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D3.7 - Electric vehicles and charging stations roll-out strategy and analysis in Groningen

WP 3, Task 3.6

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Author(s): Christian van Someren (HUAS), Cyril Tjahja (HUAS)

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Abbreviations and acronyms

Acronym	Description
DSO	Distribution System Operator
EV	Electric Vehicle
PED	Positive Energy District

Executive Summary

Electric vehicle (EV) charging at public charging stations is expected to account for a significant portion of Positive Energy District (PED) grid loads in the coming years (Hoekstra & Refa, 2017). It is therefore important to understand the potential impacts of EV charging on the grid to develop a functional PED. In this task, grid impact is defined as by the peak grid load resulting from EV charging.

In this task, the design, monitoring and controlling strategies for the roll-out of public EV charging stations in the North and Southeast PEDs of Groningen is outlined. Using measured EV charging patterns, a model was developed to estimate the impact of public charging stations on the electricity grid in the long term. In addition, different scenarios were modelled to estimate the effectiveness of different charge control strategies at reducing the grid impact from EV charging.

In the Southeast PED, 19 charging stations in a mixed commercial-residential area (Euroborg) were measured from mid-November, 2019, to the beginning of October, 2021. Not all charging stations were initially active, but all were active by September, 2020. During this period, a total of 4,206 charge cycles were performed, delivering a total of 77,790 kWh of electricity. The average plug-in time per charge cycle was 13.6 hours (with an average active charging time of 3.2 hours and an average idle time of 9.1 hours). The average charging station occupancy was 18.9%. The average charge cycle power was estimated at 5.8 kW and the peak load from EV charging in Euroborg was 78.4 kW.

In addition, 14 charging stations in a Park+Ride area (Harm Buiterplein), also in the Southeast PED, was measured from mid-March to mid-September, 2021. During this period, a total of 1,235 charge cycles were performed, delivering a total of 19,493 kWh of electricity. The average plug-in time per charge cycle was 11.6 hours (with an average active charging time of 3.8 hours and an average idle time of 7.8 hours). The average charging station occupancy was 24.2%. The average charge cycle power was estimated at 3.7 kW and the peak load from EV charging in Euroborg was 22.2 kW.

No measurements were taken in the North PED. Instead, EV charging patterns for this PED were modelled based on measurements of EV charging in residential areas of other Dutch cities.

Because most of the measurements taken during this study occurred during periods of COVID-19 lock-down, the measurements were compared with pre-lockdown measurements from other studies and adjusted accordingly. Specifically, rates of EV charging were assumed to 3 times higher in non-lockdown circumstances.

The number of public charging stations in Groningen is expected to increase to 500 by 2023, 1,500 by 2030 and 6,000-8,000 by 2050. As a result, the peak grid load from EV charging is estimated to increase to 3,203 kW by 2023, 9,517 kW by 2030 and 33,000-44,000 by 2050. Notably, if EV charging patterns remain comparable to the measurements, the simultaneity of EV charging is expected to decrease towards 0.5 (i.e., roughly half of charging stations will be active simultaneously).

Finally, three scenarios were modelled to estimate how the peak load from EV charging might be reduced. By limiting the combined load of a pairs of EV charging points, peak load can be reduced by up to 50% on an individual cable/transformer, and by 0.1-7% on the level of a PED. By limiting the loads of all charging stations combined, peak load can be reduced by up to 74% on an individual cable/transformer, and by 3-14% at the level of a PED. By allowing EV to charge as well as discharge, peak load can be reduced by up to 80% on an individual cable/transformer, and by 7-13% (including non-EV loads) at the level of a PED.

Keywords

Electric Vehicle (EV), Charging Station, Grid Impact

1 Introduction

Due to their relatively large loads, it is expected that increasing EV penetration will result in increased loading of existing electricity distribution grid infrastructure (van Lierop, Veldman, Vanalme, & Kling, 2010). In the Making City project, an analysis was made of existing charging stations in Groningen and other Dutch cities to estimate the impact of increasing EV charging on the local electricity grid. This analysis demonstrates the potential impacts of EV charging on the low voltage grid, especially regarding the limited capacity of existing grid infrastructure. Different scenarios were modelled to gain insight into the potential solutions to minimize these impacts by managing EV loads.

1.1 Purpose and target group

The deliverable reports the work carried out in Task 3.6, which analyses the impact of increasing E-mobility penetration on the distribution grid. The work package simulates future impacts based on measurements and projections in order to determine what grid adaptations will be required, and which strategies can be employed to reduce and postpone grid reinforcement. The results of this study are generalized for applications in other districts and cities and will be used as input for the long-term City Vision strategy that will be developed in WP1, Task 1.5, among others.

1.2 Contribution partners

In this section the contributing partners to this report and their responsibilities are explained.

Table 1: Contribution of partners

Partner nº and short name	Contribution
3 – GRO	Provide measurements from 19 charging stations in the Southeast district of Groningen, 14 charging stations in a park and ride area, and provide access to a GIS map showing likely locations of future charging stations
12-HUAS	Data analysis, modelling and final written report

1.3 Relation to other activities in the project

The following table depicts the main relationship of this deliverable to other activities (mainly deliverables) developed within the MAKING-CITY Project and that should be considered along with this document for further understanding of its contents.

Table 2: Relation to other activities in the project

Deliverable / Task nº	Relation
Task 3.2 / D3.3, D3.14	Results from this task will be used to inform task 3.2 - Simulation models of buildings, energy systems, storage and management of flows algorithms.
Task 1.5 / D1.5, D1.25 Task 3.4 / D3.5, D3.16	Scenario development will be informed by the results of task 1.5 – Development of a City Vision 2050, and task 3.4 – Smart energy systems in PED.

Deliverable / Task nº	Relation
Task 1.3	Contribute EV charging impacts to Technalia LEAP model for 2050 energy supply and demand modelling
Task 3.1 / D3.45	Development of business case for EV charge control.
Task 1.5	Input for final analysis and feasibility of PED.

2 Electric vehicle charging in the Netherlands

In the Netherlands, as of August 2021, there were 201,811 fully-electric vehicles and 125,555 plug-in hybrid electric vehicles; there were 76,588 regular charging points and 2,474 fast charging points (RVO, September, 2021). It is expected that there will be 1,9 million EV and 1,7 million charging points in the Netherlands by 2030 (Rijkdienst voor Ondernemend Nederland, 2021). A large proportion of these charging stations are expected to be public charging stations because only 30% of Dutch households have a private parking space (Hoekstra & Refa, 2017).

2.1 Charging infrastructure terminology

This section defines important charging infrastructure terminology which is referred to in this study.

This study refers to charging points and charging stations. A **charging point** is a single electric socket where one EV can be charged. Typically, a **charging station** will have two charging points.

Public charging points have a **rate of charge** of up to 22 kW, although some EV are only capable of charging at 11 kW, 7 kW, or 3,7 kW. Ten of the charging stations measured in this study have a novel setup: Each charging station is paired with another, creating a set of 5 pairs. When both charging stations in a pair are being used at the same time, constraints are imposed so that the combined rate of charge of both stations stays below a certain limit (22 kW total, or 11 kW per station if both are being used simultaneously). In the *Harm Buiterplein Park+Ride* area, the maximum charging rate for all 14 charging stations combined is limited to 250 A (57 kW), divided evenly between the active charging stations (so each charging station could deliver 4,1 kW of power if all were in use at the same time). The goal of these developments is to reduce the maximum peak load on the electricity grid.

Occupancy rate refers to the amount of time that a charging point has an EV connected to it.

Plug-in time is the amount of time that an EV is connected to a charging point. **Charging time** refers to the time that an EV is connected to a charging point and is actively charging. **Idle time** refers to the time when an EV is connected to a charging point but is *not* actively charging. **Percentage charge time** is the ratio of charging time to plug-in time (i.e., the 'non-idle' time). Typically, percentage charge time for a charging point is between 17-25% (Gemeente Groningen, Visie Openbare Laadinfrastructuur Groningen 2025, 2020).

2.2 Actions implemented in Groningen PEDs on electric vehicle charging points

The municipality of Groningen aims to stimulate electric vehicle use and plans to accommodate up to 16,000 electric vehicles by 2025. As of 2020, the municipality has installed approximately 250 regular public charging stations and 5 fast chargers. There are plans to install an additional 250 public charging stations by 2023. It is expected that approximately 1,500 public charging stations will be installed by 2030, and 6,000-8,000 public charging stations by 2050. It is assumed that each public charging station will accommodate 6-10 EV (Gemeente Groningen, Visie Openbare Laadinfrastructuur Groningen 2025, 2020).

The municipality, in cooperation with the local DSO and the provincial government, has identified 2,672 possible locations for new charging stations, as illustrated in Figure 1 below. Charging station locations are planned within 25m of existing low voltage cables which they can connect to. (Gemeente Groningen, Kaart openbare laadpalen, 2021).

The municipality aims to have a charging station within 250m of electric vehicle owners' residences/workplaces, except for the inner city where this is 500m. In order to reduce investment costs, all newly installed charging stations are planned to have 2 connection points. Since most houses in Groningen do not have private driveways, citizens can request a new charging station to be built in their area. Charging stations are installed and operated by the company Allego B.V. (the concession period ends in 2022) for the first ten years of their lifetime, at which point the city will gain control of or replace the charging stations (Gemeente Groningen, Visie Openbare Laadinfrastructuur Groningen 2025, 2020).

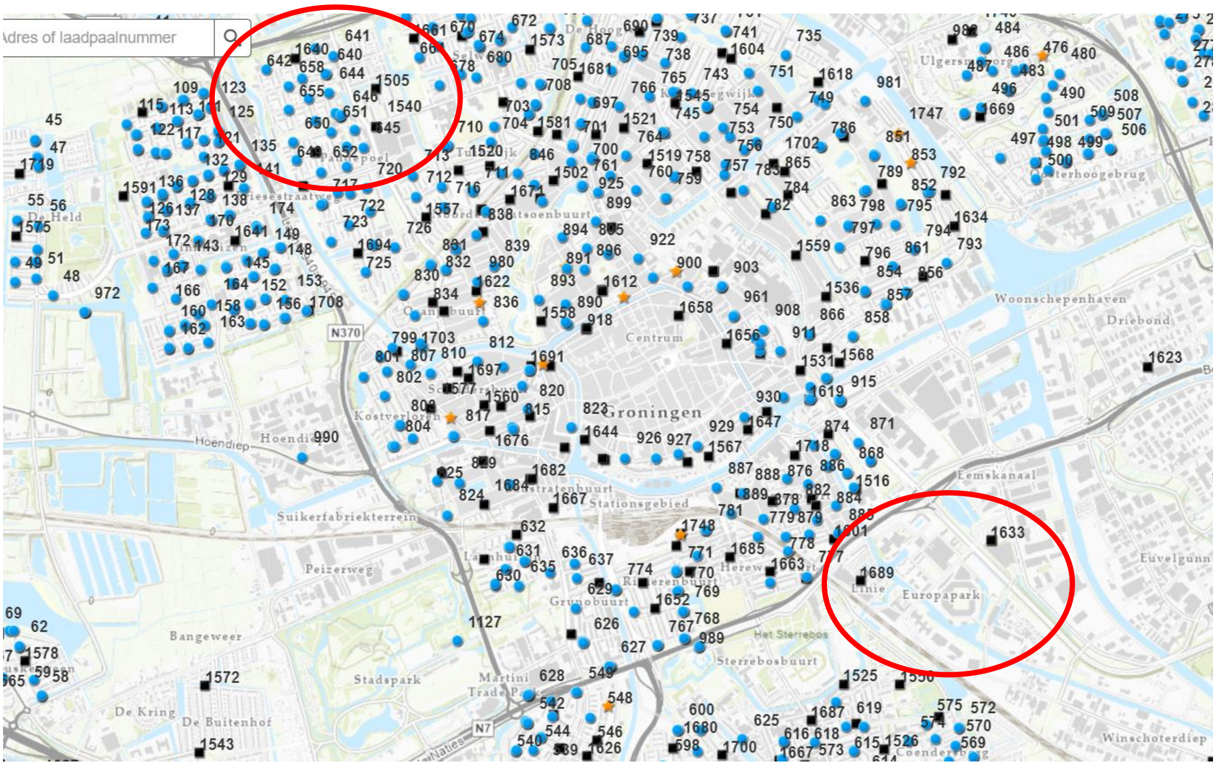

Figure 1: Planned charging stations in Groningen (Gemeente Groningen, Kaart openbare laadpalen, 2021). Black squares are existing charinging stations, yellow stars are charging stations which are being designed, and blue circles are possible locations for future charging stations. The two red circles indicate the PEDs where EV charging measurements were planned.

2.3 PED description

Data measurements were planned at EV charging stations in two neighbourhoods in Groningen, at the Euroborg soccer stadium in the southeast PED and the residential area of Paddepoel in the north PED, both of which are circled in Figure 1. Euroborg contains a mixture of residences, workplaces and commercial activities, while Paddepoel is primarily a residential area. As a result, it was expected that the charge patterns would differ between the two neighbourhoods.

The original proposal called for 14 charging stations to be implemented and measured, but at the time of writing, 20 charging stations were installed and 19 were being measured, all in the Euroborg stadium area, of which 10 have a novel setup. New Motion 'charge smart' installed Business Pro 2.1 (max. 22 kW) charging stations that are capable of performing load balancing measures. In addition, 14 charging stations were measured in the Harm Buiterplein park and ride area, adjacent to the Europapark train station nearby the Euroborg stadium. The location of the measured charging stations is indicated in Figure 2.

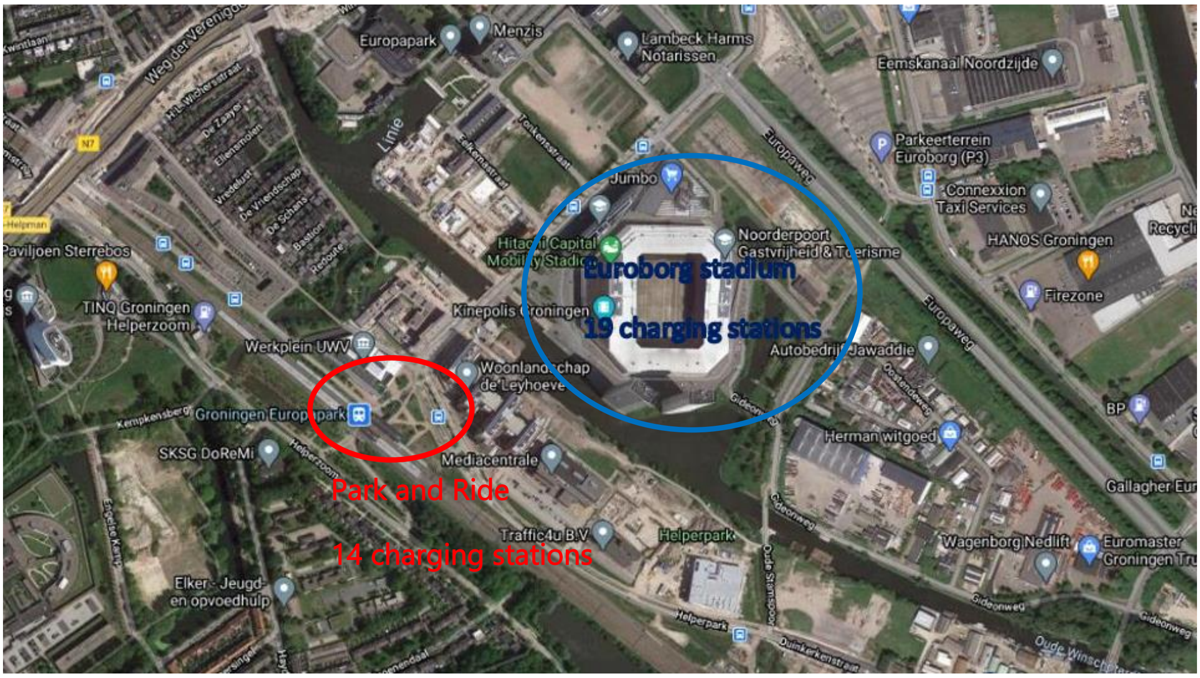

Figure 2: Location of charging stations in Southeast PED. The blue circle indicates the Euroborg stadium area, and the red circle indicates the Harm Buiterplein park and ride area.

3 Methodology for the impact analysis

3.1 Data measurements

Data from charging stations was analysed to determine probabilities and trends of EV charging cycles. The key assumption for this task was that the measurements obtained create a more or less representative sample of the PED in question. In order to validate this assumption, data was checked for inconsistencies and compared with other EV charging studies in the Netherlands. Because no measurements were performed in Paddepoel, data from other studies was used for this case (see 4.2.3).

Because the charging station measurements did not include power measurements, this was estimated using the methodology proposed by (Wolbertus, Hoed, & Maase, van den, 2016). This method assumes that each individual EV will charge at one of four rates: 3.7 kW, 7 kW, 11 kW or 22 kW. The charging patterns for each individual EV are analysed to determine which charging rate would be required for that vehicle to charge the measured amount of energy during the measured connection period. Once a charging rate is associated with a particular EV, it is assumed that that EV will always charge at that rate. Using this approach, more realistic charging patterns can be developed, idle time and charging time can be estimated, and it is less likely that the grid impacts of EV charging will be under-estimated.

Using the method described above, an analysis of measurement data was conducted to determine correlations between load patterns and external factors, such as time of day, day of week and weather. Specifically, the occupancy rate, charge start time, plug-in time, charge time, idle time, rate of charge and percentage charge time were calculated.

In addition, the impacts of weather were analysed. A 2019 study concluded that electric vehicles see an average reduction in range of 29% during outside temperatures of -7°C, due to the use of electric heaters and the reduced capacity of batteries in cold weather (American Automobile Association, Inc., 2019). Due to the relatively mild climate of the Netherlands, a less drastic range reduction and less additional charging energy is expected. It is important to understand if the average number of charge cycles per EV was higher in colder months, or if the energy per charge cycle was lower, because in that case occupancy rate (and charging infrastructure) must be planned to accommodate EV charging during colder months.

3.2 Model

The model developed for Task 3.6 generates statistically significant electric vehicle charging patterns. The model is based on the measurements taken in this and other studies. The model uses a timescale of 15 minutes, because this a common measurement window used in grid analysis studies and will allow comparisons with other studies.

The model allows for different scenarios to be tested. Key inputs include the number of charging stations, the occupancy rate of charging points, and the option to model the impacts of charge control strategies (e.g. shifting patterns in time and/or flattening power levels by lengthening cycle durations).

To account for the impact of COVID-19 lockdowns, the measurements were compared with results from pre-COVID studies. The differences were used to adjust the input parameters of the model.

Based on the chosen inputs, the model will calculate the impact of EV charging on the grid, defined by the peak load and load simultaneity of EV charging per hour of the day. In addition, EV charging flexibility and available EV battery capacity were also calculated (see 3.2.3). These data were then used to compare different scenarios.

3.2.1 Background information

Many studies exist which analyse the impact of electric vehicles on the electricity grid. For example, the *Vehicle-to-Everything* (Roks, Schurer, & Lampropoulos, 2019) and *Iris* (Massink, Persson, & Berg, 2019) projects in the Netherlands analyse the potential for using EVs as a grid balancing mechanism. EVs are considered to potentially be a highly flexible load since they stand still 90% of the time (Veldman, Gibescu, Postma, Slootweg, & Kling, 2009). For example, the Iris project concluded that the electricity grid in the city of Utrecht could be balanced if 8.5% of the city's vehicles were fully controllable EVs capable of bi-directional charging.

3.2.2 Statistical probabilities

Individual human behaviour is inherently unpredictable. However, when analysing groups of people, patterns begin to emerge. When analysing EV charging patterns, it is difficult to predict when any single EV will be plugged in and for how long, but it is possible estimate the likeliness that a *non-specific* EV will be plugged in at a given charging stating and for how long it is likely to be charging.

These probabilities are derived from measurements from existing charging stations. When determining these probabilities and applying them to scenario modelling, certain assumptions must be made. Importantly, it is assumed that the measurement sample will be representative of the general population and can be used to estimate future charging patterns. In the specific case for the city of Groningen, it is assumed that the Euroborg charging station measurements are representative of a mixed commercial/residential neighbourhood, while the Paddepoel charging station measurements are representative of a primarily residential neighbourhood.

3.2.3 Model indicators

The primary goal of the different scenarios (described in 3.3) is to determine what the peak load from charging EV is, and how much this peak can be reduced by controlling EV charging. In this study, peak load is defined as the maximum power required to charge EV during a 1-year period. There are two ways to consider the peak load: a) at the individual cable level; and b) at the neighbourhood level. At the cable level, peak load determines the minimum required grid capacity, and whether the cable is likely to become overloaded (and disconnected). This is generally referred to as network congestion. Congestion can be avoided by reinforcing the grid (which is generally costly (Brinkel, Schram, AlSkaif, Lampropoulos, & van Sark, 2020)) or managing loads locally. At a neighbourhood level, peak load determines the maximum amount of local power production (and/or power import) which is required. For a PED in particular, peak load is closely linked with power production capacity. The higher the peak load, the more production capacity is required, and the less cost efficient the energy system will be. In this study, peak load is considered from both perspectives.

To generalise the results of the study for an entire PED, the simultaneity of EV charging (g_n) for n charging stations was estimated using equation 1. Simultaneity describes the highest proportion of EV charging points which are in use at the same time. If all EV charging stations were in use at the same time, simultaneity would be 1; If half were in use at the same time, simultaneity would be 0.5. Simultaneity gives insight how much additional load can be expected from EV charging, and at what times. In equation 1, P_s is the maximum grid load (observed during simulations) and $P_{max,I}$ is the maximum charging power of a given EV. The sum of $P_{max,I}$ values is equivalent to the peak EV charging power observed during measurements (11 kW per EV). Simultaneity was calculated independently for each hour of the day. The interactions between EV charging and other projected changes to load patterns is addressed in Task 3.2.

$$g_n = \frac{P_s}{\sum_{i=1}^{n} P_{max,i}} \qquad [1]$$

The flexibility of EV charging is estimated using the methodology described in (Develder, Sadeghianpourhamami, Strobbe, & Refa, 2016). Flexibility is calculated using equation 2, where P_{FLEX} is the maximum amount of shiftable power, t is the plug-in time, Δ is the charging time, P_S is the rate of charge, and $s \in S_{FLEX}$ is number of 15-minute time periods during which EV charging can be shifted such that the EV still charges the same amount of energy as it would if no shifting occurred. The unit of flexibility is kW for a given time period; it describes how much power is able to be shifted in a given time period. For example, assuming time steps of 15 minutes, if an EV charged at 10 kW for 15 minutes, but was plugged in for one hour, the flexibility would be 40 kW over one hour (i.e., there are 4 options of where you can displace/distribute the 10 kW of charging power).

$$P_{FLEX}(t,\Delta) = \sum_{s \in S_{FLEX}(t,\Delta)} P_s \qquad [2]$$

The potential impact of bi-directional charging was modelled based on the methodology described by (Beltramo, Julea, Drossinos, Thiel, & Quoilin, 20171-6). The available storage potential of EV batteries is defined by equation 3, where $E_{Available}$ is the battery capacity made available to the system, CP is the total battery capacity, E_{min} is the minimum required state of charge of the battery and δ is a safety factor, set at 0.5. Since CP and E_{min} where unknown in this study, it was assumed that $(CP – E_{min})$ was equal to 50% of the total energy charged per session. In this way, an EV would always be at least 75% fully charged at the end of its charging session.

$$E_{Available} = (CP - E_{min}) * (1 - \delta) \qquad [3]$$

3.3 Scenarios

Scenarios were used to investigate the effect of different control strategies on EV charging patterns and their impact on the electricity grid. In each scenario, three different patterns were modelled, based on the PEDs which were studied:

1. Residential area (referred to as ‘At Home’): as in Paddepoel, EV are charged primarily in the evening;
2. Commercial area (referred to as ‘At Work’): EV are charged primarily during working hours;
3. Mixed Commercial-residential area (referred to as ‘Euroborg’): as in Euroborg, EV are charged throughout the day.

In addition, each scenario looks at projections for a number of different years:

1. 2020: 200 installed charging stations;
2. 2023: 500 installed charging stations;
3. 2030: 1500 installed charging stations.[1]

[1] In fact, the numbers of charging stations modelled for each year were 171 for 2020, 513 for 2023 and 1539 for 2030. The reasoning behind this selection of values is that they are direct multiples of 3 from the original number of measured charging stations (19) and closely align with the projections for the respective years. The reason for selecting multiples of 3 was to provide a proportional increase from year to year, thus simplifying the analysis of these increases.

It is also assumed that the usage of each charging station will increase, from providing one charge cycle every three days, to providing one charge cycle each day. In order to compare results between years, results were normalised per charging station.

3.3.1 Reference scenario

The reference scenario is a 'business-as-usual' scenario, and it describes how EV charging will impact the grid if there is no charge control. The results of this scenario provide a baseline which other scenarios can be compared to. Specifically, the hourly peak load, hourly load simultaneity, annual load flexibility, and annual available storage potential are modelled and compared.

3.3.2 Coordinated charging scenario

The coordinated charging scenario describes how EV charging will impact the grid if charging stations can communicate with one another to limit the total EV charging load on the grid. This scenario has been partially implemented in Euroborg, where each pair of charging stations are linked to limit their maximum load to 22 kW. Because the maximum rate of charge observed in this study was only 11 kW, this scenario is modelled assuming that the maximum combined load from each pair of charging points is limited to 11 kW (so that the peak load could be reduced by up to 50%).

3.3.3 Coordinated loads scenario

This scenario describes how EV charging will impact the grid if the charge cycle is coordinated with other large grid loads. The potential for EV to be coordinated with other loads is quantified by the load flexibility parameter, described in 3.2.3. Flexibility will vary depending on the charging pattern and the number of charging stations. The primary goal of flexibility is to shift EV charging loads to reduce the peak load on the grid.

3.3.4 Bi-directional charging scenario

The bi-directional charging scenario describes how EV charging will impact the grid if the EV battery is controllable by a third party, such as an aggregator. It is important to note that current EV charging stations are not capable of bi-directional charging, but they can be modified at little cost to accommodate bi-directional charging (Massink, Persson, & Berg, 2019). It is also important to note that while 2/3 of EV charging currently occurs at home, public charging points are expected to become the dominant charge location as the number of EVs increases, and thus the potential use of public charging stations for local grid balancing will become increasingly important (Hoekstra & Refa, 2017). The available storage potential of EV is quantified by the $E_{available}$ parameter, described in 3.2.3.

To evaluate the potential peak reduction on the grid including non-EV loads, the EV charging pattern was combined with a standard Dutch load profile for residential areas, scaled up to represent 2000 houses (EnergieDataUitwisseling, 2021).

4 Results

4.1 Description of charging stations

The results presented here are based on data collected from 20 charging stations located in the Euroborg soccer stadium and 14 charging stations in the Harm Buiterplein Park+Ride in the southeast district of Groningen. Charging stations were gradually brought online during the course of this project, so that not all charging stations were active throughout the entire measurement period. At the time of submission, 19 of the 20 charging stations were active, some from as early as November 2019, and some from as late as July 2020. The 14 charging stations in the Harm Buiterplein park and ride were measured from mid-March to mid-September, 2021.

All charging stations are connected to the low voltage grid.

The charging stations are able to charge at a rate of 3.7 to 22 kW, depending on the type of vehicle being charged and available infrastructure capacity (Allego BV). However, as noted earlier, 10 of the Euroborg charging stations are paired with one another, and their combined maximum rate of charge is limited to 22 kW. During the measurement period, overlapping charging cycles from charging station pairs were found to occur for a total of only 37 hours. Due to the relatively infrequent occurrence of overlap at present, it is assumed that this feature will have a relatively minor impact on the measured data.

Likewise, the combined rate of charge for the 14 park and ride charging stations is limited to 57 kW. During the measurement period, the combined rate of charge from these stations never exceeded 23 kW, so this limit has not yet been imposed.

4.1.1 Charging Station Measurements

Measurements from the charging stations are available beginning from mid-November, 2019, until mid-September, 2021. The data has been anonymized so that it cannot be linked with any particular client.

The charging stations log the details of every charge cycle. These include:

1. The cycle start time
2. The cycle end time
3. The total energy delivered, in Wh
4. The ID number of the charging station
5. The ID number of the client
6. A unique session ID number

Charging currents and voltages over time were not recorded.

4.2 Analysis of measured data

In this section, a description of the charging station measurements is presented.

4.2.1 Interpreting the measured data

As described in the methodology section, the actual rate of charge of EVs was estimated by analysing the charging patterns and assuming that each individual EV would charge continuously at a given rate. In reality, charge power may fluctuate, either as a result of charging station communication (see 4.1) or battery protection mechanisms (Develder, Sadeghianpourhamami, Strobbe, & Refa, 2016). Assuming a constant charge power throughout a cycle may not be realistic, but it does indicate the minimum grid capacity required to fully charge an EV.

An additional consideration is the time periods when these measurements were taken. Recording data over a 2-year period should give an indication of what a typical load situation is, but there are two factors which must be taken into account:

1. The data is from newly installed charging stations, so it is likely that their use will increase sharply over time.
2. Most of the measurements were taken during COVID-19 epidemic, during which time personal travel was limited and it appears that charging stations were underutilized as a result.

Keeping the above points in mind, the following analysis should be considered as an observation only. Over time, as more data is collected, a more representative charging station load pattern could be developed. To address this point, the measurements from this study are compared with the 10,000 EVs measured by *Elaad* to evaluate their representativeness (ElaadNL, 2020) (Sadeghianpourhamami, Refa, Strobbe, & Develder, 2018).

4.2.2 Southeast PED (Euroborg - Commercial area)

The initial observations described below are based on data collected from 19 charging stations from mid-November, 2019, to mid-Septembet, 2021.

During this period, a total of 4,206 charge cycles were performed, delivering a total of 77,790 kWh of electricity, for an average of 18.5 kWh per charge cycle. The average plug-in time was 13.6 hours, the average charging time was 3.2 hours, the average idle time was 9.1 hours, and the average rate of charge was 5.80 kW. Each charging point was used once every 3 days on average, and the average occupancy rate was 18.9%.

Figure 3 shows a load duration curve for the combined load of the 19 charging stations over the 2-year measurement period. The highest estimated peak demand was 78.4 kW at 13:45 on January 26, 2020 as a result of 7 charging stations actively charging simultaneously with a simultaneity of 35% (2 additional EVs were plugged but not charging).

Figure 3: Load duration curve for combined load of 20 charging stations over 2 years

To put this in context, an average Dutch household in 2018 consumed 2,790 kWh per year, with an average load of 0.318 kW (Centraal Bureau voor de Statistiek, 2019). During the measurement period, the total energy delivered by the 19 charging stations was approximately equal to that consumed by 14 Dutch households.

It is notable that some charging stations saw more use than others, with the total number of charge cycles to date ranging from 23 to 432. The average plug-in time and average rate of charge also varied per station, ranging from 4.0 to 22.9 hours and from 3.7 to 11 kW, respectively. The average energy delivered per charge cycle ranged from 16 to 33 kWh. For a visual reference, the results per charging point are presented in Figure 4 below.

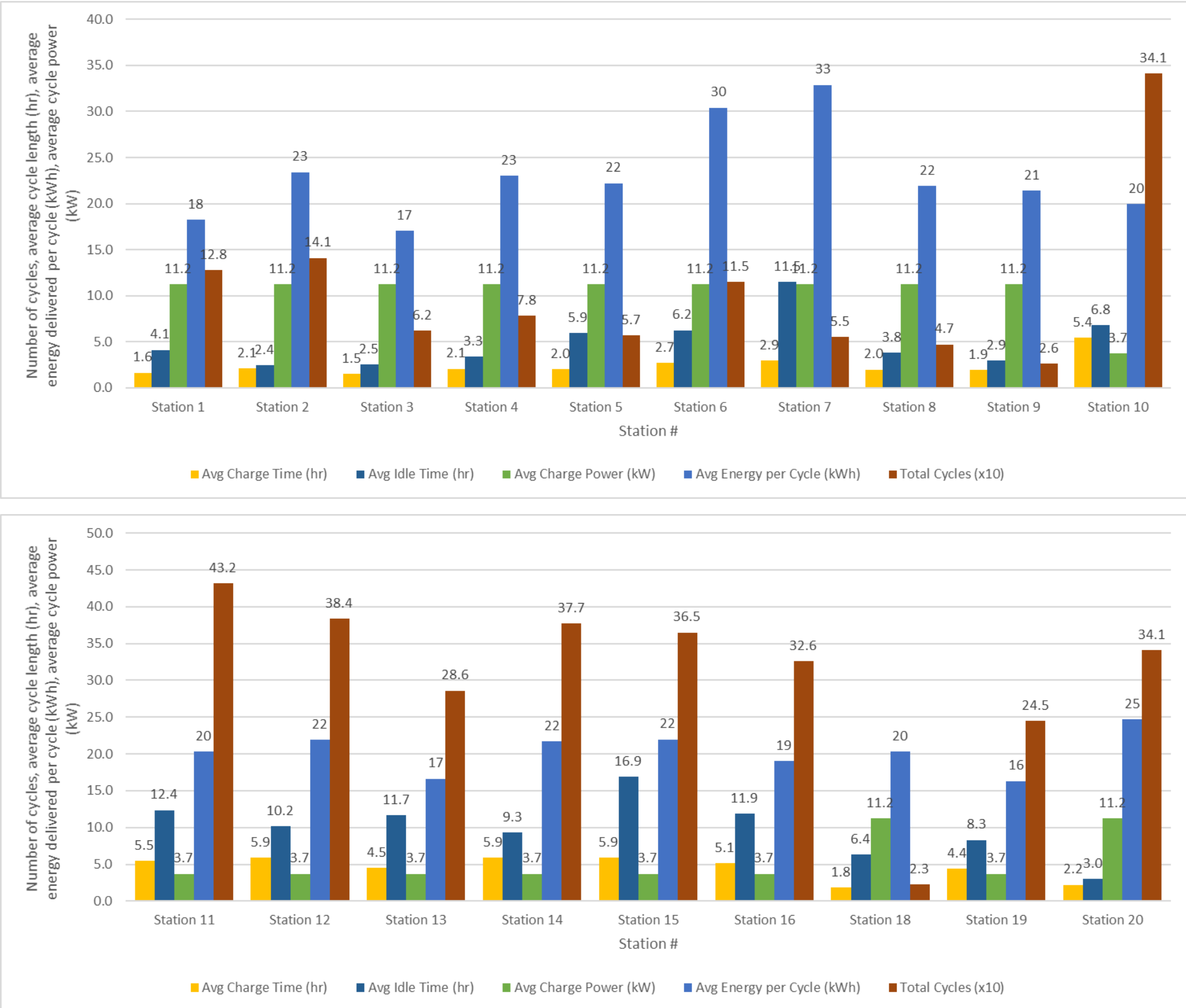

Figure 4: Total cycles, average cycle length, average energy delivered per cycle and average cycle power per charging point. Note that charging point #17 currently has no results and is omitted.

4.2.2.1 Charging patterns

It was also of interest to identify which hours of the day a charge cycle is more likely to start, and which hours of the day active charging was likely to occur. Figure 5 below shows the distribution of active EV charging hours and charging start times per hour as a percentage of the total. It is notable that charging hours are fairly evenly distributed over the day, whereas charging start times are clustered in daytime hours.

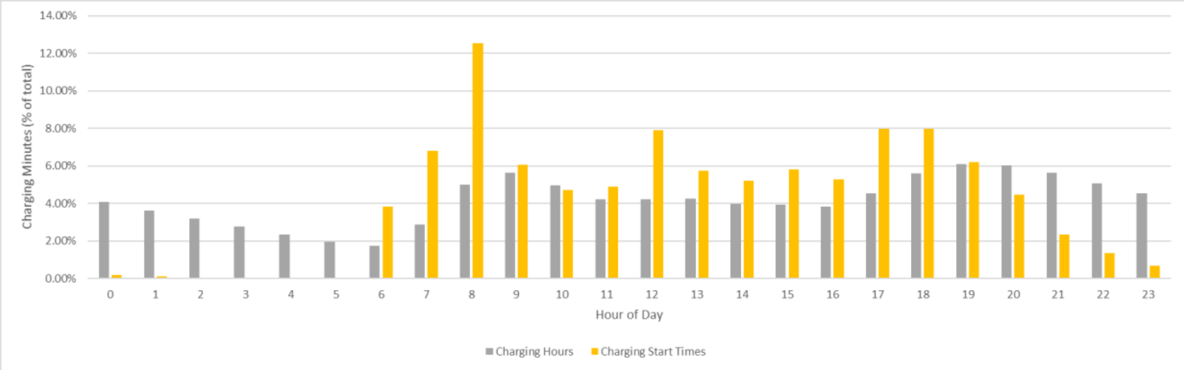

Figure 5: Percentage of charging start time and active charging time for each hour of the day

Figure 6 illustrates the cumulative load of the 19 Euroborg charge points. The bars represent the average loads at present, excluding days with no EV charging (i.e., assuming that at least one charge point is used each day). The large standard deviations indicate that charging power can fluctuate significantly from day to day, and fluctuates more over daytime hours than night-time hours. Finally, higher averages on weekdays during the day than on weekends is observed, a trend which is expected in a mixed commercial/residential area which is likely to have more EVs plugged in during weekdays.

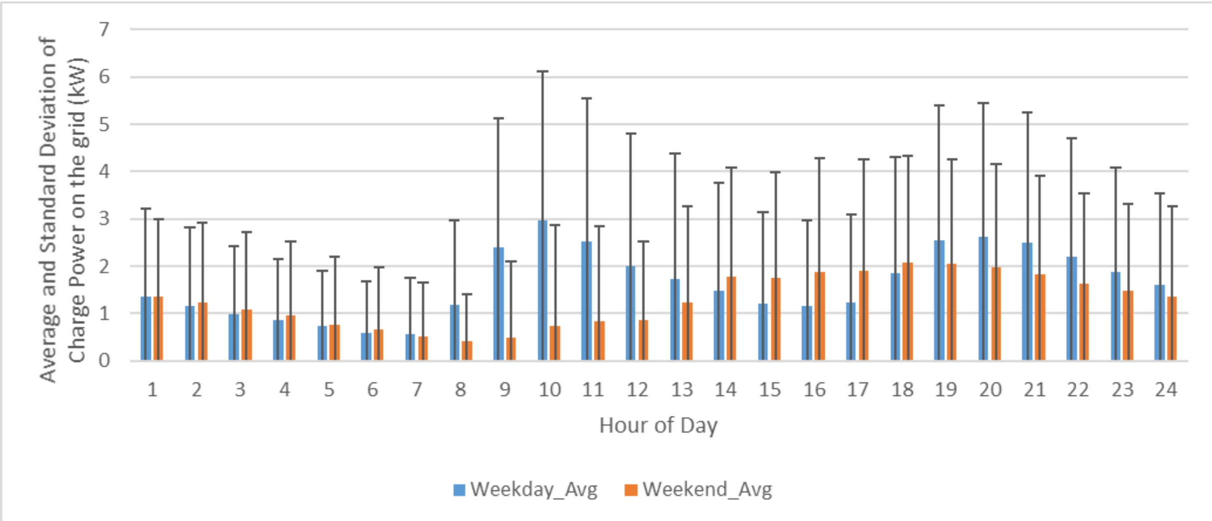

Figure 6: Average EV charging power in Euroborg, excluding days with no EV charging. Results are presented per hour of the day, divided between weekdays and weekends and showing one standard deviation

4.2.2.2 Temperature effects on measurements

Figure 7 shows the average energy per cycle (orange), monthly number of charge cycles (blue), and average energy per charge cycle (green), all averaged over the 19 Euroborg charge stations. As expected, the total number of charge cycles tends to be higher in winter months, likely due to lower battery capacities in cold weather requiring more frequent EV charging. Similarly, energy requirements for EV tend to be higher in colder months, likely due to heating requirements.

Note that the number of charge cycles recorded in June is very low. It is unclear what the cause of this anomaly is, but it is likely a measurement error.

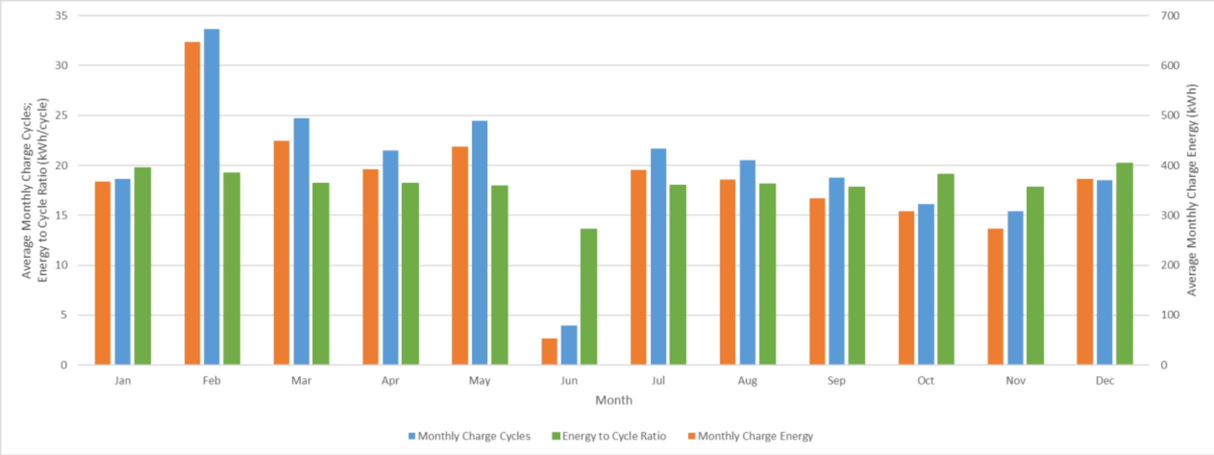

Figure 7: Monthly charge cycles (blue), monthly average energy per charge cycle (orange) and average energy per charge cycle (green)

4.2.2.3 COVID-19 effects on measurements

Before the COVID-19 lockdowns, between mid-December, 2019, and April 1, 2020, the Euroborg charging stations delivered a total of 5,478 kWh. During the COVID-19 lockdowns, between April 1 and June 1, 2020, the charging stations delivered a total of 2,159 kWh. Before and during the lockdowns, the average daily electricity delivered dropped from 50.7 kWh to 35.6 kWh, a decrease of 29.8%. Since fewer charging stations were operational during the pre-shutdown months than during the shutdown months, an increase in the amount of electricity delivered would normally be expected. The decrease in energy delivered is too large to be explained by weather effects alone (see 3.1), and is likely the result of decreased EV use during the lockdown period.

These findings illustrate the profound impact which the COVID-19 shutdown has had on electric vehicle use, and reinforce the earlier statement that the data collected during this period are not representative of normal EV charging behaviour.

To account for this, it was assumed that EV charging stations will normally be used once per day, instead of once every 3 days as was observed in Euroborg.

4.2.2.4 Observed differences with other studies

To judge how representative the data from this study is, the observations were compared with data from Elaad, which observed over 1 million charge sessions and 53,000 customers (Sadeghianpourhamami, Refa, Strobbe, & Develder, 2018). Figure 8 and Figure 9 compare the Elaad data with the data from this study (blue bars). The data from Elaad are divided into two cases, charging occurring at home (grey bars), and charging occurring at or near a workplace (yellow bars). To compare the different data sets, the data from the reference study was scaled to have the same number of annual charging sessions as observed in MAKING-CITY.

From Figure 8, it can be seen that the average power of car charging in this study was higher than in the reference cases. This is likely due to the increasing charging power of EV, a trend noted by (Refa & Hubbers, Impact of smart charging on EVs charging behavior assessed from real charging events, May 19-22, 2019), which observed that average charging power increased from 4.05 to 5.86 kW between 2017 and 2019. Notably, the average energy per charge cycle was lower than in the reference cases, possibly a result of lower EV battery capacities or more frequent charging due to the high availability of charging stations in this study. Finally, the average idle time observed in this study was comparable to an at-home charging pattern.

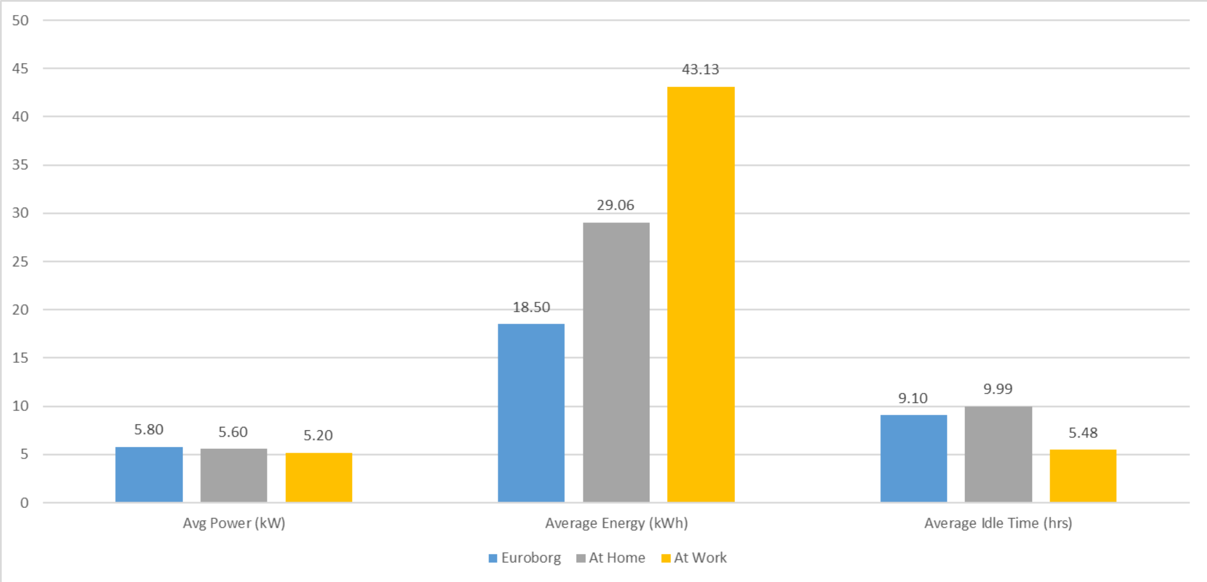

Figure 8: Average charge power, anergy per charge cycle and average idle time from Euroborg, compared with at-home and at-work EV charging data from Elaad

Figure 9 compares charging start times between this study and the two Elaad cases. Notably, the start times observed in this study appear to match some combination of the start times observed in the two cases. This finding indicates that EV charging in Euroborg is likely representative of a mixed commercial/residential area.

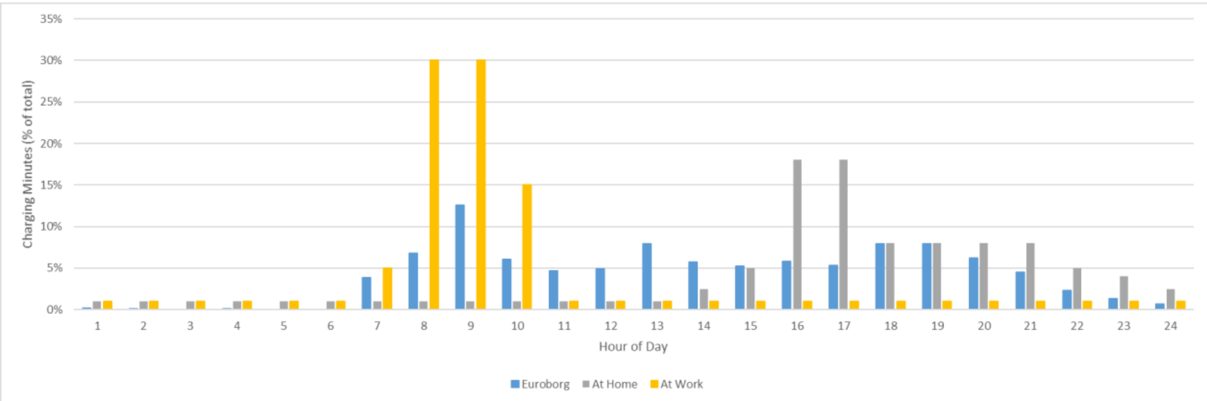

Figure 9: Charging start times, compared with at-home and at-work EV charging data from Elaad

4.2.3 North PED (Paddepoel - Residential area)

No measurements were taken in Paddepoal. Instead, Paddepoel is represented by data from Elaad, as described in (Sadeghianpourhamami, Refa, Strobbe, & Develder, 2018). This article describes EV charging patterns in residential areas in other cities in the Netherlands. It is assumed that the trends observed in these cities will be representative of residential areas in Groningen.

As illustrated in Figure 9, charging start times in a residential area like Paddepoel (the grey bars) are largely expected in the evening hours, with a peak between 16:00 – 18:00. The average charging time is expected to be 3.45 hours, and the average idle time is expected to be 10 hours, resulting in an average plug-in time of 13.45 hours. The average charge power is expected to be 5.6 kW, although this is expected to increase in the coming years (Refa & Hubbers, Impact of smart charging on EVs charging behavior assessed from real charging events, May 19-22, 2019).

4.2.4 Harm Buiterplein (Park and Ride area)

The observations described below are based on data collected from 14 charging stations from mid-March to mid-September, 2021, in the Harm Buiterplein park and ride area.

During this period, a total of 1,235 charge cycles were performed, delivering a total of 19,493 kWh of electricity, for an average of 15.8 kWh per charge cycle. The average plug-in time was 11.6 hours, the average charging time was 3.8 hours, the average idle time was 7.8 hours, and the average rate of charge was 3.7 kW. Each charging point was used once every 2 days on average, and the average occupancy rate was 24.2%.

Figure 10 shows a load duration curve for the combined load of the 14 charging stations over the 6-month measurement period. The highest estimated peak demand was 22.2 kW at 20:45 on April 5, 2021 as a result of 6 charging stations actively charging simultaneously (1 additional EV was plugged but not charging).

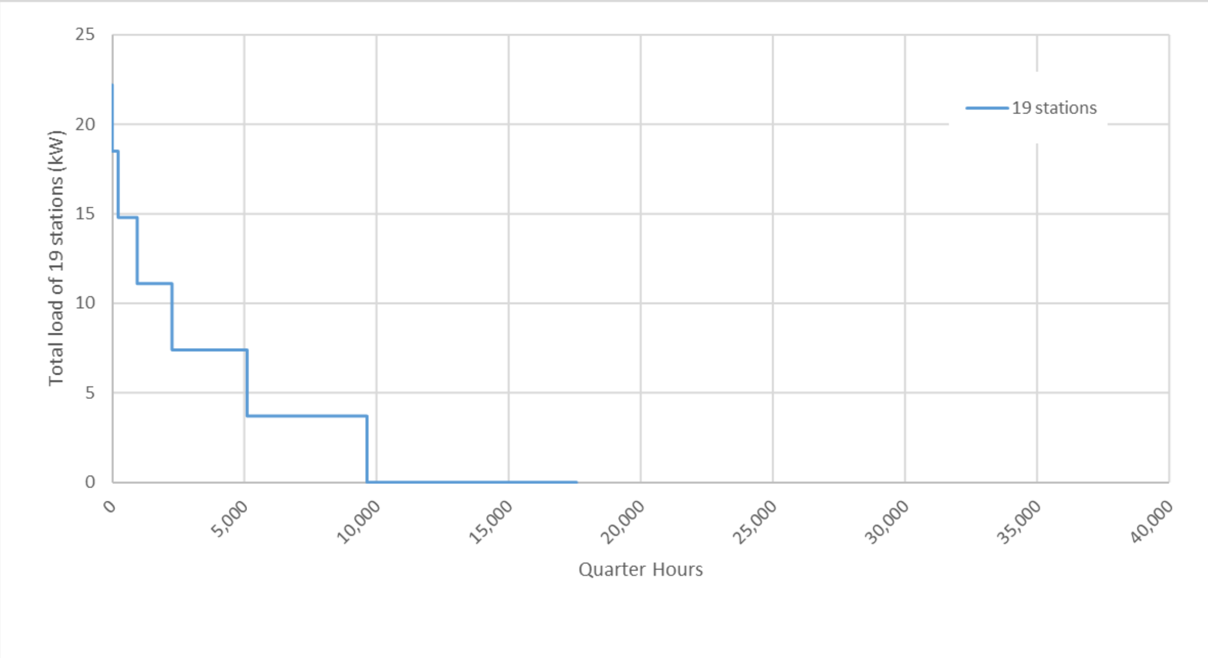

Figure 10: Load duration curve for park and ride (14 charging stations) over 6 months

It is notable that some charging points saw more use than others, with the total number of charge cycles to date ranging from 4 to 210 per charge point. The average plug-in time varied per charge point, ranging from 4.8 to 14.9 hours, while the average rate of charge was consistently 3.7 kW. The average energy delivered per charge cycle ranged from 11 to 16 kWh. For a visual reference, the results for individual charging points are presented in Figure 11 below.

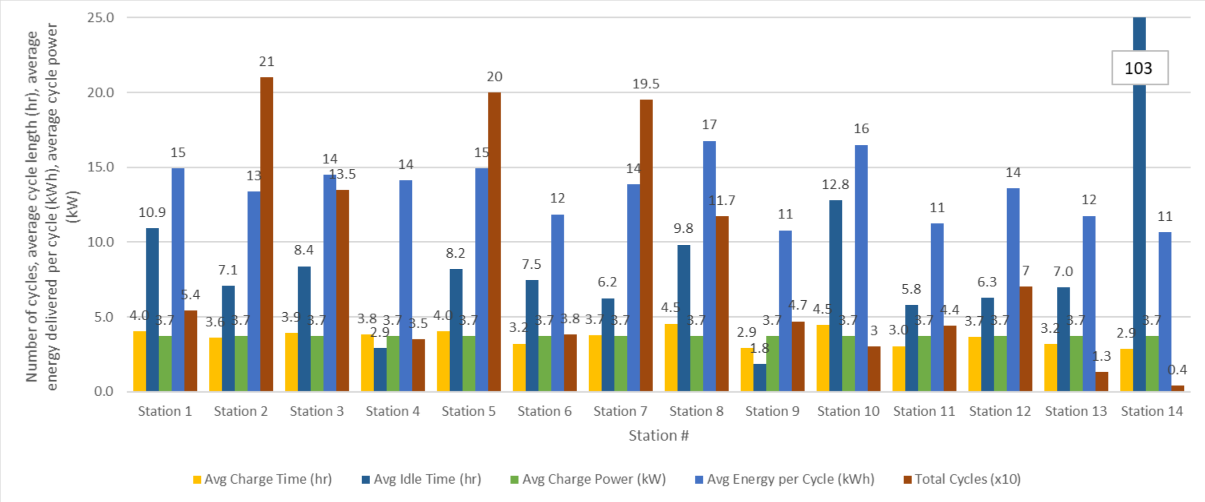

Figure 11: Total cycles, average cycle length, average energy delivered per cycle and average cycle power per charging point (Note: the average idle time for Station 14 was 103 hours)

4.2.4.1 Charging patterns

It was also of interest to identify which hours of the day a charge cycle is more likely to start, and which hours of the day active charging was likely to occur. Figure 12 below shows the distribution of active EV charging hours (grey bars) and charging start times (yellow bars) per hour as a percentage of the total. It is notable that charging hours occur primarily in the evening and night, whereas charging start times are primarily in the afternoon and evening. This is comparable to an at-home charging pattern, as shown by the grey bars in Figure 12.

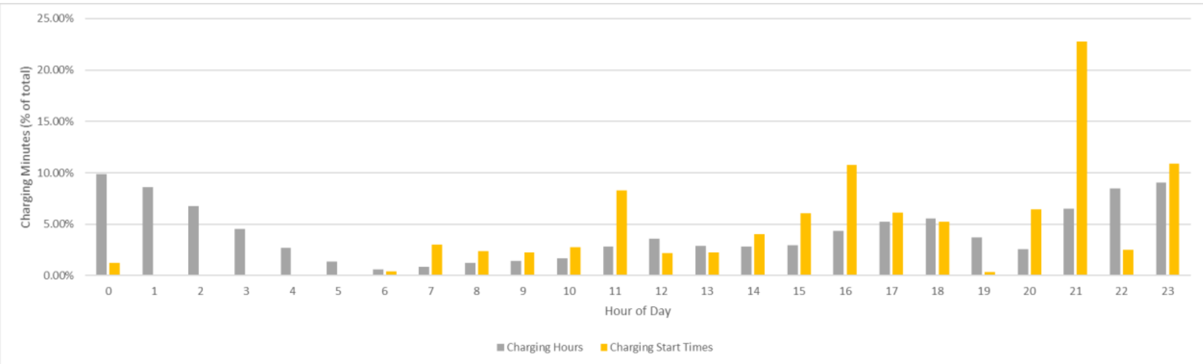

Figure 12: Percentage of charging start time and active charging time for each hour of the day

Figure 13 illustrates the cumulative load of the 14 Harm Buiterplein charge points. The bars represent the average loads at present, excluding days with no EV charging (i.e., assuming that at least one charge point is used per day). The large standard deviations indicate that charging power can fluctuate significantly from day to day, and hour to hour. Finally, weekend loads tend to be more clustered during night-time hours, whereas weekday loads tend to be more clustered during evening hours.

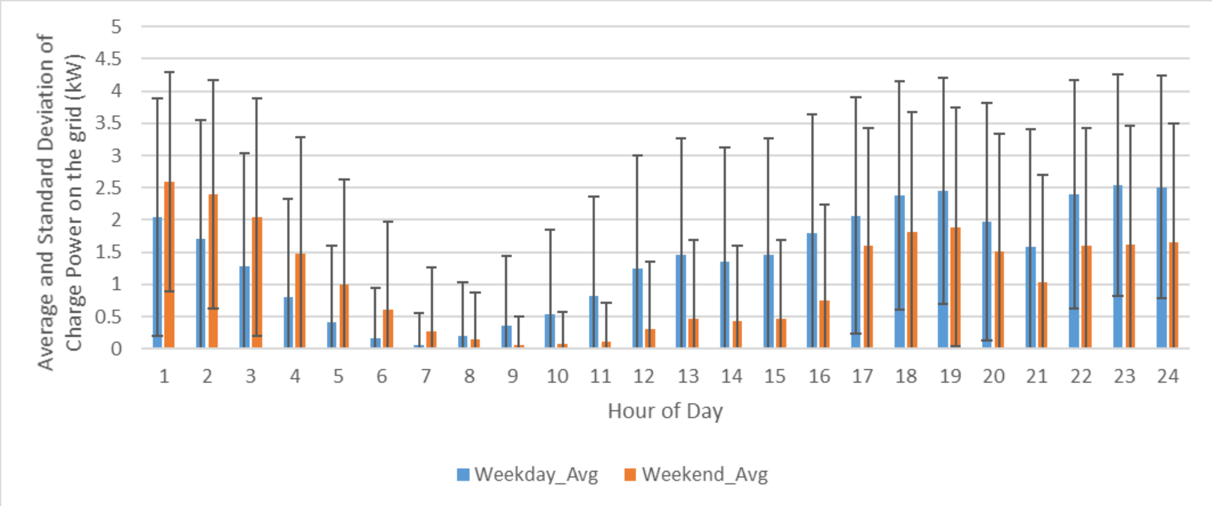

Figure 13: Average EV charging power in Harm Buiterplein, excluding days with no EV charging. Results are presented per hour of the day, divided between weekdays and weekends and showing one standard deviation

4.3 Future impact of charging stations in Groningen

In this section the modelling results from the scenarios described in section 3.3 are presented. The tables below has as summary of the results for the different years of analysis and the effectiveness of different load control strategies at reducing peak loads. The table presented is based on a the charging pattern from Euroborg (a mixed commercial-residential area). The results from the residential area and commercial area charging pattern were nearly the same, so they are not shown. The following sub-sections describe the results presented here.

Table 3: Effective peak reduction for different EV charge control strategies for different scenarios

Number of charging points	2 (single cable)	19 (measured)	171 (2020)	513 (2023)	1539 (2030)
Peak Load (kW)	22	153	1120	3203	9,517
Peak Reduction: Coordinated Charging (%)	50%	7%	0,6%	0,2%	0,1%
Peak Reduction: Coordinated Loads (%)	74%	14%	11%	5%	3%
Peak Reduction: Bi-directional Charging (%)*	80%	13%	9%	8%	7%

**Note: for bi-directional charging, peak reduction includes shifting of non-EV loads, whereas for the other scenarios, peak reduction refers only to a reduction of EV charging load.*

4.3.1 Reference scenario

The reference scenario describes what the grid impact of EV charging could be as more charging points are installed. The maximum possible load is easily calculated (11 kW times the number of charge points), but such a high load is unlikely to occur due to the simultaneity of EV charging. Figure 14 shows the simulated simultaneity factor of EV charging for 19, 171, 513 and 1,539 charging points, assuming one charge cycle per charge point per day in all cases. Results are shown for the charging patterns observed in Euroborg (blue dots), and the at-home (grey dots) and at-work (yellow dots) charging patterns from *Elaad*.

As shown, for all 3 charging patterns, as the number of charging points increases towards the 2023 and 2030 projections (513 and 1,539 installed charging points, respectively), simultaneity approaches a value of roughly 0.50. This is an expected outcome, and corresponds with observations for household load patterns (van Oirsouw, 2012). This finding is notable because it implies that, initially, as the grid impact will likely not increase proportionally to the number of installed charging stations. However, beyond a certain threshold (potentially around 1,200 charging points), grid impact *will* increase more or less proportionally with the number of installed charging stations. To help illustrate this point, refer to Figure 15. Here it can be seen that the estimated load on the grid (yellow line) is less than the maximum possible load on the grid (orange line, which assumes that all charging stations are charging simultaneously). The difference between the two lines is accounted for by the decreasing simultaneity, the impact of which is more obviously shown by the grid load normalized per charging point (blue line).

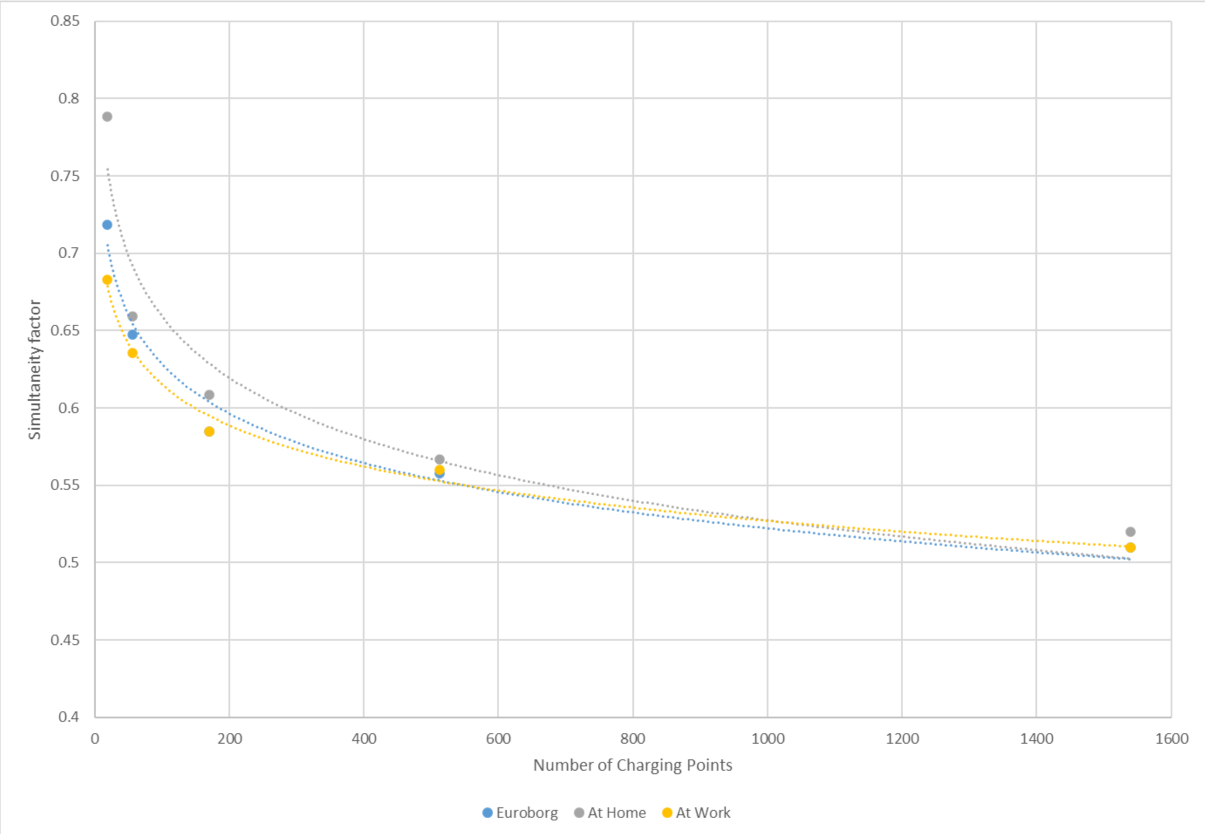

Figure 14: Simultaneity factor for Euroborg (blue), at-home (grey) and at-work (yellow) EV charge patterns, based on the maximum simulated charging power for 19, 57, 171, 513 and 1,539 charging points

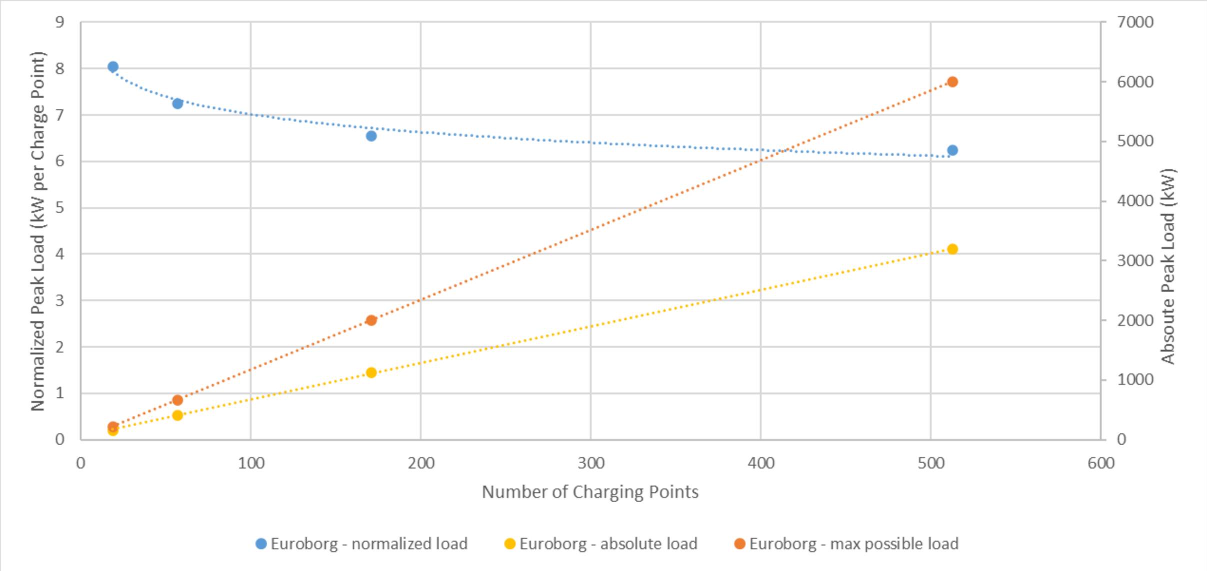

Figure 15: The estimated relative (blue), absolute (yellow) and maximum possible (orange) peak load from an increasing number of charging stations, using the Euroborg charging pattern

4.3.2 Coordinated charging scenario

By coordinating charging, the maximum load from two linked charging points was limited to 11 kW. Therefore, when considering only two linked charging points, peak load could be reduced by up to 50%. However, when considering a PED as a whole, the impact of coordinated charging is highly dependent on simultaneity.

When simulating coordinated charging for 19 charging points using the Euroborg charging pattern, the peak grid load from EV charging was reduced from 116 kW to 108 kW, a reduction of roughly 7%. For 171 charging points, the peak grid load from EV charging was reduced from 1,120 kW to 1,113 kW, a reduction of only 0.6%. With an increasing number of charging stations, simultaneity is expected to decrease (i.e., it becomes less likely that a specific pair of charging points are active at the same time).

Similar results were found for the at-home and at-work charging patterns. This result is to be expected because EV charging simultaneity is naturally much lower with a higher number of charging points, so the potential benefit of coordinated charging, *from a district-wide perspective*, will be correspondingly lower. However, at the level of an individual cable, peak reduction will remain at 50%.

4.3.3 Coordinated loads scenario

Figure 16 shows the potential flexibility for the Euroborg, at-home and at-work charge patterns. Flexibility describes the amount of power which can be shifted during an average charge cycle. More flexibility implies that there are more possibilities for shifting loads. As can be seen, Euroborg had a higher flexibility than both the at-home and at-work patterns. This is primarily the result of the longer idle times observed in Euroborg (longer idle times present more possibilities for shifting loads). However, longer idle times also come with the trade-off that the charging infrastructure is not being used efficiently (i.e., another EV cannot use the charge point during idle times).

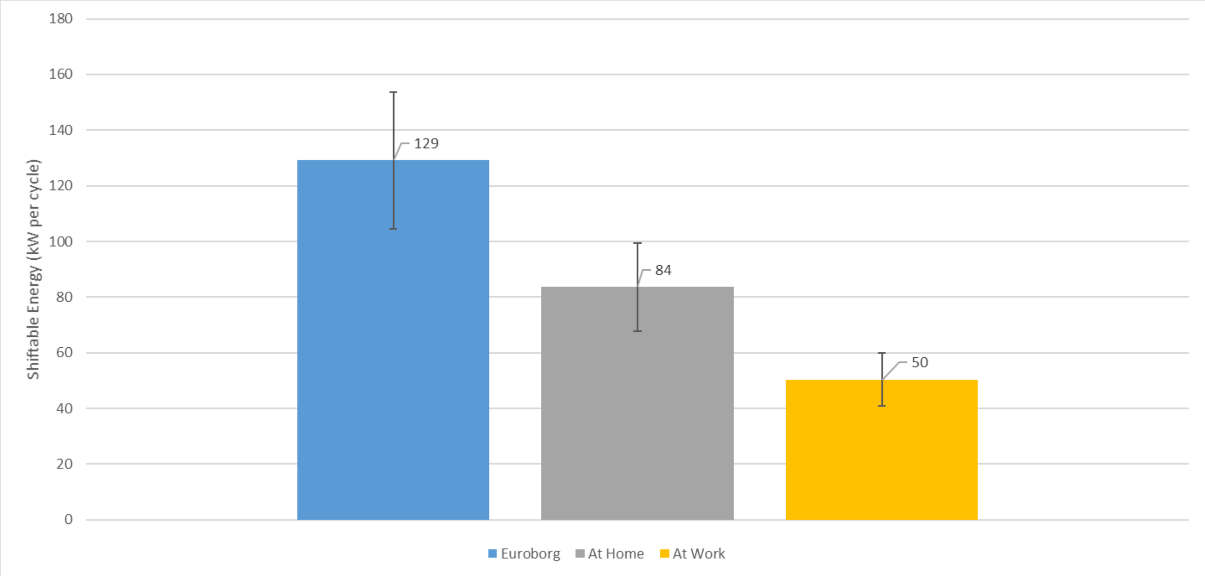

Figure 16: Average and one standard deviation of potential flexibility per charging point for the Euroborg, at-home and at-work charge patterns

Making use of flexibility could reduce the peak load on the grid, to a larger extent than the coordinated charging scenario. In a simulation of 19 charging points using the Euroborg charging pattern, it was found that coordinated loads could reduce peak load for the PED by roughly 14%, assuming that each individual load could be shifted by up to 6 hours. For 171 charging points, the peak load reduction for the PED was found to be roughly 11% (again, assuming that each individual load could be shifted by up to 6 hours). These values are comparable with the *Smart Charging Den Haag* study, which found a peak reduction of 13% by controlling EV charging (Nationale Agenda Laadinfrastructuur, 2021). At the level of an individual cable, peak reduction could be as high as 74%.

For the at-home and at-work charging patterns, which have less flexibility (due to shorter plug-in times), the potential peak load reduction is correspondingly shorter. For example, for 19 charging stations using the at-home charging pattern, the peak load at the PED level could be reduced by roughly 5%. At the level of an individual cable, peak reduction could be as high as 66%.

Compared with the coordinated charging scenario, coordinated loads show a higher potential to reduce peaks. This can be explained by two factors: 1) Unlike in the coordinated charging scenario, an EV load can be reduced by more (or less) than 50%, as required; 2) Since all active charging stations are coordinating with one another, simultaneity (i.e., the odds that a pair of linked charging points are simultaneously active) is less of a determining factor.

The potential for flexibility could be further exploited to reduce grid loads if it is coordinated with other patterns, such as solar panel production, or heat pump consumption. This potential is discussed in Tasks 1.5 and 3.4.

4.3.4 Bi-directional charging scenario

The potential of bi-directional charging is best quantified by the amount of battery capacity which is available to manage grid loads. Available battery capacity is, of course, limited to the times of day when an EV is likely to be plugged in (as shown in 4.2), so its potential useability is likewise restricted.

Figure 17 shows the potential available battery capacity for an average EV following the Euroborg, at-home and at-work charging patterns. One standard deviation of available battery capacity is also shown. The difference between the different charging patterns results from how available battery capacity was calculated. Because the actual battery capacities were unknown, available battery capacity was based off the energy charged. This means that available battery capacity was likely under-estimated in all cases, but it also guarantees that all EV will be *at least* 75% charged at all times.

How effectively this battery capacity can be utilized is highly situational, and further details are described in Tasks 1.5 and 3.4. However, it can be said that using bi-directional charging can reduce grid impact by *at least* as much as the coordinated loads scenario, and potentially much more, depending on the other electrical loads in the PED.

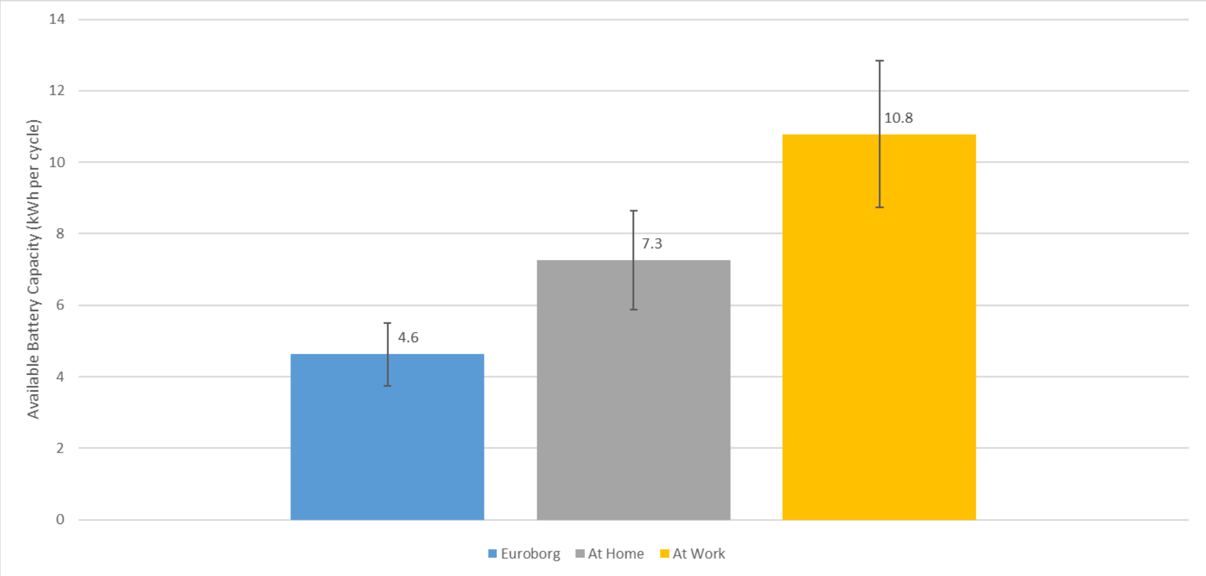

Figure 17: Average and one standard deviation of potential available battery capacity per charging point for the Euroborg, at-home and at-work charge patterns

Notably, bi-directional charging can help to offset other grid loads (e.g., heat pumps) by providing energy from relatively close by. This has the advantage of reducing distribution infrastructure loads, assuming that the EV is located near the far end of a distribution cable which also supplies houses/businesses. In an area like Euroborg or Paddepoel, this method can be used to smoothen a demand curve over a 7-15 hour period (depending on when the EV are plugged in and the load pattern from other sources). In Euroborg, for example, it could be possible to reduce the PED-level peak load (including non-EV loads) by up to 13%, assuming a standard electricity consumption pattern (EnergieDataUitwisseling, 2021). At the level of an individual cable, peak reduction would be comparable to the coordinated loads scenario.

Since bi-directional charging can help reduce the impact of non-EV grid loads, EV charging simultaneity has less influence on the effectiveness of bi-directional charging at reducing grid loads. However, in a park and ride situation, like Harm Buiterplein, the advantages of bi-directional charging will be minimal (since there are likely few non-EV loads to offset).

5 Discussion

5.1 Current grid impacts of EV charging

Currently, charging station loads tend to cluster in the early morning and evening, roughly corresponding with the traditional 'double hump' electricity demand pattern. For the electricity grid, this is not ideal, since this will result in a significant increase in the peak electricity load.

However, it has also been observed that there is much potential flexibility for EV charging (due to long idle times), which could be exploited to reduce this peak. However, shifting EV charging times or using bi-directional charging poses a dilemma: longer idle times provide greater EV flexibility, but also result in less occupancy of the EV charging stations. Therefore, to increase EV charging flexibility, more EV charging infrastructure will be required. Currently, this is not an issue, since on average charging stations are used only once every 3 days. But as the ratio of EV to charging stations increases, either additional grid capacity (allowing more EV to charge simultaneously) or more charging stations (allowing EV to be plugged in for longer periods) will be required.

5.1.1 Fast charging compared with slow charging

Fast charging was not measured in this study because it is highly inflexible. Fast charging is typically used for brief periods (1/2 – 1 hour), with very high rates of charge (50 – 150 kW) and almost no idle time (0 – 20 minutes) (Sadeghianpourhamami, Refa, Strobbe, & Develder, 2018). In addition, users of fast charging expect their EV to be fully charged as quickly as possible (Bailey & Axsen, 2015). Therefore, it provides few options for managing grid loads, and is a load source which must be accommodated rather than exploited.

5.2 Future grid impacts of EV charging

It is difficult to predict how EV charging patterns will develop over time. In this study, it was assumed that charging patterns observed to date will be representative of the future. If this assumption is correct, then simulations reveal that EV charging simultaneity is likely to decrease as the number of charging stations increases (assuming that each charging station is still used at most once per day). This finding is important because it shows that on a cable or transformer level, managing EV loads is very impactful (reducing peak EV charging loads on that cable or transformer by up to 50%). However, at a district level, due to the low simultaneity of EV charging (roughly 0,5), managing EV loads between only 2 charging stations will have a minimal impact. Coordinating multiple charging stations, on the other hand, can consistently reduce the peak load from EV charging at a district level by more than 10%. Bi-directional charging could potentially reduce this peak load even further, but this approach is highly dependent on other load patterns in the district.

5.2.1 Uncertainty

Several assumptions were made in this study which have a large influence on the results. These assumptions are described here.

It was assumed that current EV charging patterns will be representative of the future. It has already been shown that this is not the case, since EV rates of charge have been gradually increasing over the past few years. However, it is not yet clear how quickly these rates of charge will change in the future, and if they will meet some maximum value. Further, it is uncertain if the times when EV are charged will remain the same. The impacts of COVID-19 have been noted in this study, but it remains unclear if this will have long-term consequences.

It was assumed that each charging point would be used at most once per day. If charging points are used more frequently, then all of the results regarding EV load simultaneity and flexibility must be re-evaluated.

5.2.2 Model validation

To minimize uncertainty, the model was validated by simulating results from present, and comparing them with measurements. Specifically, the details of 19 modelled charging points are compared with the 19 measured charging points in Euroborg.

Figure 18 compares the annual load duration curve for the 19 measured charging points with 19 simulated charging points. As can be seen, the simultaneity of the simulated charging points appears to be slightly higher than the measurements, resulting in higher cumulative loads on average. This is likely the result of some of the simplifications of the model, such as defining charging start times on a quarterly basis. As such, it is more likely that charging cycles will overlap. This is not expected to have a large impact on the final results, because the simultaneity has been shown to decrease significantly (towards 0.5) with a larger number of simulated charging points.

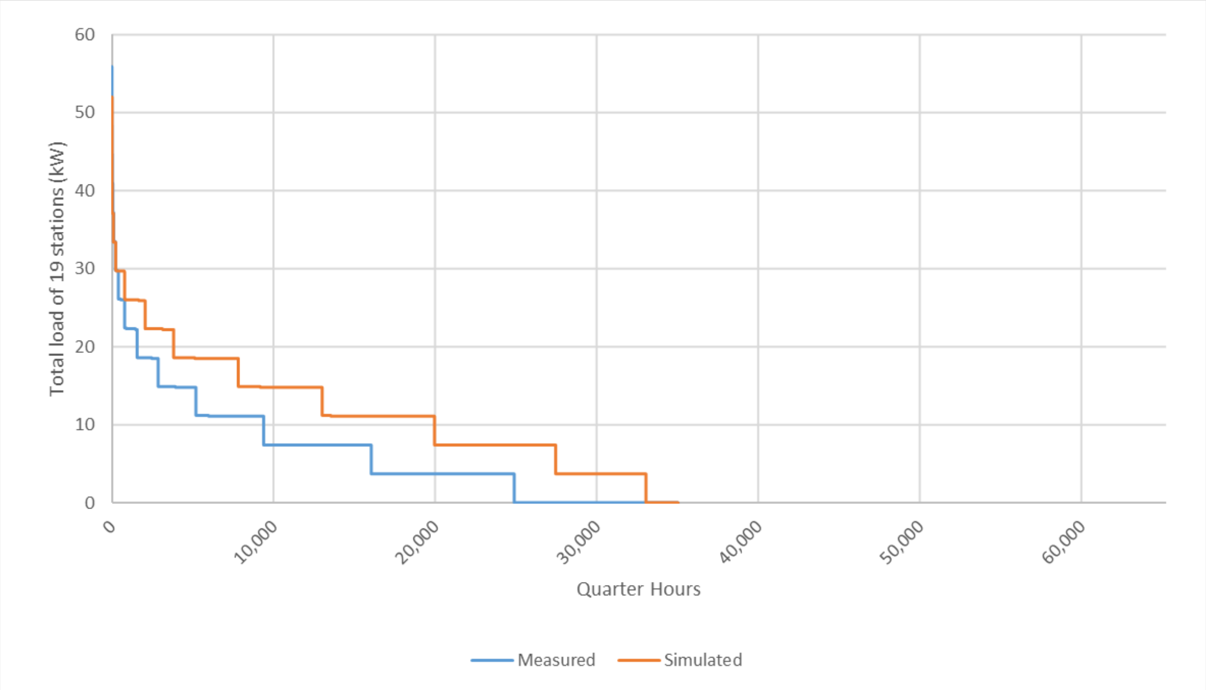

Figure 18: Comparison of modelled and simulated load duration curve for one year

Figure 19 compares the behaviour of an average simulated charge point with an average measured charge point. For the most part, the values are comparable. The simulated charge points tend to have a slightly higher power and a slightly longer charge time, resulting in slightly more energy consumed per charge cycle on average. In contrast, the average idle time for the measured charge points tends to be longer than the simulated idle time. The annual number of charging cycles are close to 100 in both cases. In summary, the behaviour of a simulated charge point is very comparable with a measured charge point, indicating that the results of the model can be trusted.

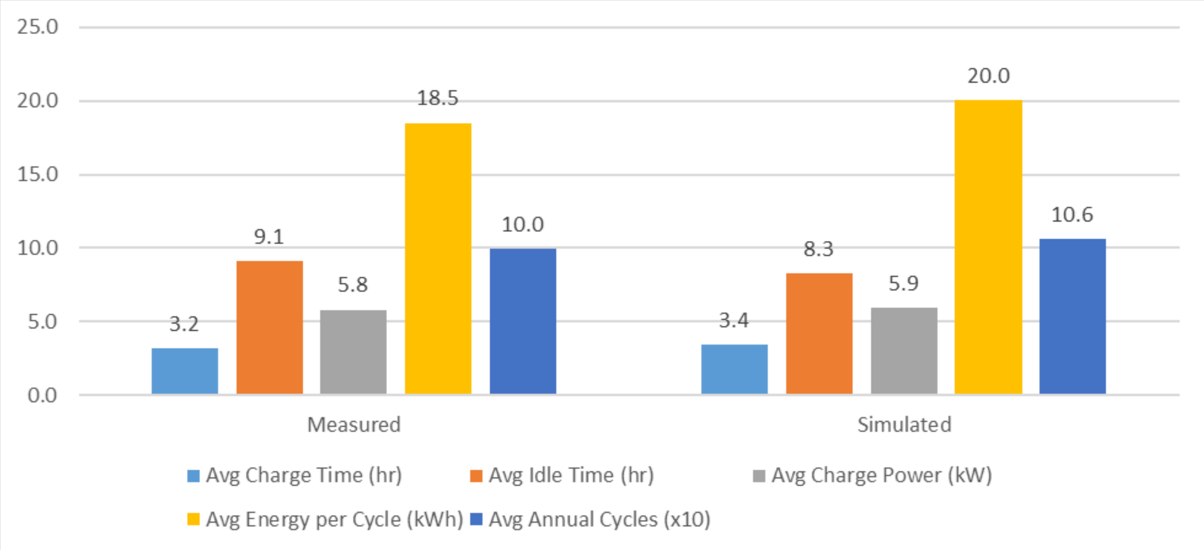

Figure 19: Comparison of an average measured and simulated charge point

5.3 Possible strategies to reduce grid impacts

The different scenarios present different strategies to reduce grid impact. Coordinated charging was highly effective at reducing peak loads at a local level (i.e., at an individual cable or transformer), but less effective when considering a city-wide level (due to the expected decrease in charging simultaneity as the number of charging stations increases). Coordinated loads provided a larger, and more consistent, reduction in grid loads. However, coordinating hundreds of charging stations is complex. Finally, bi-directional charging provides a significant amount of potential energy storage, but how effectively this storage can be utilized is highly situational. Table 4 compares the peak reduction potential for the different scenarios, at both the PED level and the individual cable level. All results are estimates based on the Euroborg charging patterns, and are representative of the other charging patterns.

Table 4: EV charging peak reduction potential for different scenarios

Scenario	EV Peak Reduction (PED level)	EV Peak Reduction (cable level)
Coordinated Charging	0-7%	0-50%
Coordinated Loads	11-14%	0-74%
Bi-directional	13%*	0-80%

**peak reduction includes shifting non-EV loads*

5.4 Applicability of results for other cities

It is notable that the charging patterns from Euroborg (a mixed commercial-residential area) did not resemble either the at-home or at-work charging patterns described by Elaad, but rather a mixture of the two types of patterns. The Harm Buiterplein (park and ride) charging pattern was also distinctive. There may be other charging pattern 'types' which are not yet identified. In any case, these observed charging patterns provide some insight into how EV charging patterns might evolve in different use areas. In order to properly plan and manage energy infrastructure in a PED, it will be important to know which EV charging pattern is likely to apply in that particular case. The more specific the charging pattern which is referenced, the better a PED can plan to accommodate and control it.

Other cities can use the charging patterns presented in this study as a basis for planning EV charging infrastructure in similar PEDs (specifically, mixed commercial-residential areas, and park and ride areas).

6 Future work

No measurements of EV charging in purely residential and purely commercial areas were made in this study. Based on other studies, a residential charging pattern was assumed. But as was observed in Euroborg, not all neighbourhoods follow the 'at-home' or 'at-work' charge patterns observed in other studies. Therefore, it is important to properly categorise a neighbourhood's charging patterns before charge control strategies can be analysed and implemented.

As noted earlier, average EV rates of charge are expected to continue increasing in the coming years. A longer-term study will be required to determine the rate of increase and to plan charging infrastructure accordingly.

One of the findings in this study is that EV charging simultaneity is expected to decrease as the number of charging stations increases (i.e., more people are expected to charge their EV during 'non-standard' times). However, this finding should be validated with future measurements.

Additionally, a power flow analysis of the grids in the PEDs should be performed, using the charging patterns presented here as inputs. Such an analysis would give insight into the potential of EV charging to overload sections of the grid (resulting in a local outage), and voltage variations/instability which could result from EV charging. Such problems could necessitate additional grid reinforcement or power quality management systems, such as batteries.

Finally, the impact of COVID-19 has been observed in reduced rates of EV charging. It will be important to study whether this reduction has a continued impact in the coming years (as people work more from home), or if EV charging return to a sort of 'status quo'.

7 Conclusions

EV are expected to be a major consumer of electricity in the future; a single EV could consume as much as an average Dutch house, and with a higher average load while it is charging. This study illustrates the tendency for EV to cluster their charging at specific times of day (depending on the type of area being looked at, e.g., residential, commercial, park and ride), and also shows the tendency of EV charging power to increase over time. Therefore, EV charging will put significant strain on existing grid infrastructure if nothing is done to mitigate these impacts.

To estimate the future impacts of EV charging on the grid, a model of EV charging was developed and validated using the measurement data from this and other studies.

In Euroborg, the peak load from EV charging was found to be 78.4 kW. However, this value is expected to increase as the occupancy EV charging stations increases. For example, as occupancy of EV charging stations increases from once per 3 days to once per day, the peak load is expected to increase to 153 kW.

As the number of charging stations increases, the peak load from EV charging is also expected to increase. However, the rate of peak load increase is expected to increase more slowly than rate of the increase in charging stations. For example, when going from 19 to 57 charging stations (a 300% increase), the peak load is expected to increase from 153 kW to 413 kW (a 270% increase). This discrepancy results from the fact that, based on current observations, EV charging simultaneity is expected to decrease towards approximately 50%.

Three scenarios were modelled to estimate how the peak load from EV charging might be reduced. By limiting the loads of pairs of EV charging stations, peak load on an individual cable can be reduced by up to 50%. At the level of the PED, peak load can be reduced by up 7% (although this value decreases sharply as the number of charging stations in a PED increases). By limiting the loads of all charging stations combined, peak load on an individual cable can be reduced by up to 74%. At the level of the PED, peak load can be reduced by 11-14% (although this value decreases sharply as the number of charging stations in a PED increases). By allowing EV to charge as well as discharge, peak load on an individual cable can be reduced by up to 80%. At the level of the PED, peak load (including non-EV loads) can be reduced by roughly 13%.

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