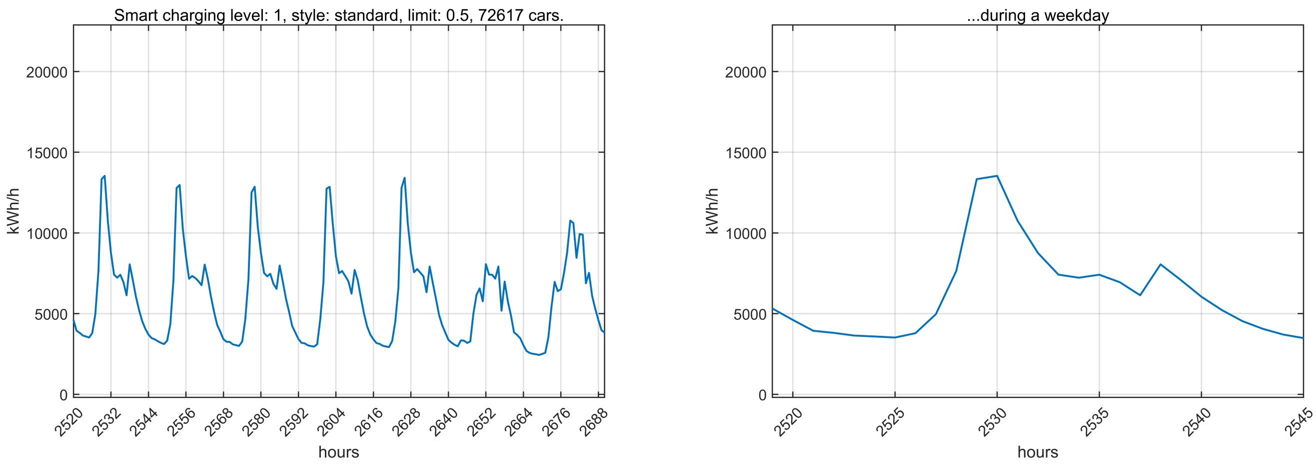

Figure 13: *Level 1 charging with standard style and limit = 0.5*

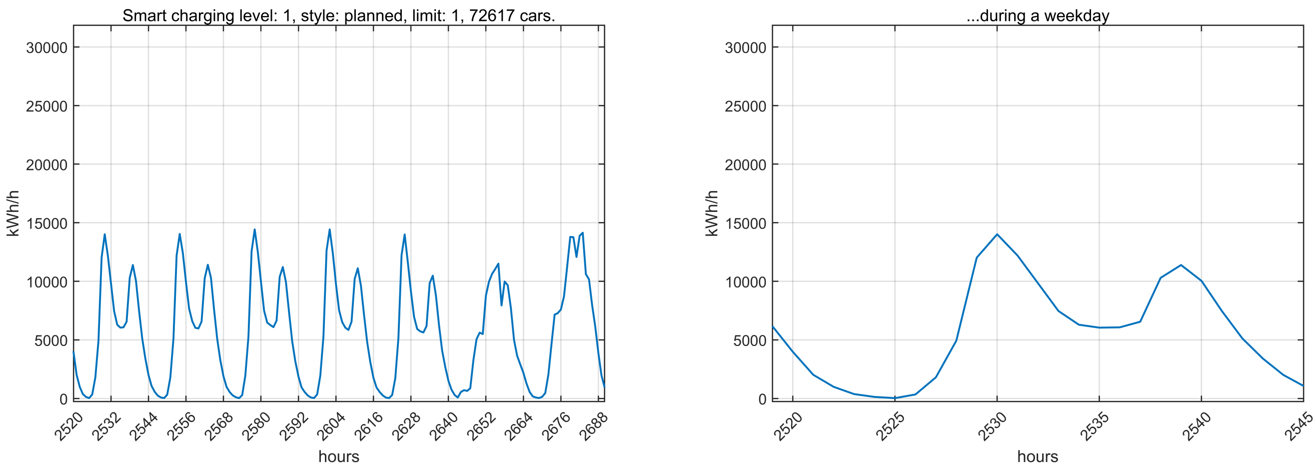

Figure 14: *Level 1 charging with planned style and limit = 1*

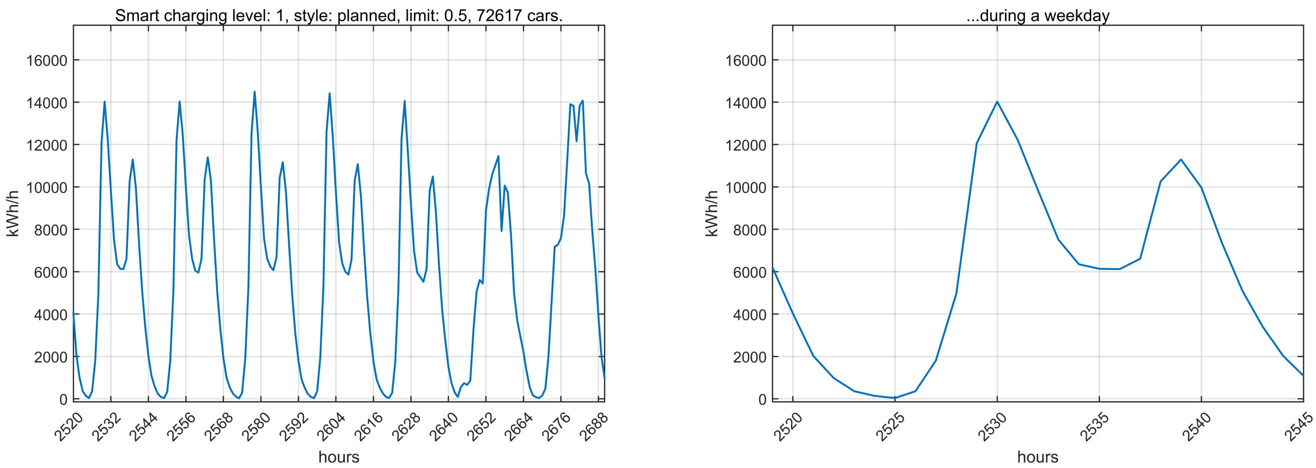

Figure 15: *Level 1 charging with planned style and limit = 0.5*

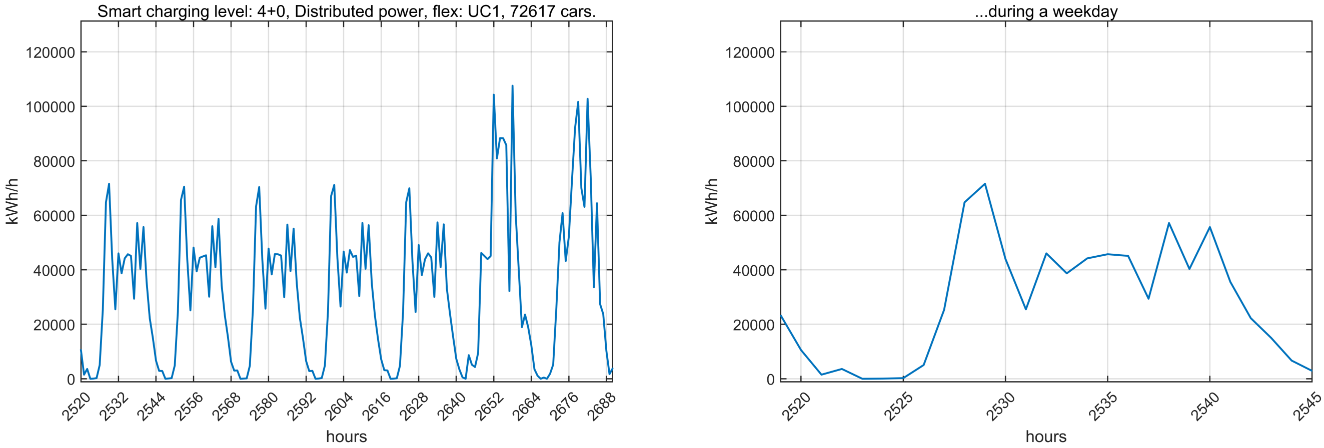

Figure 16: *Level 4+0 charging with distributed charging power and UC1 flexibility conditions*

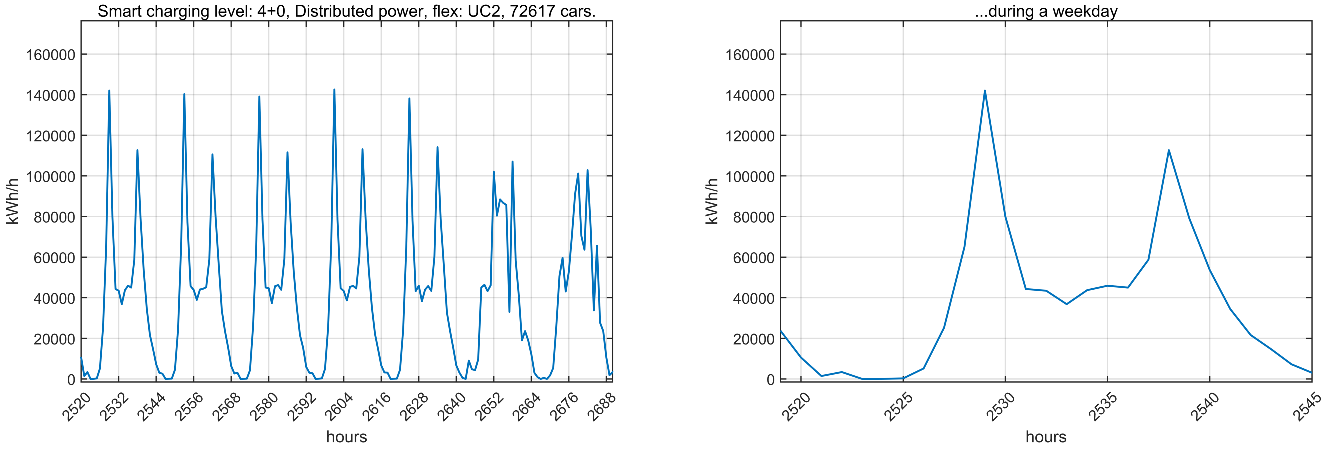

Figure 17: *Level 4+0 charging with distributed charging power and UC2 flexibility conditions*

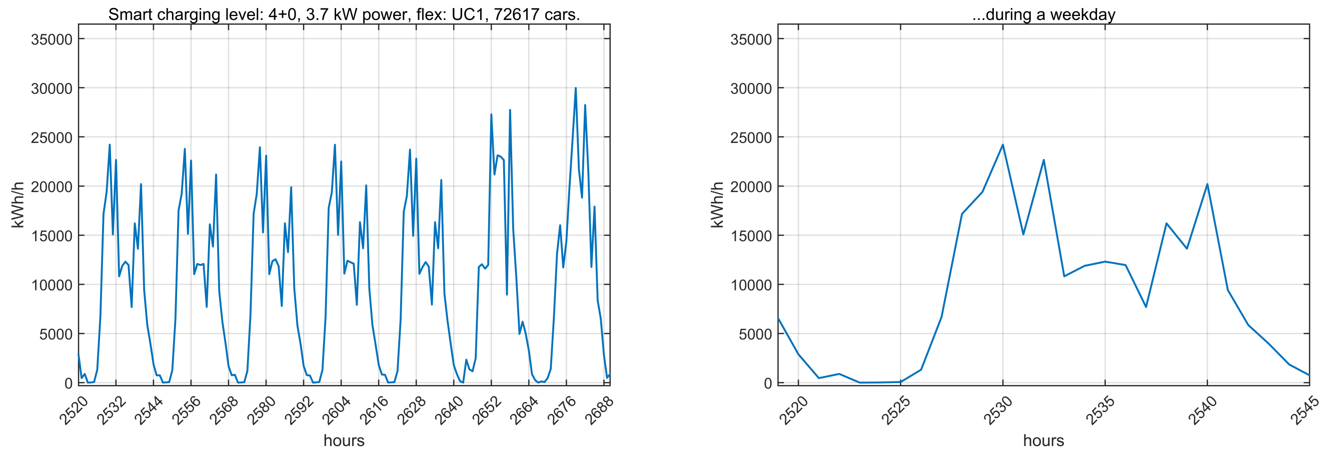

Figure 18: *Level 4+0 charging with 3.7 kW charging power and UC1 flexibility conditions*

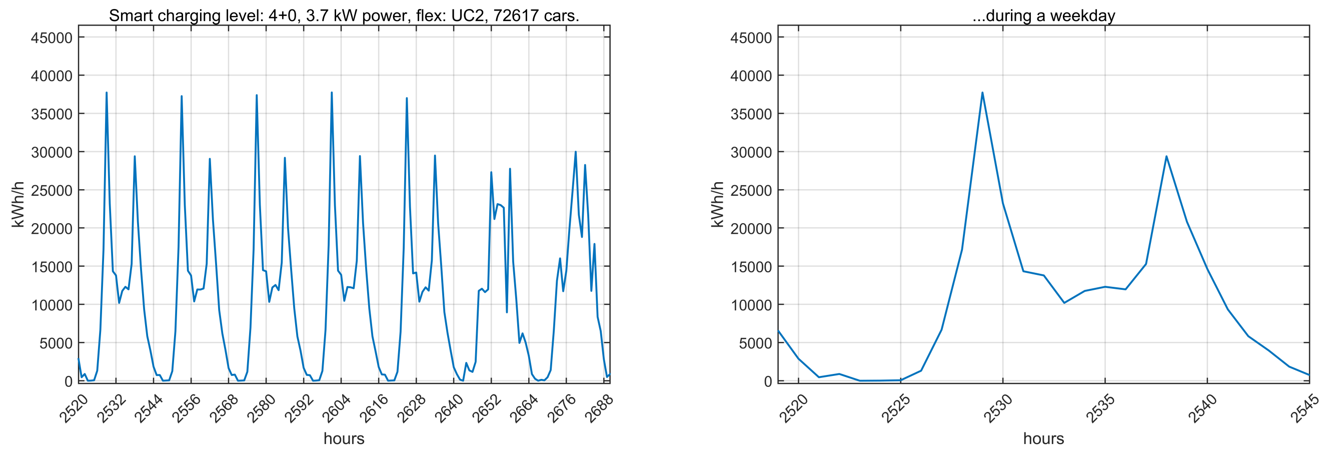

Figure 19: *Level 4+0 charging with 3.7 kW charging power and UC2 flexibility conditions*

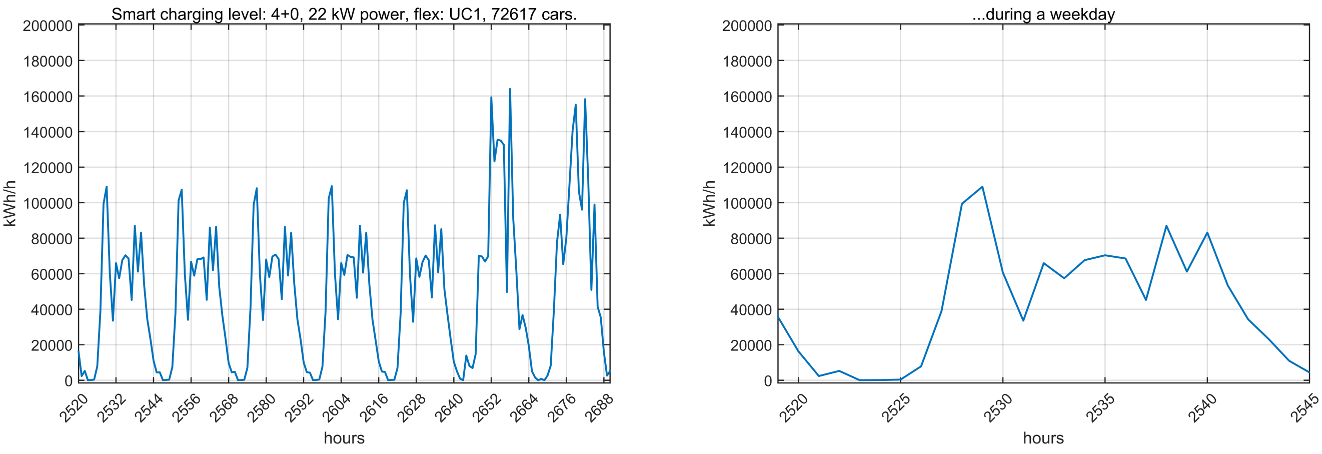

Figure 20: *Level 4+0 charging with 22 kW charging power and UC1 flexibility conditions*

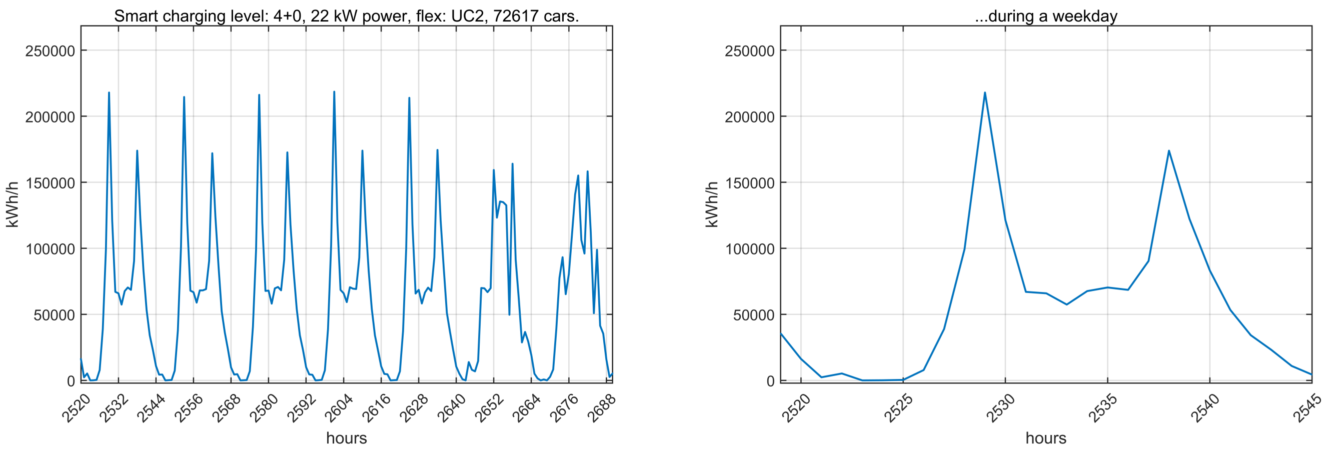

Figure 21: *Level 4+0 charging with 22 kW charging power and UC2 flexibility conditions*

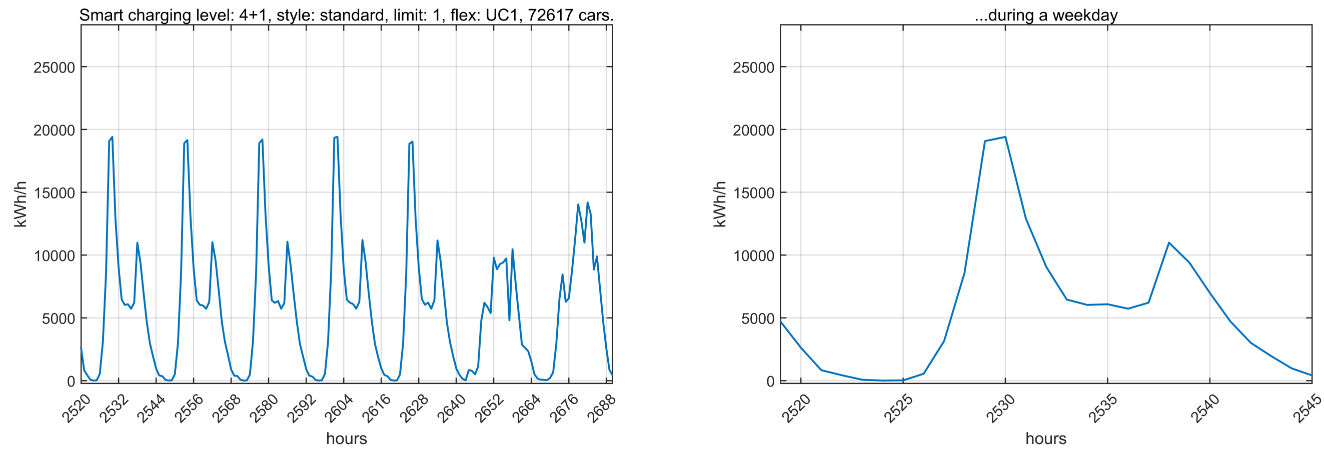

Figure 22: *Level 4+1 charging with standard style, limit = 1, and UC1 flexibility conditions*

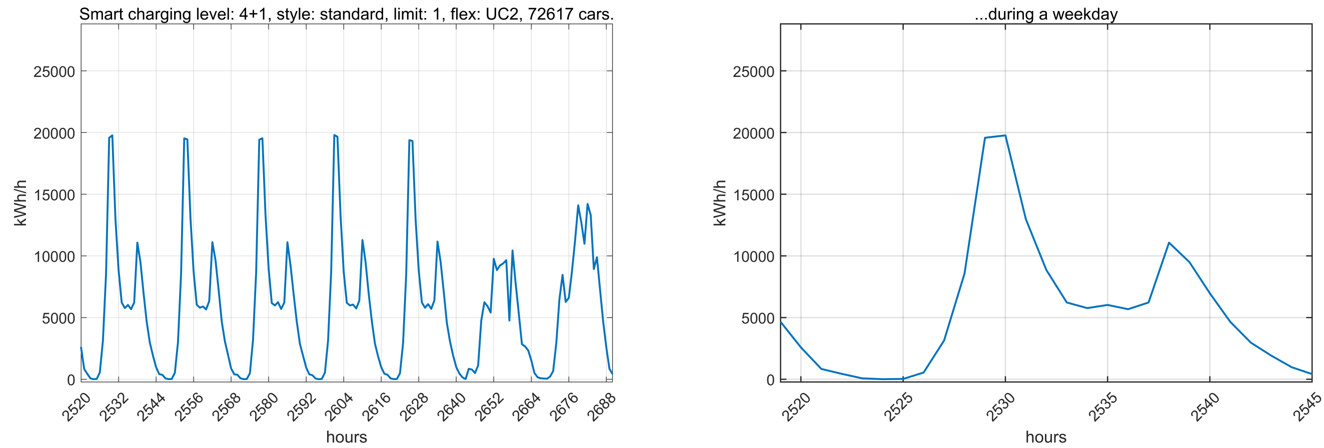

Figure 23: *Level 4+1 charging with standard style, limit = 1, and UC2 flexibility conditions*

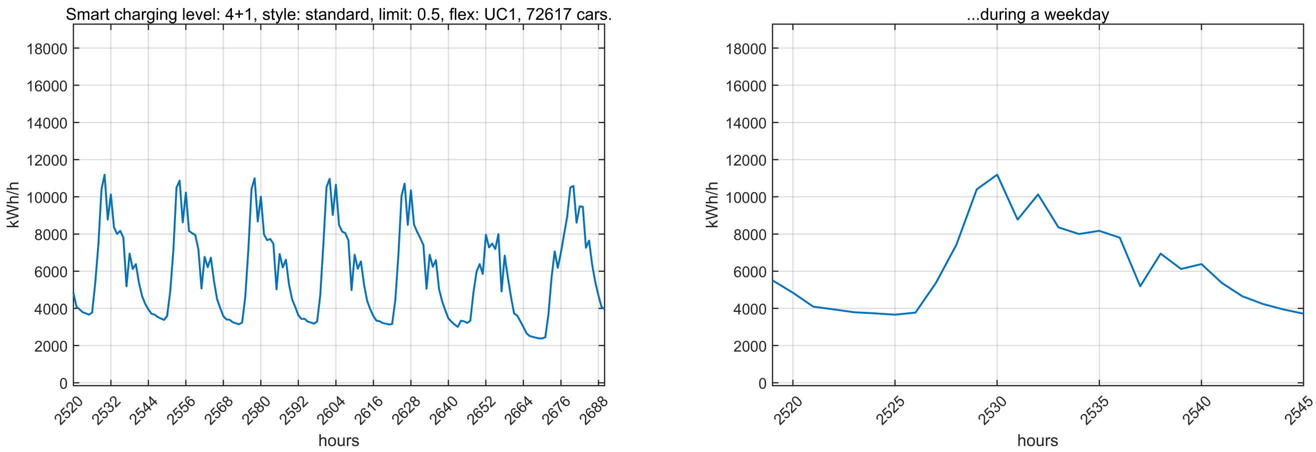

Figure 24: *Level 4+1 charging with standard style, limit = 0.5, and UC1 flexibility conditions*

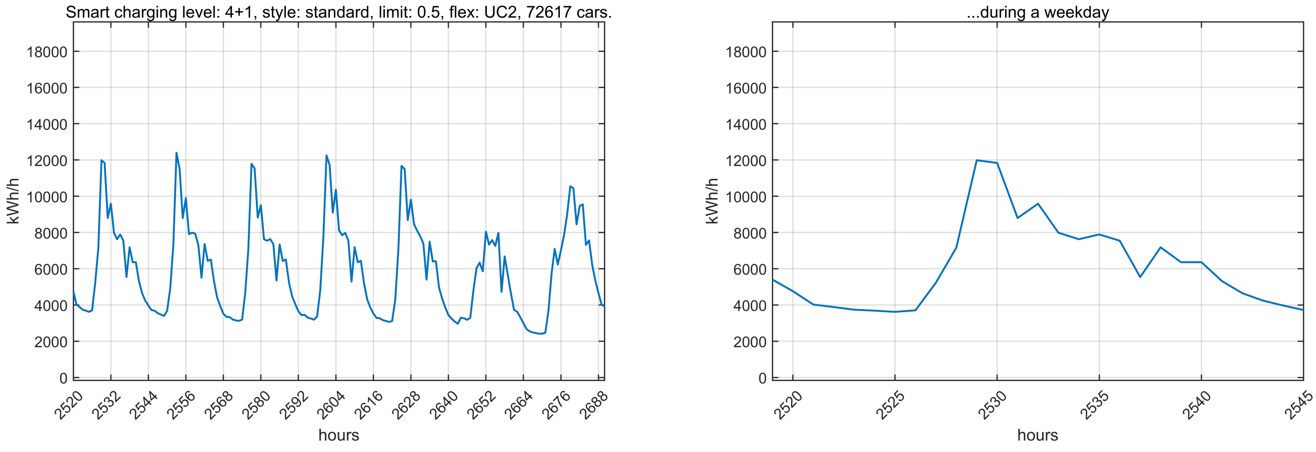

Figure 25: *Level 4+1 charging with standard style, limit = 0.5, and UC2 flexibility conditions*

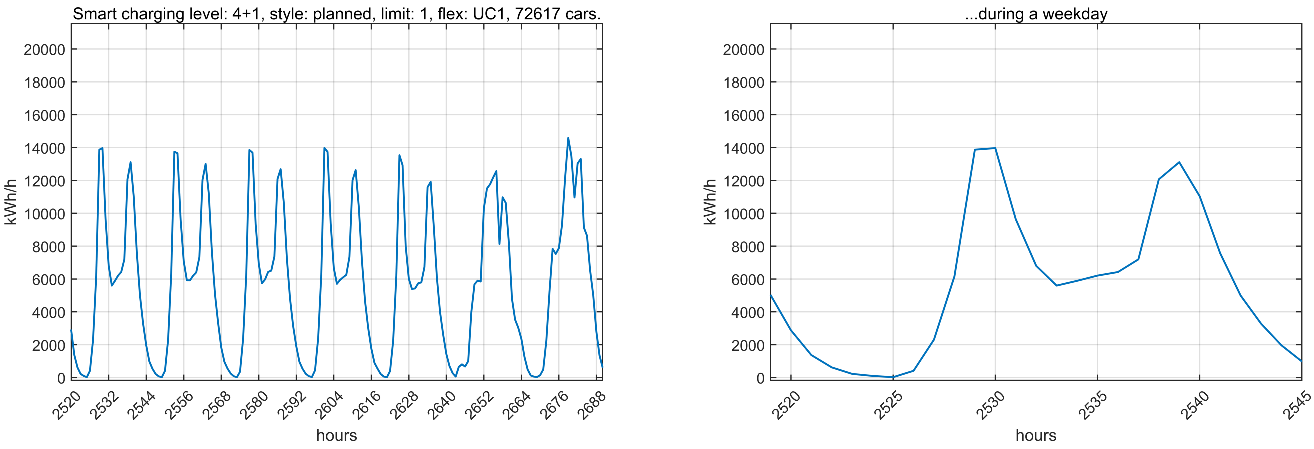

Figure 26: *Level 4+1 charging with planned style, limit = 1, and UC1 flexibility conditions*

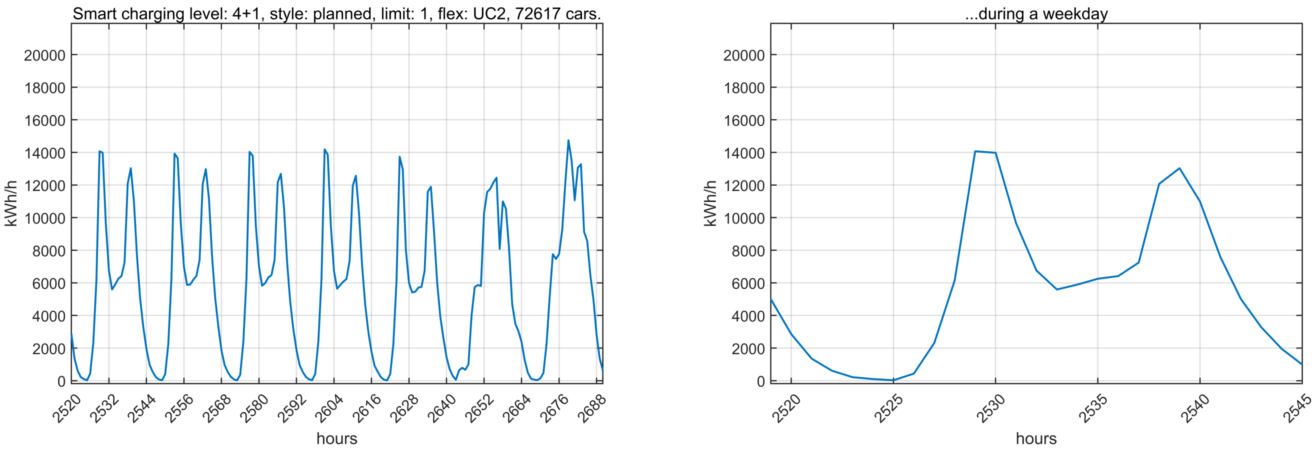

Figure 27: *Level 4+1 charging with planned style, limit = 1, and UC2 flexibility conditions*

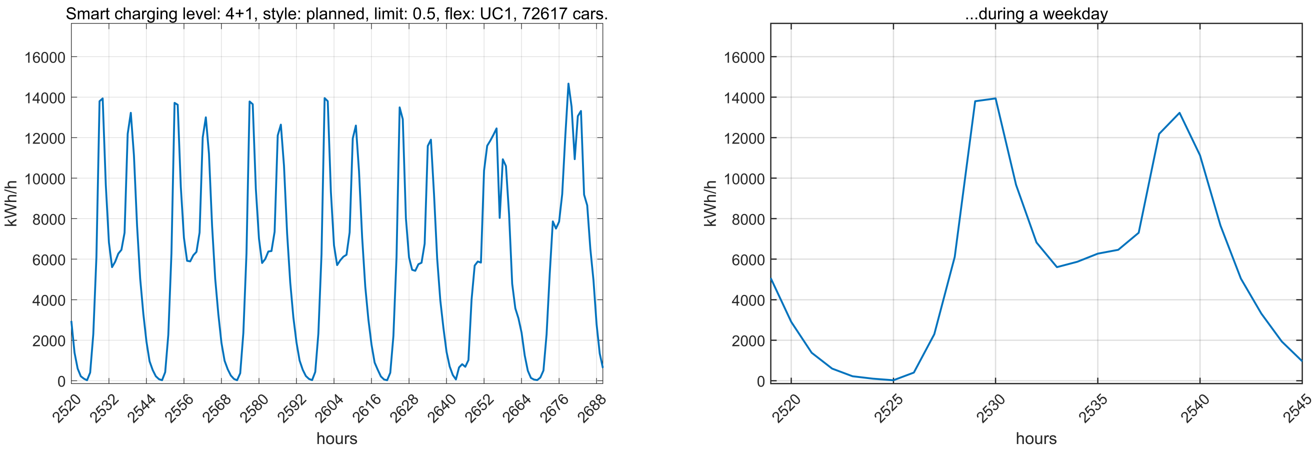

Figure 28: *Level 4+1 charging with planned style, limit = 0.5, and UC1 flexibility conditions*

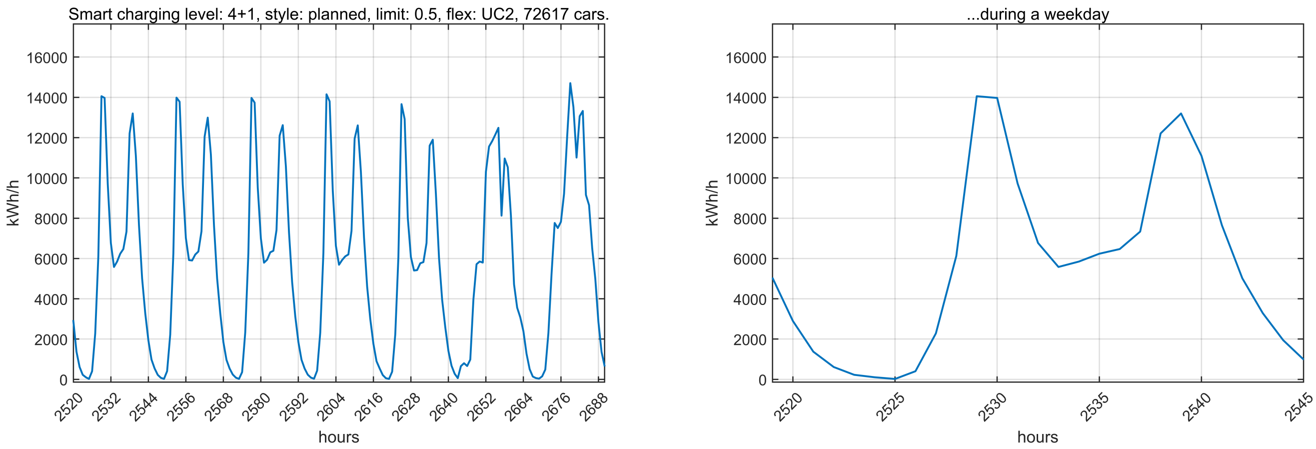

Figure 29: *Level 4+1 charging with planned style, limit = 0.5, and UC2 flexibility conditions*