CHARGE MANAGEMENT OF ELECTRIC VEHICLES AT HOME

Testing smart charging with a home energy management system

ENEXIS NETBEHEER enpuls Elaadnl MAXEM

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Management summary

Household energy consumption is on the rise with the advent of large energy-consuming appliances, such as electric vehicles (EVs) and heat pumps. This increases the demand for energy and (peak) capacity demand. Managing these appliances can eliminate the need for major investments in grid reinforcement. Such capacity management is a prerequisite for an affordable energy transition. One possible solution is to introduce charge management for electric vehicles at households using a home energy management system (HEMS).

Research question

This pilot study examines the role of a HEMS in communicating a capacity profile from a grid operator to households. The main research question is: *To what extent can grid operators lower the peak load of the low-voltage electricity grid by controlling the charging of electric vehicles at households, and how do consumers experience this?* This pilot is designed to provide insight into the required technology, as well as the impact and acceptance among households. The goal is to identify a scalable solution that provides flexibility to grid operators and avoids grid congestion. The pilot is an initiative of Enexis Netbeheer, Enpuls, ElaadNL and Maxem. It was initiated in September 2017, with a lead time of two years, consisting of one year of preparation and one year of charge management.

Research method

To answer the research question, the researchers set up a pilot study. The participants in the study were 138 Dutch households with a battery electric vehicle (BEV), a home charge point and a HEMS. Charge management was operationalized by sending maximum capacity limits from the distribution system operator (DSO) Enexis to the aggregator Maxem, managing the charging sessions of the EVs via the HEMS. Both dynamic and static charge profiles were applied and studied. The degree of constraint of the charge points was changed regularly to determine the impact of charge management.

Via a mobile application, participants had the possibility of manually overriding the control signal. Half of the participants were given a financial incentive to provide flexibility to the DSO, which depended on their use of the override function. To gain deeper insight into the attitude and experience of end users towards charge management, the data research was accompanied by behavioral research.

Results and conclusions

Applying charge management via a HEMS at households can significantly reduce the grid impact of charging EVs. The pilot found that dynamic charge management resulted in a 40% reduction in peak load on the low-voltage grid. A concept with static charge management proved not to be useful: it shifted the peak load to a later point in time without reducing its magnitude.

Charge management was successfully operationalized using the Open Smart Charging Protocol (OSCP). Some practical obstacles occurred, such as calculating the impact of charge management. Furthermore, currently none of the available protocols both fully matches the exact use case of this pilot and is widely accepted or used by a large part of the industry.

We conclude that charge management via a HEMS has a minimal effect on the attitude and experience of participants. The behavioral research shows that participants generally have a positive attitude towards charge management. A large majority of the participants are willing to continue using charge management. There was no observable difference in attitude towards charge management between the start and end of the pilot.

Although data shows that participants did not use the override function frequently, most participants indicated that having the function is important. Some even described it as "essential." The existence of a financial incentive for the participant had no impact on the attitude and experience towards charge management. Data shows that participants who were given a financial incentive did not exhibit deviant charging behavior. Despite this finding, participants indicate they find financial incentives attractive and hold a positive attitude towards them.

Recommendations

Based on the results and conclusions, the researchers recommend the following areas for further research:

- Trying different communication protocols and examining the communication and data exchange between parties.
- More focus should be placed on creating a standardized protocol that can communicate with both EVs and heat pumps. Researchers should also explore how to harmonize and standardize a possible solution that is not dependent on a specific DSO or aggregator.
- The method for calculating the impact of charge management needs to be studied in greater detail to provide a more accurate calculation of grid impact.
- The reasons why people value the override function should be studied in greater depth. Instead of measuring afterwards, direct user-interaction can provide more insight into why people use the override function.
- Some participants indicated they would have appreciated more information. Therefore, more research should be conducted on how to provide such information.
- Different customer propositions should be studied to investigate whether people are willing to provide more flexibility in return for an (extra) financial benefit.
- Consider a larger pilot group and, if possible, a more diverse group and different household compositions.
- Map and monitor where home energy management systems will arise and within what timespan. Follow this up by considering the development of such devices, along with the quantities and locations in which they are expected to be adopted.

List of abbreviations

BAU	business as usual
BEV	battery electric vehicle
BRP	balance responsible party
DSO	distribution system operator
ELMO	Enexis Load Management Optimizer
EV	electric vehicle
HEMS	home energy management system
OCA	Open Charge Alliance
OCPP	Open Charge Point Protocol
OSCP	Open Smart Charging Protocol
PHEV	plug-in hybrid electric vehicle
PV	photovoltaic
TSO	transmission system operator

List of definitions

aggregator
The role of the aggregator is described as a demand service provider that combines multiple flexibility sources and offers this flexibility to DSOs, TSOs, BRPs or other market parties

avoided usage
The (calculated) amount of energy that was not used because of charge management in a specific time period

capacity profile
A time series of values of the available grid capacity for charging for the next day

charge management
Charging an EV via a home energy management system using external DSO signals

domestic electricity consumption
Energy use from domestic electric appliances that cannot be controlled (e.g. water heater, stove, oven)

DSO
The role of the DSO is to operate, maintain and, if necessary, develop the distribution system within its territories, including interconnections to higher-level systems. This includes ensuring that sufficient grid capacity is available and the system's stability criteria are met.

setpoint
The power or capacity value that is set by an external signal, which has to be followed/taken into account

transformer substation
A substation where energy is converted from medium voltage to low voltage

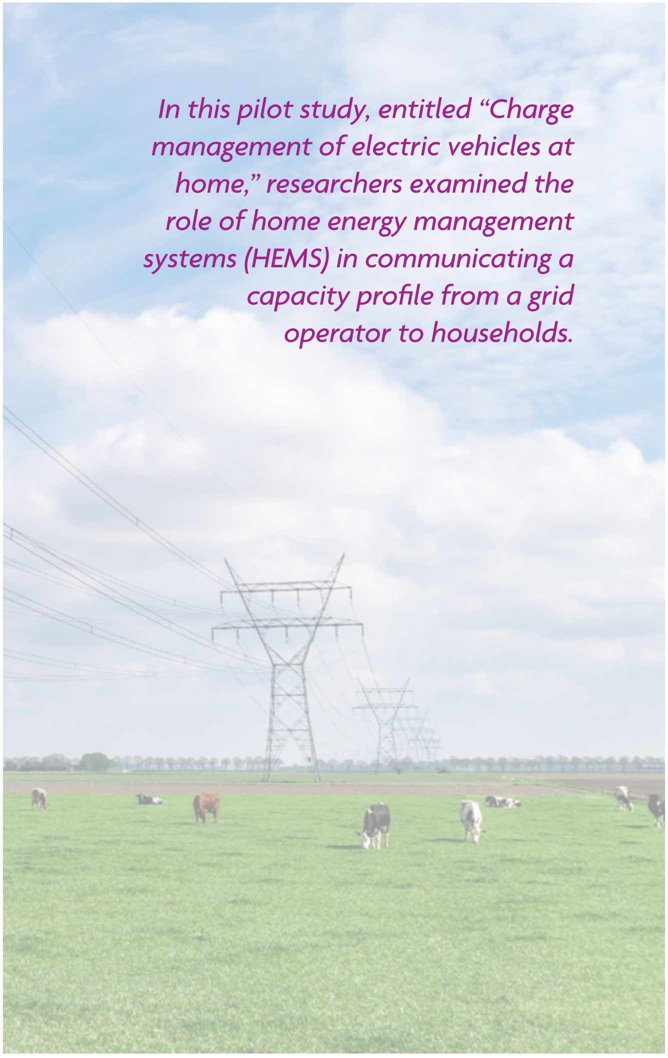
1. Introduction

We are in the midst of an energy transition. Step by step, society is transitioning from fossil fuels to renewable energies like solar and wind power, and from gas to electricity. Electricity consumption is on the rise in households, due mainly to the introduction of heat pumps and electric vehicles. A trend towards more electrification is expected in the upcoming years. This will lead to more diversity in household energy consumption, where households with a heat pump and one or more electric vehicles will have a higher energy and (peak) capacity demand than households without these appliances.

The electricity grid in the Netherlands consists of three levels: high voltage, medium voltage and low voltage. Rising household electricity consumption and capacity demand creates a peak load in the low-voltage grid and impacts transformer substations. Additionally, current household grid connections are not designed for simultaneous electric cooking, electric heating and charging an electric vehicle. Smart use of large energy-consuming appliances decreases simultaneous capacity demand and so helps eliminate the need for major investments in grid reinforcement. Such energy management is necessary for keeping the energy transition affordable.

One way to potentially avoid grid reinforcements is to communicate the available grid capacity to households and use this to control the capacity demand of large electric appliances such as electric vehicles and heat pumps. In this pilot study, entitled "Charge management of electric vehicles at home," researchers examined the role of home energy management systems (HEMS) in communicating a capacity profile from a grid operator to households. The pilot provides insights into the required technology, and their impact and acceptance among households in controlling large energy-consuming appliances. The goal is to identify a scalable solution for flattening the capacity demand of large energy-consuming appliances in households; one which provides flexibility and prevents grid congestion. Such a solution must be applicable regardless of the grid operator or aggregator.

The project was initiated in September 2017 with a lead time of two years. These two years consisted of one year of (technical) preparation and participant recruitment and one year of actual household charge management. The project was initially intended to include heat pumps as well as electric vehicles. However, the idea to include heat pumps was discarded due to various factors including the low number of heat pumps among participants, the high variety of types of heat pumps and the lack of a standardized communication protocol. This report describes the pilot set-up in detail, followed by the results, conclusions and recommendations for further research.



In this pilot study, entitled "Charge management of electric vehicles at home," researchers examined the role of home energy management systems (HEMS) in communicating a capacity profile from a grid operator to households.

1.1 Stakeholders

The “Charge management of electric vehicles at home” pilot study is an initiative of Enexis Netbeheer, Enpuls, ElaadNL and Maxem. The Urban Technology department of the Amsterdam University of Applied Sciences was also a partner in the pilot project, responsible for designing and conducting behavioral research.

ENEXIS NETBEHEER

Enexis Netbeheer is one of the seven distribution system operators (DSO) in the Netherlands. The main task of a DSO is to install and maintain the energy grid and distribute electricity from where it is generated to houses and businesses. Enexis Netbeheer is part of Enexis Group.

enpuls

Enpuls is a young, independent Dutch organization of visionaries, business thinkers and concept developers focusing on accelerating the energy transition. Enpuls develops visions of how the energy transition can be effectively facilitated and achieved. Enpuls is part of Enexis Group.

Elaadnl

ElaadNL is the leading knowledge and innovation center in the field of Smart Charging and the charging infrastructure in the Netherlands. It is a joint initiative operated by the Dutch DSOs.

MAXEM®

Maxem is a specialist in energy management for households and commercial locations. Controlling between 1 and 255 charge stations per location, Maxem allows homeowners and property owners to seamlessly integrate e-mobility and sustainable energy into existing energy infrastructure.

Amsterdam University of Applied Sciences

Amsterdam University of Applied Sciences was the behavioral research partner during this pilot study. The Urban Technology research program studies solutions for urban challenges in the field of mobility and logistics, spatial planning, renewable energy and circular economy.

2. Research design

This chapter describes the research design in detail. The first paragraph describes the research questions, followed by an in-depth description of the research method. The subsequent paragraph elaborates on the technique used. The chapter ends with an explanation of how charge management was operationalized during this pilot study.

2.1 Research question

This research focuses on answering the following main research question:

To what extent can DSOs (i) lower the peak load of the low-voltage electricity grid by (ii) applying charge management to electric vehicles among households, and (iii) how do consumers experience this?

To answer the three components of the main question underlined above, the researchers formulated sub-questions related to impact, technology and acceptance. The sub-questions are formulated as follows.

(i) Impact

What is the impact of dynamic and static charge management on the peak load of the low-voltage electricity grid?

(ii) Technology

How is household charge management operationalized in this pilot?

a. Which adjustments to applied protocols are necessary to enable charge management via a HEMS?
b. What practical obstacles arise in operationalizing charge management?
c. What does the technical implementation look like and how is this coordinated between the stakeholders?

(iii) Acceptance

How does charge management via a HEMS and a financial incentive affect the participants' attitude and experience towards charge management?

2.2 Research method

The researchers set up a pilot study to assess how controlling home charge points impacts the grid and the households involved. Households with battery electric vehicles (BEV) and a home charge point were invited to participate in the study. A HEMS was used to gain access to the home domain. In this pilot, the HEMS Maxem was used to measure and control energy flows among the households. Maxem is a commercially available product that supports households in managing their energy flows and prevent them from exceeding the capacity of their grid connections. It can, for example, balance generated solar energy and the charging of an electric vehicle. It also provides insight via an application on mobile devices.

2.2.1 Recruitment of participants

The initial aim was to recruit a total of 250 households. To recruit participants, the product Maxem Flex was introduced alongside the regular, existing Maxem Home. In addition to being able to manage in-home capacity demand based on the fixed maximum connection capacity, the Maxem Flex was expanded to offer the functionality of receiving DSO signals that can apply a dynamic grid limit. The product normally has a retail price of €495 (status: 2017) and a monthly fee of €6.95. An incentive of €250 was offered per participant to make the Maxem Flex product more attractive than Maxem Home. The incentive was used to lower both the retail price and to give a 50% discount on the monthly fee for the Maxem.

To attract customers to participate in the pilot, two different methods were applied: (i) discount on retail price and monthly fee and (ii) incentives for existing Maxem users.

(i) Discount on retail price and monthly fee

Maxem Flex was offered with a discount on the retail price and monthly fee at the start of the pilot. It quickly became apparent that, despite the fact that the price was lowered, not all new customers chose Maxem Flex. The reason for this is that customers do not always purchase the Maxem directly. More often, the Maxem is purchased by installation companies who resell their product to the end user. Installation companies are not incentivized to purchase the cheaper product (in this case, the Maxem Flex) because this influences their financial margin. Furthermore, it is more complex for them to resell the Maxem Flex product, because the details of the pilot have to be explained to customers. Eventually, this method resulted in insufficient customer attraction for the project to proceed. Therefore, the recruitment period (which started in November 2017) was extended.

(ii) Incentives for existing Maxem users

To acquire enough participants, the researchers decided to recruit via the existing database of Maxem users. Since these existing customers had already purchased a Maxem Home without any discount, they were offered a cashback incentive for joining the pilot. The cashback amount was equal to the discount that new Maxem Flex customers were offered.

This approach proved to be more efficient than recruiting new customers, because existing Maxem users already owned a Maxem. Furthermore, existing Maxem users could be reached more easily via existing communication channels. Recruitment ended in September 2018. The final participant group consisted of 138 households. This still deviates from the initial aim to recruit 250 households. In light of the difficulties in recruiting participants, the researchers decided to start the pilot with this lower number of households. Although the initial aim was to recruit at least one-third of the customers in the Enexis area, this criterion was not met.

The participants agreed to hand over control of their charge point to the aggregator (Maxem) on behalf of the DSO (Enexis). Via the mobile application that comes with Maxem, participants were given the option of manually overriding the control of their charge point at any time (see Figure 1). By clicking the override button, participants could temporarily stop the control signal and charge their vehicle at the regular speed. After 24 hours, the default control signal was restored.

Because the participants were distributed throughout the Netherlands, they were modelled as if they were virtually connected to the same low-voltage network. When there was an imminent risk of exceeding the grid capacity of this (virtual) network, the power consumption of the charge points could be reduced by remote control. For that purpose, the DSO sent a control signal to the aggregator, and the aggregator distributed this signal to all participants via a HEMS.

2.2.2 Research population

The research population consisted of 138 participants, all of whom possess the HEMS Maxem, own a home charge point that is connected to the HEMS, drive an electric vehicle and have signed up to participate in the pilot study. To investigate different control strategies, four groups of participants were created, as described below. Participants did not know which group they were assigned to or which profile was applied.

Figure 1: Interface of the Maxem mobile application

Group 1: Dynamic signal

In this group (34 participants), dynamic charge management was applied. This means that the network capacity available for charging is allocated evenly between the charge points that are active (actually charging a vehicle). However, the available network capacity for charging changes continuously depending on the fluctuating amount of domestic electricity consumption (see Figure 2). This domestic demand already occupies part of the network capacity and cannot be controlled. By forecasting domestic electricity consumption (which is highly predictable), the remaining network capacity available for charging can be determined. Next, the active charge points can be controlled accordingly, so the total load does not exceed the capacity of the network. Figure 3 shows an example of the resulting dynamic control signal that is sent to the active charge points.

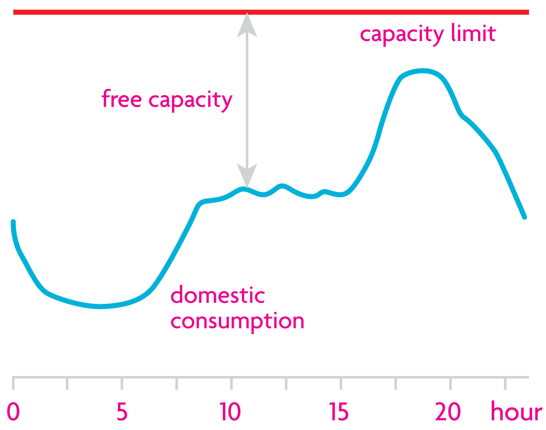


Figure 2: Example domestic daily load pattern

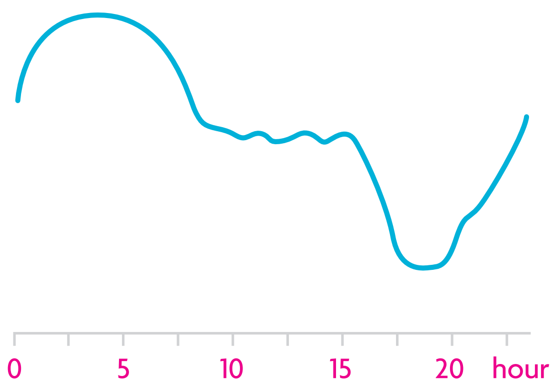


Figure 3: Example daily dynamic control signal for EV charging

The advantage of dynamic control is that it potentially leads to optimal utilization of the network capacity. The downside is the complexity of the system, which makes it less transparent for the end user and more susceptible to errors or malfunctioning.

Group 2: Static signal

In this group (34 participants), static charge management was applied. This means that all charge points receive a fixed amount of capacity, regardless of the currently available capacity in the network and regardless of the state of the charge points (active or inactive). The allocated amount of capacity for charging was only reduced during daily time periods of known high domestic electricity consumption. These peak hours are in the evening between 17:00 and 22:00. Therefore, the signal for static control during a day looks like Figure 4.

The advantages of static control are that it is robust and easy to implement and is understandable and predictable for the end user. The question, however, is whether it helps to optimally utilize the electricity network.

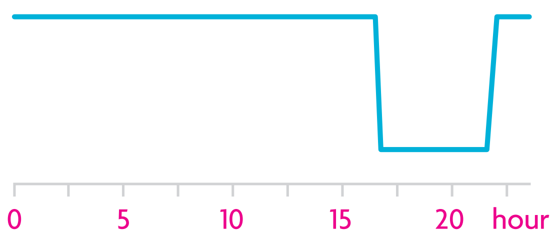


Figure 4: Example daily static control signal for EV charging

Group 3: Dynamic signal with incentive

In this group (36 participants), dynamic charge management was applied (as in group 1) but combined with a financial incentive. Unlike group 1, the participants in group 3 received a financial reward for providing flexibility to the DSO. This reward depended on the use of the override function to temporarily cancel charge management. Each participant in the incentive-group was given a fictitious budget of €50. They could use the override function twice a month without financial consequences. With every third or more overrides, €1 per override would be deducted from their budget. This allowed researchers to study the influence of a financial incentive on user behavior.

Group 4: Static signal with incentive

In this group (34 participants), static charge management was applied (as in group 2), also combined with a financial incentive. The mechanism to apply this incentive was the same as described for group 3.

2.2.3 Impact on the network

For each group, the network was modelled as if the participants were virtually connected to the same low-voltage network. To investigate the impact of charge management on the network, the charge points of the participants in each group were controlled throughout one year (September 2018 through August 2019). During this period, the degree of constraint of the charge points was changed regularly by varying the assumed available network capacity. This enabled researchers to study the influence on the peak load and the extent to which the peak load could be reduced without causing inconvenience for the end user.

To determine the impact of charge management on the network, the researchers compared the network load with and without charge management. This reveals the extent to which the network's peak load is reduced. To achieve this, the researchers measured regular domestic electricity consumption and the electricity consumption of each charge point separately at 15-minute intervals for each household. Adding all individual measurement data per group enabled the researchers to simulate the total load of the (virtual) network.

When charge points are constrained, this reduces the peak load of the network. For each charge point, it is possible to estimate the amount of energy that was curtailed (the "avoided" or "shifted" energy). This is the specific amount of energy with which the network would have been loaded if no constraint had been applied. Knowing this enables us to estimate the peak load of the network without constraint and compare it to the electricity consumption that has been measured with constraint. This reveals the extent of peak reduction caused by charge management. Figure 5 illustrates this principle.

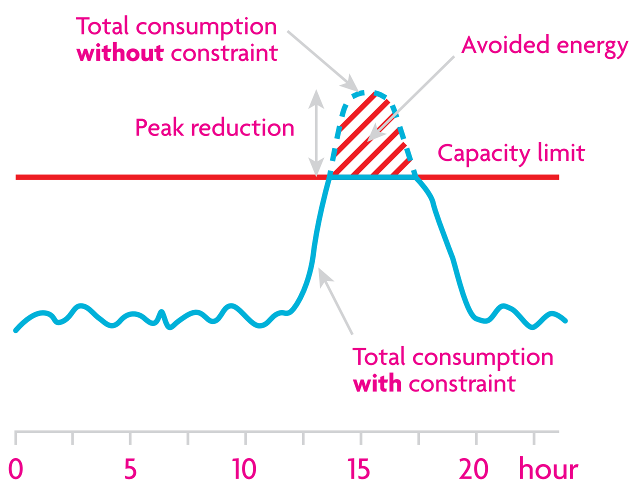


Figure 5: Determining how charge management reduces peak load

2.2.4 Behavioral research

To gain deeper insight into the attitude and experience of the end user with regard to charge management, the data research was accompanied by behavioral research. Since controlling a charge point affects the charge speed of the electric vehicle, participants might notice that it takes longer than usual to fully charge the battery. As mentioned before, all participants had the possibility of manually overriding the control signal at moments they wanted to charge with regular charge speed. They could do so via the mobile HEMS application with a single action: clicking a button. These overrides were registered and analyzed. Behavioral research was conducted in the following three steps to investigate the participants' perception of charge management, the override function and financial incentives:

1. Firstly, a quantitative baseline measurement was carried out. At this point (September 2018), no charge management had been applied yet. Questions were asked about basic characteristics of the participants, behavior in terms of electric mobility, motivation, experience with the HEMS without charge management and their expectations. In total, 91 unique and complete surveys were filled in.
2. Secondly, after six to seven months of charge management, a qualitative measurement was conducted based on twenty interviews (March through April 2019, five respondents per group). Respondents were selected based on their use of the override function. Both participants who used the override function frequently and respondents who did not use the override function were included. Topics consisted of experience and opinion on charge management, usage and understanding of the override function and attitude towards financial incentives and charge management.
3. The final behavioral measurement was a second quantitative survey conducted after one year of charge management (September 2019). Participants were asked questions about the same topics as before, now with the addition of their experiences with charge management, the override function and the financial incentives. A total of 89 unique and complete surveys were filled in. To determine whether participants had a different attitude at the start than at the end, the researchers asked them to provide their zip code in the two surveys. This made it possible to link the two surveys to each other and see whether there were any differences in the users' responses. The zip code was used because it is a general number that cannot be traced to individual households, thus complying with privacy requirements.

In total, demographic data on 103 unique participants is known. This means that a large portion of the respondents filled in both surveys.

2.3 Technology

This section describes the technical aspects of the research design and provides more detail on how charge management was operationalized among the households.

2.3.1 Architecture

The architecture used during the project supports different functionalities. One of the necessary functionalities was the ability to control in-home capacity demand. Since no direct technical interfaces from the DSO to the end user were available, Maxem was used to perform this in-home power usage control. The Maxem platform was adapted to receive DSO signals.

These signals were created and sent by a DSO system called Enexis Load Management Optimizer (ELMO), a system developed by Enexis for pilot projects related to charge management of electric vehicles. This system has two options for sending signals:

- Sending grid signals based on (manual) DSO input
- Sending grid signals based on historical data and/or weather data

Based on privacy and scalability aspects, the choice was made not to send DSO signals to all individual HEMS devices, but to send aggregated signals and let an intermediate system divide the available power over the different households (in this case, Maxem). This choice not only addresses privacy aspects by using signals that are aggregated rather than individual, but also allows for the intermediate system or party to use its own specific "algorithm" for dividing the aggregated signals among the individual systems. Although this was not done in the project, this algorithm could, for example, be based on customer subscriptions with different priorities and pricing. Under current rules and regulations, DSOs are not allowed to offer different pricings to households.

The DSO signals that were used were both static signals and dynamic forecast signals. The signals consisted of the maximum amount of available capacity in the grid for the next 24 hours. An updated signal was sent every 15 minutes ("rolling forecast"). The following types of signals were used:

- **Static signals:** Fixed profiles of 15-minute values that were uploaded manually into the ELMO system. The manual upload contained seven days of 15-minute values with the maximum capacity per timeslot, per day of the week.
- **Dynamic signals:** These signals consisted of 24-hour forecasts of 15-minute values with the maximum capacity for that timeslot. These forecast signals were based on historical data and weather information of a weather station geographically located near the center of the pilot group. Weather data was included because data showed that the majority of the households had solar panels (PV). This has a large influence on the load of the grid. Using self-learning (comparing weather forecasts and actual observations), the algorithm was trained to include the impact of the weather on the power consumption and production forecasts of the relevant pilot groups.

See Figure 6 for a schematic overview of the architecture described so far.

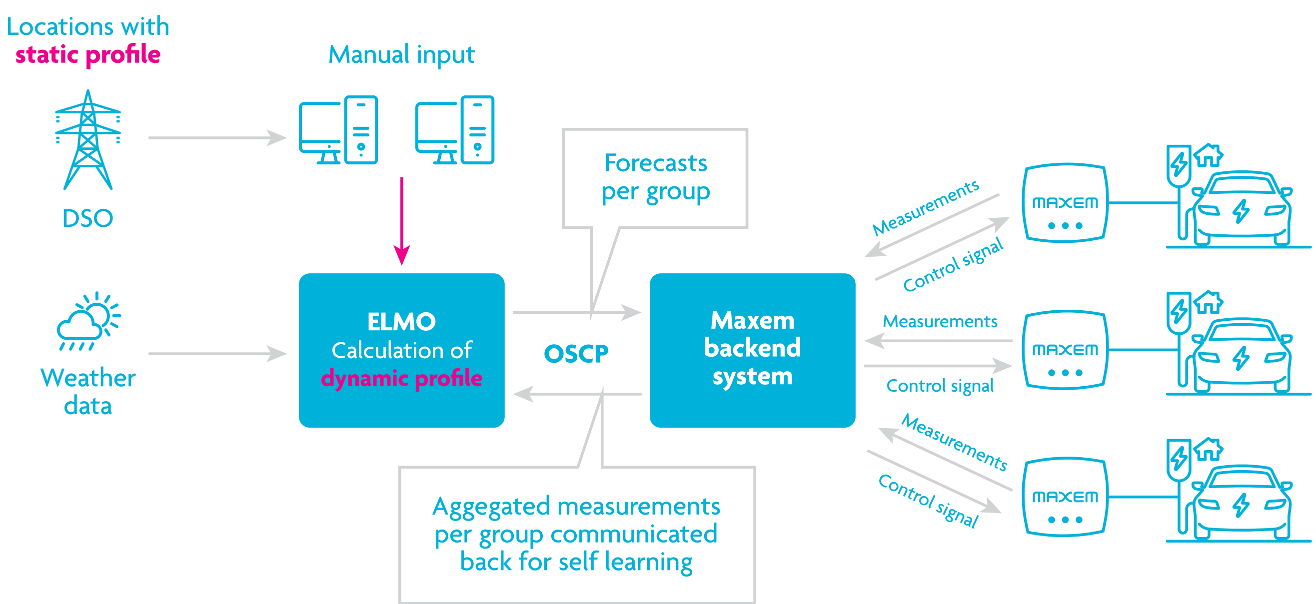


Figure 6: Overall technical architecture

Based on these forecasts and the grid capacity, the researchers calculated maximum limits. Because of the use of maximum limits for groups of households, the challenge was to be able to make a statement about the amount of energy that was not used because of charge management. Because it is impossible to directly measure not-used energy, this was calculated by the HEMS devices. This calculation is described in detail in paragraph 2.3.6 below.

The following paragraphs provide more details about the architecture of the pilot.

2.3.2 ELMO

As mentioned earlier, the abbreviation ELMO stands for Enexis Load Management Optimizer. This system was designed for pilot projects. Its main functionalities are:

- containing topology information for specific parts of the grid;
- collecting metering data from an external source;
- using this metering data to create a forecast of the grid usage;
- translating this grid usage forecast into a forecast of available grid capacity; and
- communicating this forecast of available capacity in the form of a DSO limit to an aggregator that can adjust its power usage to comply with this maximum limit.

Because it was developed as a pilot system, ELMO is not connected to the DSO's existing internal systems. The layout of the grid can be stored in the system as a simple model. This part of the grid then has to be measured, which is done using external metering devices. This involves metering of power and, for some locations, includes weather information (forecasts as well as observations). The metering data is collected by ELMO and prepared to calculate forecasts of power usage and production (i.e. forecasted PV load based on expected weather).

The DSO signal sent by ELMO is calculated by subtracting the forecastable capacity from the maximum grid capacity of the transformer or cable (i.e. the "congestion point") in question. The capacity that is left is then divided among the flexible loads. Flexible loads are not included in the forecast. In this specific project, the loads that can be predicted are the household loads, including PV (based on weather forecasts) and excluding the electric vehicle; see Figure 7.

The flexible loads in this case are the electric vehicles, the charging speed of which can be adjusted using the HEMS.

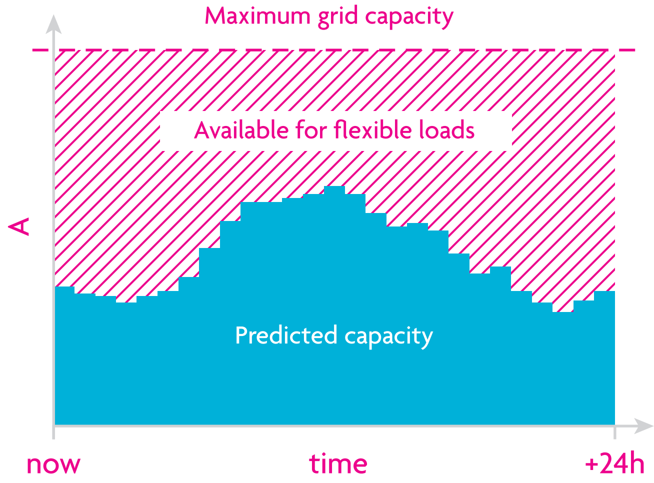


Figure 7: Maximum grid capacity vs. predicted capacity and flexible loads

For this project, ELMO calculated the expected power usage of the households, excluding the EVs that are charging, based on historical data and weather information. This information was combined in an algorithm to calculate the expected load on the grid. The algorithm used was multiple linear regression. The capacity available for the EVs is calculated by subtracting the outcome of the calculation from the maximum grid capacity. This calculated amount was then sent to the Maxem backend system, which converted the aggregated signal into individual signals per household.

2.3.3 OSCP

To communicate the available capacity to the Maxem backend system, the project used a standard protocol. Different standards were considered, such as OpenADR and the Open Smart Charging Protocol (OSCP). The researchers chose to use OSCP for the sake of simplicity, and due to the fact that it matches the use case of this project. OSCP is a free, open protocol maintained by the Open Charge Alliance (OCA).

The main functionality of OSCP consists of communicating available capacity from a utility to parties in the market. It also supports exchanging aggregated metering data between the aggregator and the utility. In this case, metering data from Maxem was communicated to the Maxem backend system, which aggregated the data and forwarded it to the DSO using OSCP.

The Maxem was capable of sending the following types of measurements: total usage, avoided usage and uncontrollable usage. For OSCP to support these different measurement types, a minor adjustment was made in the OSCP messages. This modification was communicated back to the OCA as a possible feature for a next version of OSCP.

2.3.4 Maxem

Maxem's main function is to control the home charge point based on real-time energy data coming from the home grid, charge stations and other devices, such as solar panels and heat pumps. It allows the EV to charge using all the remaining capacity of the home grid while preventing overload.

The new variant "Flex" adds the following functionalities to the Maxem's framework:

- the Maxem backend can accept setpoints from the DSO's system (ELMO) and communicate those via the Maxem device to the charge point;
- the Maxem device determines the amount of energy that has been avoided, by observing the setpoint; i.e. what would the EV have used, had it not been constrained;
- the Maxem backend aggregates and sends the relevant data to ELMO to create a self-learning loop to make the rolling forecast.

Furthermore, the Maxem mobile application needs to show whether the DSO signal is active, and participants should be able to override this setpoint to continue charging without constraint. This adds the following functionalities to the Maxem's framework:

- the mobile app indicates whether the DSO signal is active;
- the mobile app can disable flex, which lifts the individual setpoint. A button was added to switch off the DSO signal for up to 24 hours;
- the Maxem backend registers these overrides as part of the behavioral research to assess the effect of the financial incentive. Each time a participant uses the override button, the mobile app sends a notification to the Maxem backend.

2.3.5 Communication with ELMO

The individual Maxems do not communicate directly with ELMO. Instead, the Maxem backend was adapted to take care of this communication. ELMO sends its forecasted setpoints for each group to the Maxem backend, where they are stored. The Maxem backend then sends individual setpoints to the individual Maxems in each group.

Each individual Maxem in a group sends a report about its energy usage each minute. These reports are aggregated in the backend and stored there. The Maxem backend periodically sends 15-minute reports for each group to ELMO.

2.3.6 Calculating avoided usage

When Maxem constrains the charge point by sending a setpoint, the amount of "avoided" energy must be known in order to determine the impact of charge management. The researchers developed a method for estimating the amount of energy that would have been consumed when charging an EV if the charge point had not been constrained and the DSO signal had not been active. A functionality was added to Maxem's firmware, enabling the researchers to calculate this so-called "avoided usage." The firmware must be capable of handling the following three scenarios:

1. The EV is already charging when it receives a DSO signal

The EV has already started a charging session and receives a DSO signal (see Figure 8):

- While the Maxem is charging, it continuously stores the actual current of the past minute as uncontrolled reference energy when the DSO signal is inactive;
- When the Maxem receives a setpoint for the charge station that activates charge management, the EV continues charging and complies with this constraint by lowering its current.
- For each minute under constraint, the Maxem calculates the difference between the uncontrolled reference energy and the actual measured energy, which yields the avoided energy. This is reported to the backend.
- The uncontrolled reference energy is only valid for up to 15 minutes. Every 15 minutes, a new reference energy is determined by shortly releasing the setpoint and letting the EV charge without constraint for one minute. This generates information about what the actual current would have been had the charge management not been active, which also indicates the avoided usage.

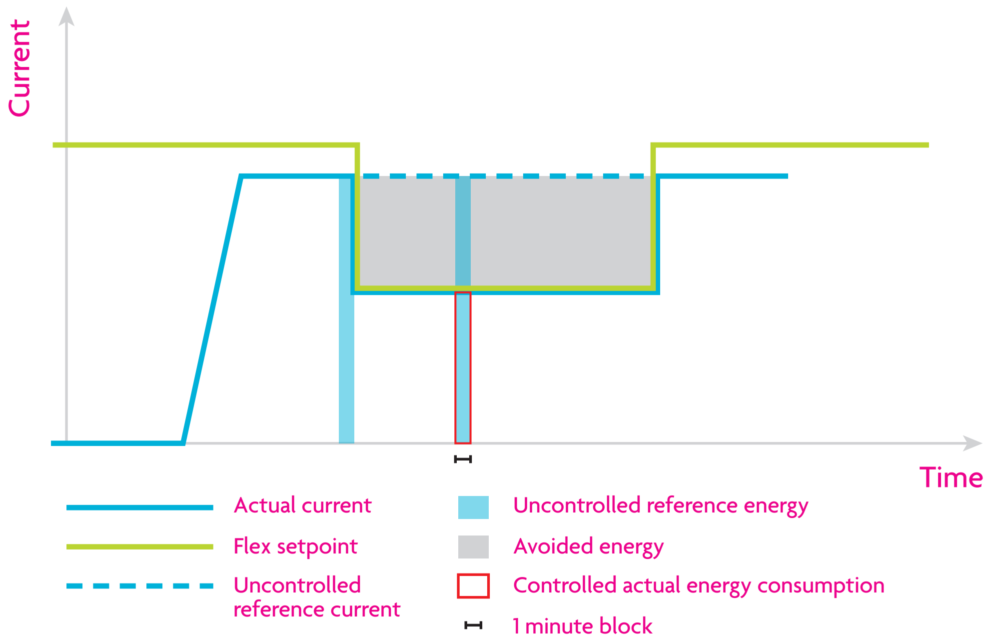


Figure 8: EV is already charging when it receives a DSO signal

2. EV starts charging during grid constraint

Charge management is already active when the EV starts a new charging session (see Figure 9):

- The Maxem runs without constraint for one minute to determine the reference current.
- After this minute, the EV continues charging and complies with the constraint by lowering its current.
- For each minute under constraint, the Maxem calculates the difference between the uncontrolled reference energy and the actual measured energy, which yields the avoided energy. This is reported to the backend.
- The uncontrolled reference energy is only valid for up to 15 minutes. Every 15 minutes a new reference minute is determined by releasing the setpoint and letting the EV charge without constraint during this minute.

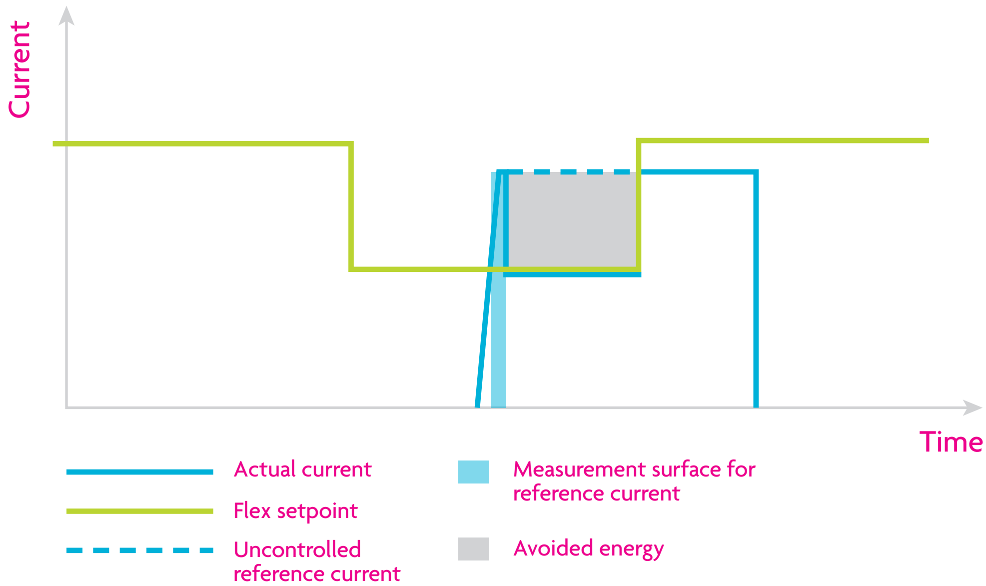


Figure 9: EV starts charging during flex session

3. The EV uses less energy near the end of a charging session

Determining the reference current by disabling the DSO signal for one minute makes the estimation of (unconstrained) EV energy consumption more accurate. However, during this minute, there will be no avoided usage, because the Maxem device releases the setpoint at that time. Data shows that near the end of a charging session, the EV lowers its actual current in a couple of steps. During this "ramp down" period, which can take between 30 and 45 minutes, the avoided usage calculations are less accurate if the reference current remains unchanged. The effect on the calculations is much greater in that case than when running the reference minute regularly (see Figure 10):

- While the Maxem is charging, it continuously stores the actual current of the past minute as uncontrolled reference energy when the DSO signal is inactive.
- When the charge station receives a setpoint that activates charge management, the EV continues charging and complies with this constraint by lowering its current.
- For each minute under constraint, the Maxem calculates the difference between the uncontrolled reference energy and the actual measured energy, which yields the avoided energy. This is reported to the backend.
- The EV starts to ramp down and the actual current drops, making the reference current less accurate. As a result, calculations of avoided usage are too high, since the actual uncontrolled energy is dropping, while the reference current has not changed.
- After 15 minutes, a new reference current is determined by releasing the setpoint and letting the EV charge without constraint during this minute. The current during this minute is lower than the original reference current at the start of the charging session. This method yields a more accurate calculation compared to using the same reference current during ramp-down time.

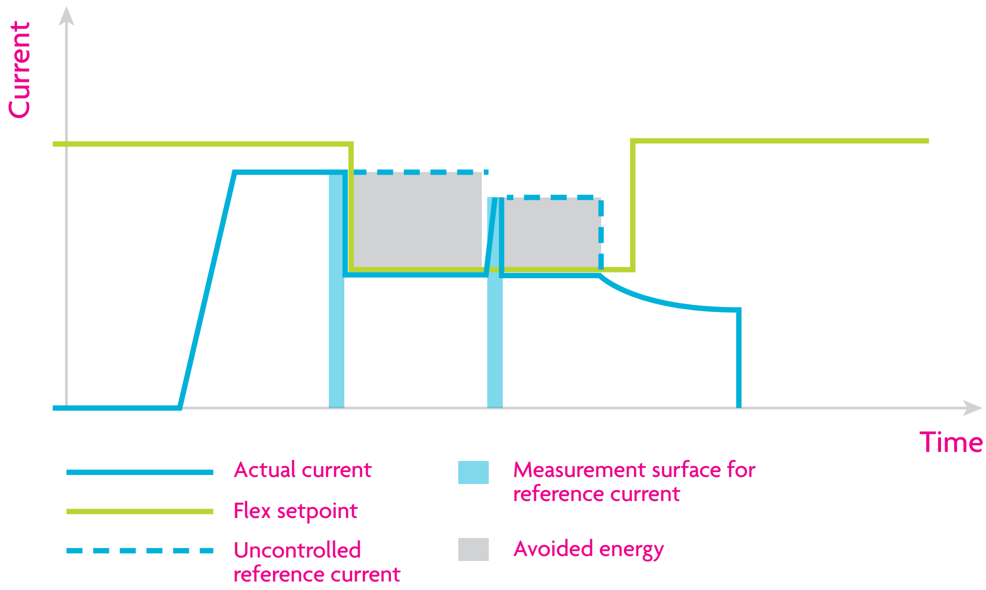


Figure 10: EV uses less energy near the end of a charging session

Since the avoided energy cannot be *measured*, the method described above was developed to *calculate* it. Because the firmware was adapted to handle these three scenarios, researchers can make an accurate calculation about the actual impact of charge management.

2.4 Charge management

As mentioned earlier, the goal of charge management is to attain a maximum peak load reduction of the network without causing inconvenience to end users. To examine this, the degree of constraint of the group of charge points was varied during the pilot period, and the effects on the network load were monitored.

2.4.1 Dashboard

To monitor the results of charge management, an interactive dashboard was built. The dashboard enabled researchers to monitor all parameters necessary for examining the impact of charge management. The dashboard allows researchers to zoom in on every detail, at any date and time. For example, Figure 11 shows part of this dashboard with a visualization of the load profiles for one day for one of the dynamic signal groups.

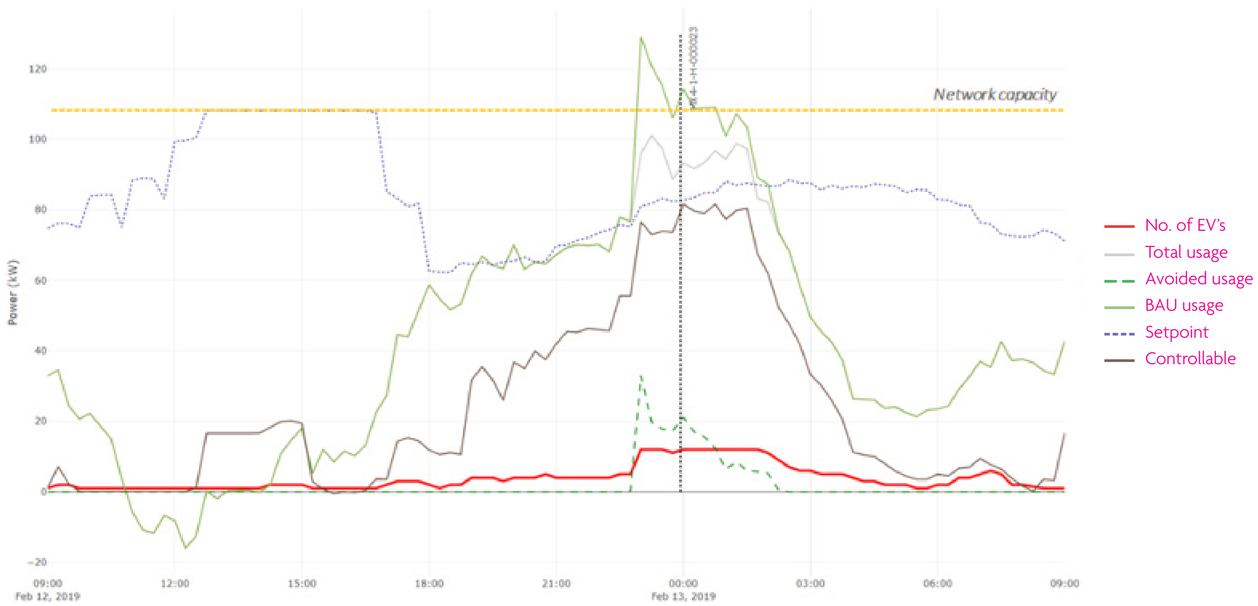


Figure 11: Visualization of load profiles for dynamic charge management

Table 1: Explanation of terminology used in the interactive dashboard

Terminology	Explanation
No. of EVs	Number of electric vehicles charging simultaneously
Total usage	Total load of the network, consisting of controllable usage and domestic consumption
Controllable usage	Part of the network load caused by charging of EVs; this load can be controlled remotely
Setpoint	The power or capacity value set by an external signal. In this chapter, this refers to the free capacity of the network available for charging; i.e. network capacity minus expected domestic consumption
Avoided usage	The amount of energy that has been curtailed or shifted to another point in time by application of a constraint
BAU usage	The value of the network load if no constraint had been applied (business as usual); i.e. total usage plus avoided usage

The red line in Figure 11 shows how many participants in a group are charging their vehicles simultaneously **(No. of EVs)** at a certain time. The resulting load of the network is called **controllable usage**, as we can control it by sending a setpoint to the charge points. The **total usage** is the total load of the network, consisting of the controllable usage and the domestic load (not shown), which is not controllable. This usage is called non-controllable because the energy needed for other electric appliances should not be affected by charge management. This total load cannot exceed the (assumed) network capacity. Based on this network capacity and the expected domestic load, the remaining capacity for charging can be determined. This is sent to and applied to the entire group in the form of a setpoint. This **setpoint** is allocated evenly to the individual active charge points, making sure that the total controllable usage does not exceed the group setpoint, as can be seen in Figure 11. Limiting controllable usage in this way ensures that total usage does not exceed network capacity.

When such constraints are applied to the charge points, a certain amount of energy is curtailed. This energy can be regarded as **avoided** at that particular point in time. The total load of the network without constraint can be reconstructed by adding this avoided usage to the total usage. In Figure 11, this is referred to as **"BAU usage."** The actual peak load reduction by charge management is therefore made visible: BAU usage has been reduced to total usage.

Finally, Figure 11 also shows whether one of the participants used the override function. This is shown as a vertical dotted line at that moment in time. A large number of overrides may indicate that the actual setpoint is too strict and probably causes too much inconvenience for the participants.

Analogous to Figure 11 for the dynamic signal groups, Figure 12 shows part of the dashboard with the load profiles for one day for one of the static signal groups. The setpoint (± 3000 kW) is much higher than the maximum power (± 120 kW) in this figure and is therefore not included. The setpoint is sent to each individual charge point and only valid between 17.00 and 22.00. Avoided usage is therefore only visible in this time period. Outside this time period, BAU usage and total usage coincide. The depicted vertical dotted line again represents the use of the override function.

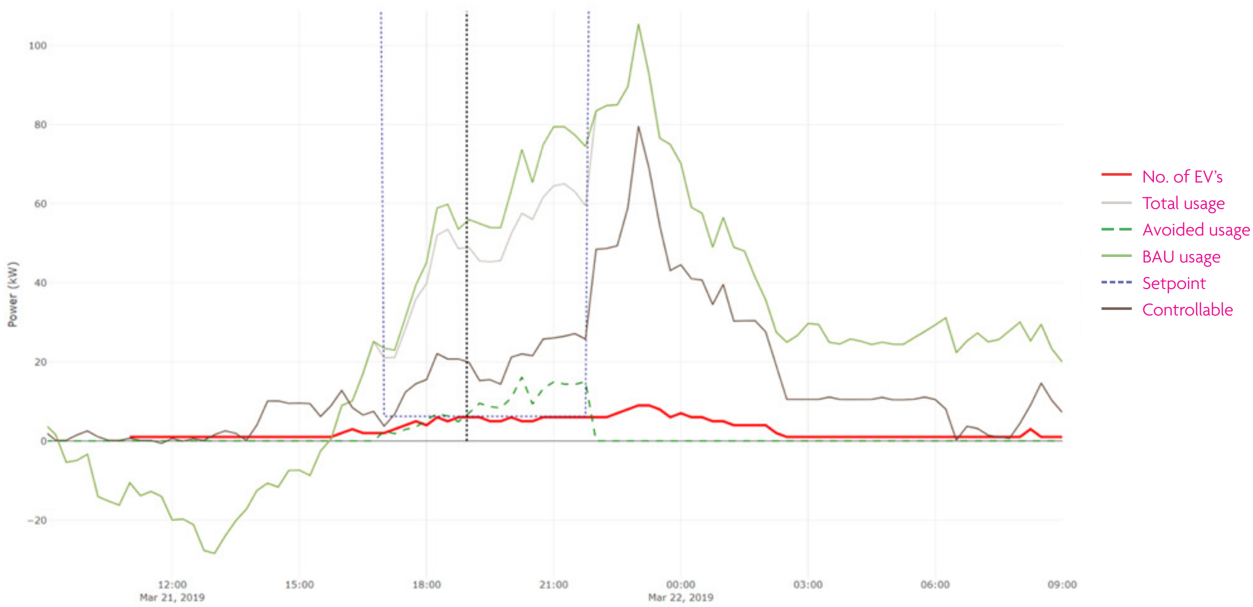


Figure 12: Visualization of load profiles for static charge management

Using this dashboard throughout the pilot period, the researchers were able to evaluate the effects of the actual constraint on a weekly basis. These insights could then be used to define new values of the constraints per group.

2.4.2 Constraint variation during the pilot

For the groups with dynamic charge management, the constraint was varied by assuming different values for the total capacity of the grid. Figure 13 shows how the assumed capacity of the grid for the dynamic signal groups was changed during the pilot period. Each signal was kept at a constant value for at least three weeks to monitor user behavior. For the dynamic signal groups, the assumed grid capacity is expressed as a percentage of the maximum peak load without charge management (maximum BAU usage). A grid capacity of 75% means that the peak load had to be reduced by 25% to avoid exceeding grid capacity. Figure 13 shows that the assumed grid capacity was gradually reduced during the pilot period to a minimum of 60%, requiring a peak load reduction of 40% to avoid exceeding the capacity limit. Towards the end of the pilot period, the assumed grid capacity was gradually increased again.

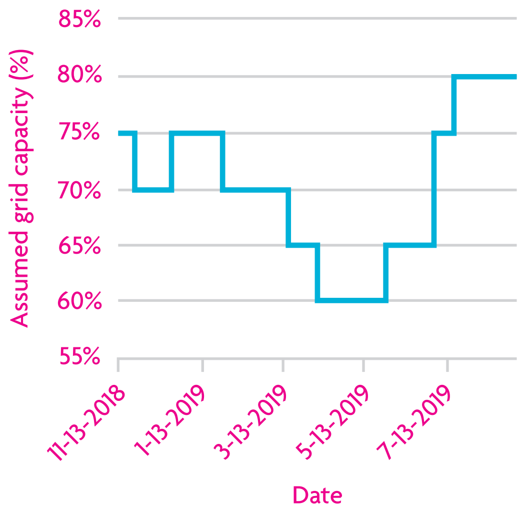


Figure 13: Capacity of the grid (dynamic signal groups)

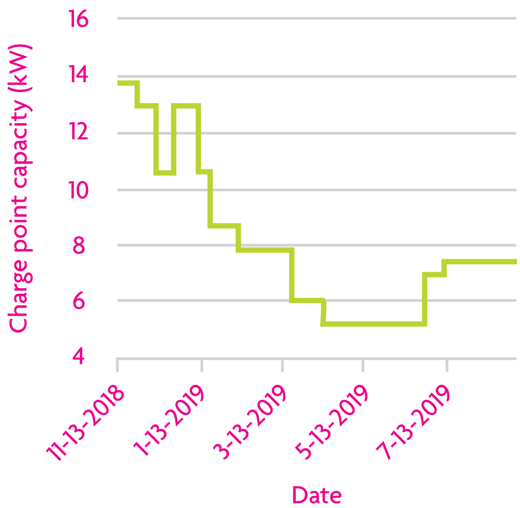


Figure 14: Capacity of a charge point (static signal groups)

For the groups with static charge management, the constraint was varied by assuming different values for the maximum capacity that was allocated to each charge point. Figure 14 shows how this individual charge point capacity has been changed during the pilot period: starting from 14 kW and decreasing to a minimum of 5 kW and then increasing again to 7 kW. As mentioned, the constraint for the static signal groups was only applied between 17:00 and 22:00.

Changing the setpoints as indicated in Figures 13 and 14 affected both network load and end user experience. These effects are discussed in the chapter "Results".

3. Results

This chapter describes the results of both the data research and the behavioral research. These separate studies complement each other. Together, they provide a conclusive answer to the research question. The chapter is divided into the following sections: a general description of the participants, the impact of charge management, the override function, effect of the financial incentive and the willingness to continue using charge management in the future.

3.1 General description participants

The surveys filled out by participants provided demographic data for 103 respondents: 98 men and 5 women. Their average age is 49 years, with the youngest respondent being 25 and the oldest 79. Respondents mainly work in IT (30%) and healthcare (15%). To a lesser extent, respondents work in consultancy (7%), the financial sector (5%), construction (4%) and the energy sector (4%). Half of the respondents live in a detached house (50%), followed by a semi-detached house (28%) or a terraced house (17%). 69 households (67%) have solar panels on their own home, and 19 households (18%) have a heat pump. These 19 households also all have solar panels.

3.1.1 Characteristics and usage of EVs

Of the 103 respondents, 100 drive a BEV and three drive a PHEV. When we look at the BEVs we see that 79 respondents drive a Tesla (64 drive a Model S; 15 drive a Model X), 5 respondents drive a BMW i3 and 5 respondents drive a Renault Zoe. The other 14 respondents drive other vehicles (Hyundai, Mercedes, Nissan, Opel, Volkswagen, Volvo, Kia).

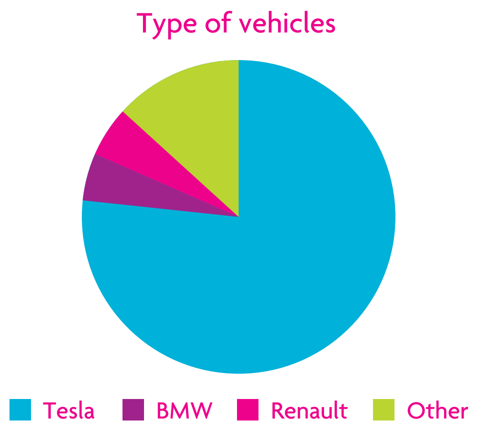


Figure 15: Distribution of type of vehicles of participants

The reasons for purchasing an electric vehicle are mainly sustainability (82x), financial benefits (75x), interest in innovation (74x), preparation for the future (25x) and driving characteristics (64x). Respondents could indicate multiple answers. The average mileage is 30,601 kilometers per year. This is more than twice the national average in the Netherlands: in 2017 an average Dutch passenger car drove 13,000 kilometers.

Most respondents drive their EV seven days a week. On average, the EV is used six days a week. Respondents' vehicles were mainly bought through business purchase structures (54%) or business lease structures (34%). Private purchase (10%) or private lease (3%) are less common.

3.1.2 Charging behavior

On average, respondents charge their EV four times a week, and the EV is connected to the charger for 9.7 hours during a charging session at home. However, the standard deviation here is high (5.3), which shows that there are large differences in the answers. A majority, 63%, indicates that their vehicle is connected to the charge point between eight and twelve hours on average. Figure 16 shows the distribution.

91% of the respondents also charge at other charge stations than at home. Most respondents charge once a week or less at (Tesla) fast chargers or public charge stations. 47% of the respondents use charge points at work as well.

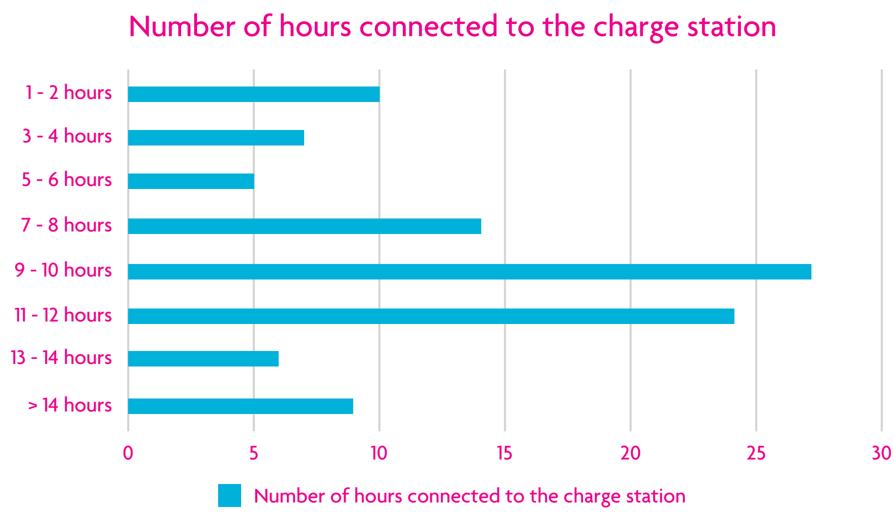


Figure 16: Average number of hours that the EV is connected to the charge station

When asked at what time respondents start a charging session at home on average, five categories could be identified based on the answers (N=89). Figure 17 gives an overview. 28% of the respondents mention that they start a charging session during the evening peak hours (17.00 - 20.00). 56% of the respondents start their charging session after the evening peak hours. Only 3% indicates they start a charging session before the start of the evening peak hours. 12% of the respondents reported charging at home at varying times.

16% (14 respondents) point out that they have changed their charging behavior since the start of the pilot with charge management. These respondents charge more often in the evening or night, charge more often at work, on the road or at other locations or charge more often during the day.

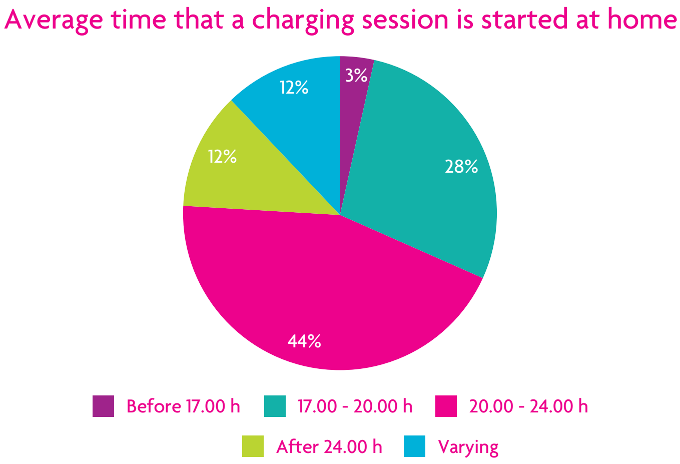


Figure 17: Average time that a charging session is started at home

3.2 Impact of charge management

To get a first impression of the effects of charge management in the four different groups of participants, the researchers considered the daily load profiles measured during the pilot period.

Figure 18 shows the average load profiles on a working day for groups 1 to 4 ("inc" stands for "incentive"). As mentioned before, these incentive groups received a reward if they did not use the override function too often.

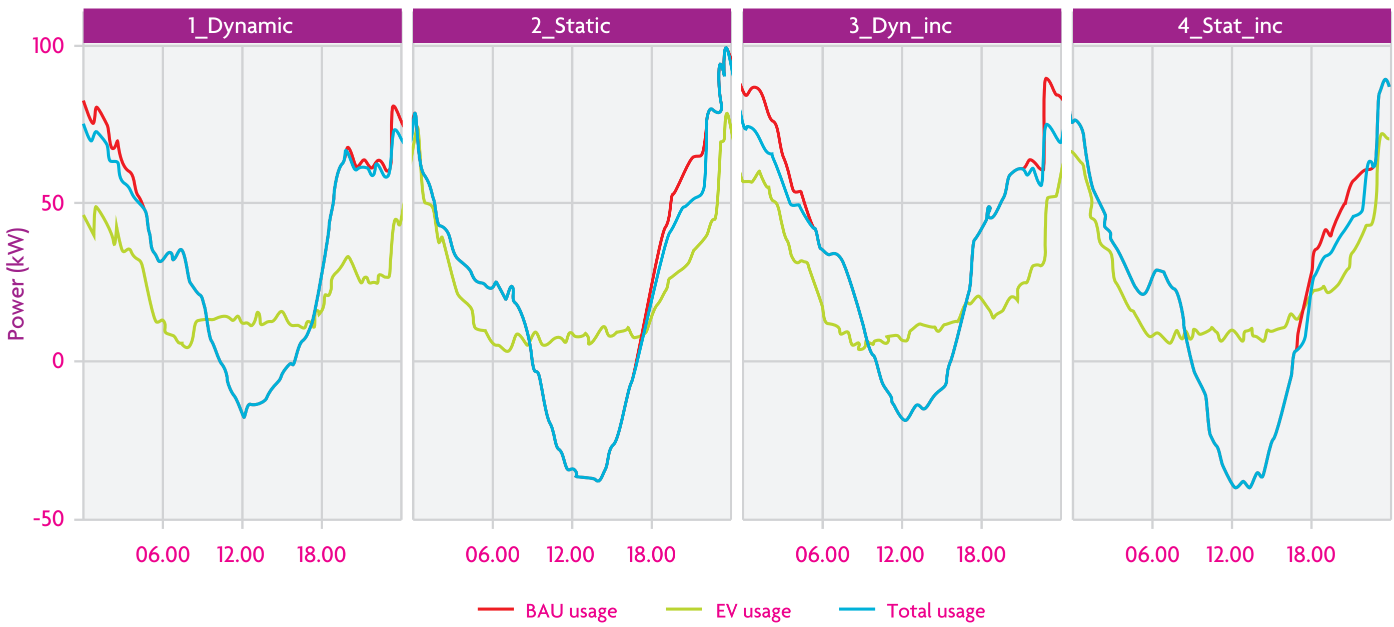


Figure 18: Average daily load profiles

A first observation is that the "total usage" reaches negative values during daytime. This is caused by the solar panels of a considerable share of the households, but which are clearly not evenly distributed among the groups. Accordingly, the participant survey showed that 67% of the respondents have solar panels. It can also be seen that "EV usage" shows a sudden peak at 23:00. This indicates that some of the households wait for the low energy-tariff period (which generally lasts from 23:00 to 07:00) before they start charging their vehicle. In fact, 80% of the respondents stated that they use a day-and-night tariff. It is also known that many vehicle types allow for the charge time to be programmed in advance. Based on the often-occurring sudden peaks in EV usage at 23:00, it is likely that this functionality was used by a number of participants.

For the dynamic signal groups, a reduction of the peak load can be observed: "total usage" is lower than "BAU usage" during periods of high load. For the static signal groups, a load reduction is visible between 17:00 and 22:00, but we can also see that the peak load of the static signal groups has not been reduced. This is because some of the charge sessions start at 23:00, while the constraint is only active until 22:00. Another more fundamental effect is that relieving the constraint at 22:00 leads to a load increase from the EVs that are charging at that moment. The peak load may then only be shifted to a later point in time without any reduction.

3.2.1 Variation of the constraint

Figure 18 gives an impression of the average peak load reduction during an average day. This peak load reduction depends on the actual value of the setpoint. For the dynamic signal groups, Figure 19 shows the avoided usage on a weekly basis as a function of the minimum setpoint in that same week. Notably, the peak load reduction is correlated with the setpoint.

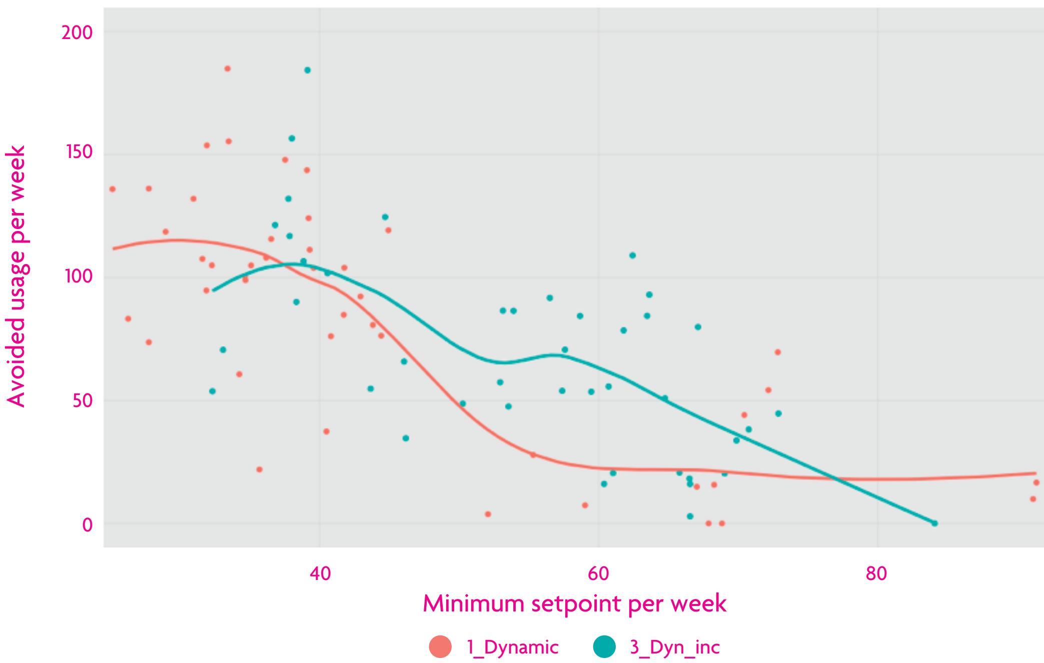


Figure 19: Correlation between avoided usage and setpoint for the dynamic signal groups

As expected, we see a negative correlation between avoided usage and the setpoint. The avoided usage shows a downward trendline, correlated with the height of the minimum setpoint. The setpoint in the dynamic signal groups is dependent on the number of active charge points. Because of this, the setpoints displayed in Figure 19 represent the minimum setpoints per week.

We can conclude that the lower the setpoint, the higher the avoided usage and thus the higher the peak load reduction. No correlation could be found for the static groups between the setpoint and avoided usage. The differences between the static groups might therefore be due to other differences between both groups; for example, a non-fully homogeneous composition (see Figure 20).

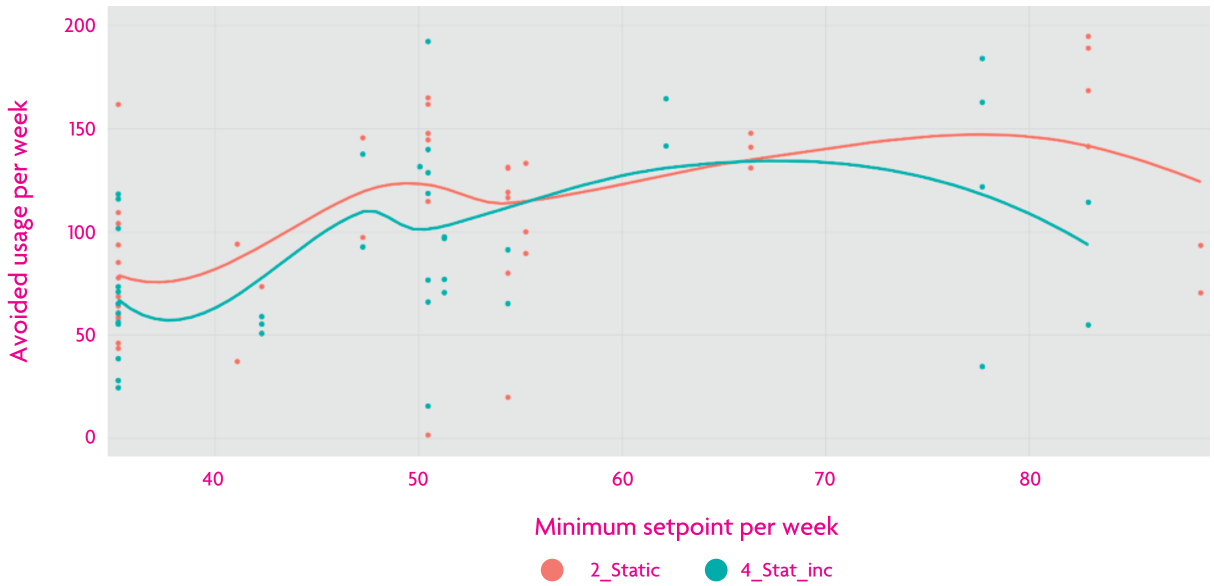


Figure 20: Correlation between avoided usage and setpoint for the static signal groups

3.2.2 Peak load reduction

Figure 18 shows a certain reduction of the peak load for an average day. It is worthwhile to examine the maximum peak load reduction achieved during the pilot period. Figure 21 shows the relative peak load reduction (the ratio of total usage and BAU usage) during the period with maximum constraint (April/May 2019). The relative peak load reduction has been ordered from high to low, resulting in a duration curve. For the dynamic signal groups, a peak load reduction of up to 40% has been achieved, and for the static signal groups, even up to 50%. For the dynamic signal groups, this reduction corresponds to the minimum assumed grid capacity of 60% (Figure 13). A stricter constraint had no further effect on the peak load, because during this pilot, the charge points were given a guaranteed minimum available capacity of 6A. That is because current standards between charge points and EVs do not allow for a charging current below 6A. Values below 6A cause the EV to stop charging, which causes an inconvenience to the end user.

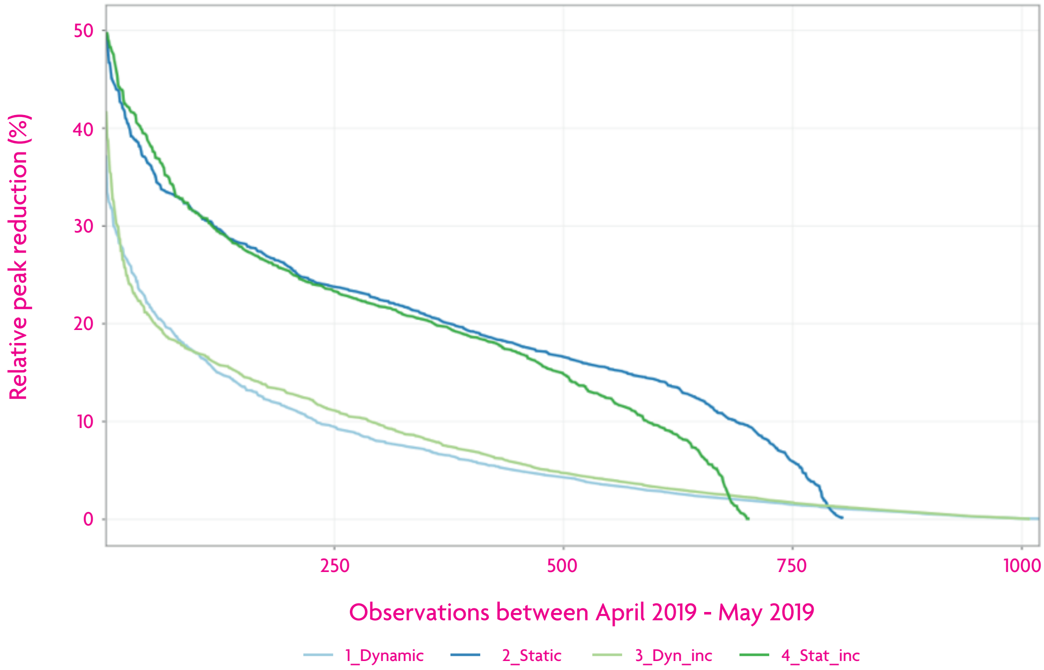


Figure 21: Duration curves of relative peak load reduction with maximum constraint

The results in Figure 21 suggest that charge management for the static signal groups is more effective than for the dynamic signal groups, because the peak load reduction of the static signal groups is larger. However, as observed in Figure 18, a constraint applied between 17:00 and 22:00 does not actually lead to a reduction of the peak load. This is also visible in Figure 22. Here, we see a certain reduction of the load for the static signal groups, but the peak load is not affected, or it could even be increased by shifting energy from the constrained to the unconstrained time period.

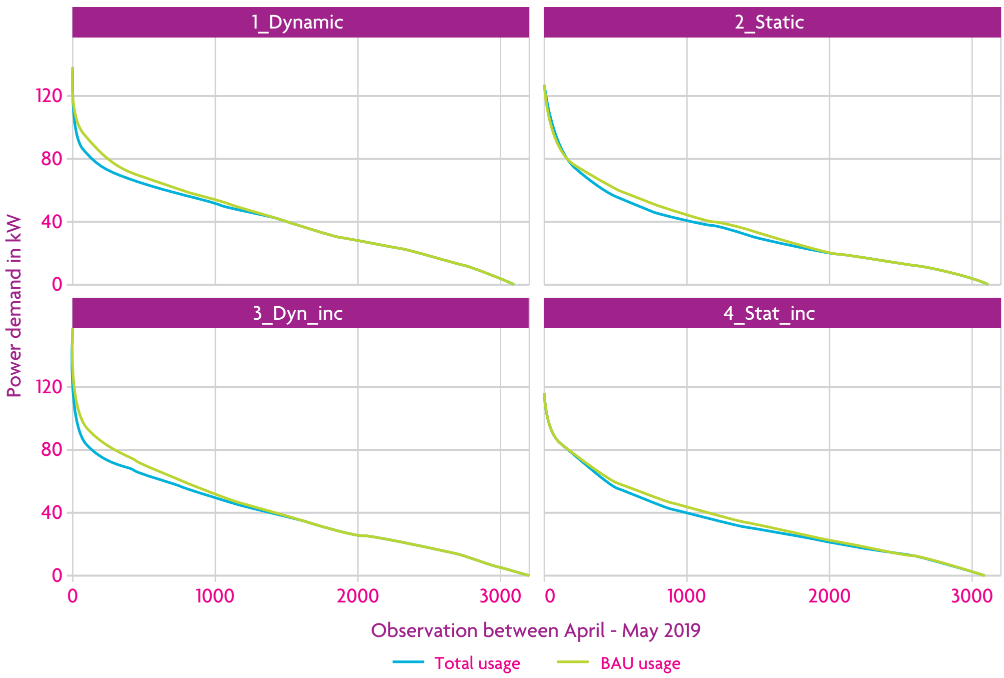


Figure 22: Duration curves of total usage and BAU usage with maximum constraint

3.2.3 Participants on charge management

The behavioral research (N=89) reveals the following findings: 52% (46 respondents) noticed that charge management was applied. Of the respondents who did notice charge management, 59% were in an experiment group with a static control profile, 35% were in an experiment group with a dynamic control profile, and for 7% the control profile is unknown. Respondents mentioned that they mainly noticed charge management during the EV's charging session. They noticed the EV charging more slowly or taking longer to charge, or they noticed that the EV was charged with less power. 7% of the 46 respondents indicated that the vehicle occasionally stopped charging or that several charging sessions took place in one night.

55% noticed the charge management especially in (and at the beginning of) the evening, but also during the day (17%), in the afternoon (15%), in the night (7%) or in the morning (4%). 14% sometimes encountered problems because the vehicle was insufficiently charged due to charge management. Respondents mostly reported using the override function when this occurred. Additionally, one respondent charged at a Tesla supercharger, another respondent charged at the destination. Three respondents encountered problems due to technical reasons.

To measure the attitude towards charge management, respondents in both surveys responded to eight statements about charge management, such as: "Charge management of electric vehicles is a suitable solution for preventing an overloaded energy network" and "I feel the need to contribute to a stable energy network." Respondents rated these statements on a Likert scale from 1 (fully disagree) to 7 (fully agree). The average scores of the first and second survey were respectively 5.5 and 5.3. The difference between the scores is so small that no conclusion can be reached. The average score means that there is a predominantly positive attitude regarding charge management. Notably, the statement "I want to be able to interrupt the charge management at all times, so my electric vehicle can charge at regular speed" clearly scores the highest and shows that respondents consider the possibility of interrupting charge management to be very important. No significant differences were found in the attitude towards charge management between the four experiment groups.

29% of the 89 respondents of the second survey wanted to receive more information about charge management during the pilot, especially about the times at which charge management took place (17%).

3.3 Overrides

The use of the override function, to cancel charge management for a maximum of 24 hours, can be viewed as a measure of the potential inconvenience caused to the pilot participants and of the level of acceptance of charge management. It would seem logical that the stricter the constraint, the higher the number of overrides. However, as Figure 23 shows, for the dynamic signal groups there is no significant correlation between the number of overrides and the value of the setpoint. The same was observed for the static signal groups.

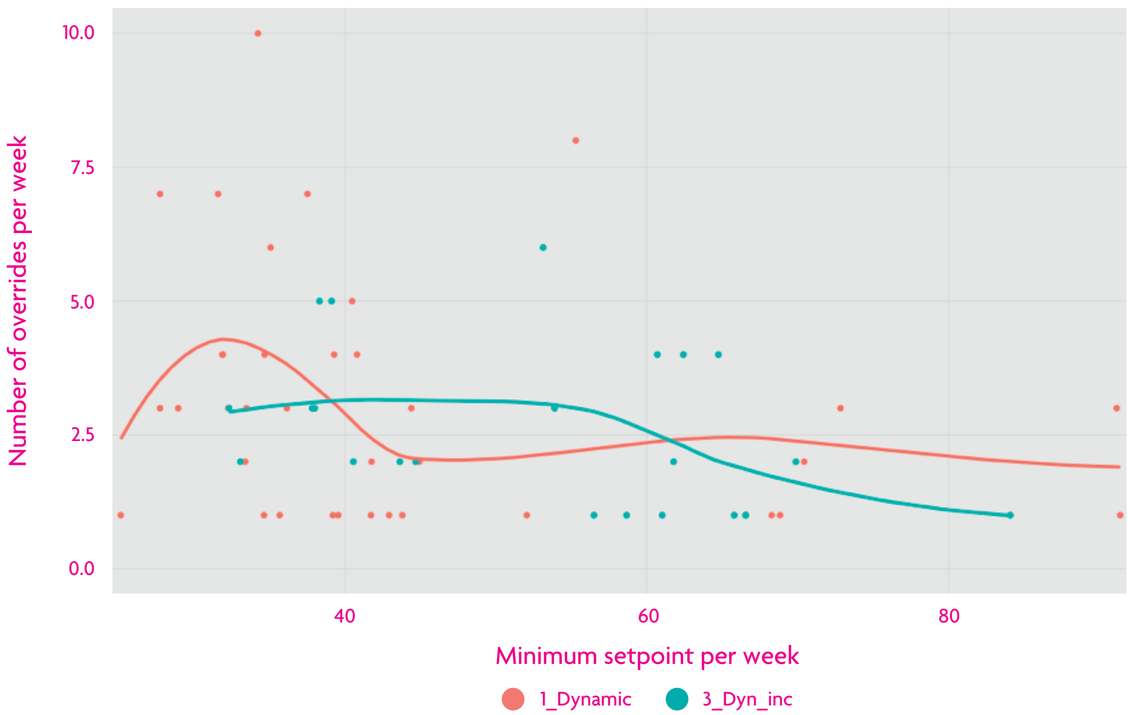


Figure 23: Correlation between the number of overrides and setpoint for the dynamic signal groups

This means that the use of the override function is triggered by aspects other than the strictness of the constraint. In other words: changing the constraint does not result in other levels of (in)convenience related to charging the EV. The results of the behavioral research shed more light on this.

3.3.1 Participants on the override function

When participants (N=89) were asked if they were aware of the override function, 87% answered that they were familiar with this function. For 18%, it was unclear how the override function should be used. In the second survey, 63% (56 respondents) said they did not use the override function during the pilot period. 16% (14 respondents) used the override function because of curiosity or to test its function. Occasionally, the override function was used either to check the correct settings, as a mistake, because there were problems with charging or because of other technical problems.

Notably, almost half of those interviewed indicated that the override option was essential for their participation in the project. One interviewee said, "I would not have joined this pilot if I did not have the choice to override charge management." In addition, half of the interviewees thought the override option was a good and useful option, lowering the threshold for participation and making it less stressful. A minority of the respondents thought the button was a good addition, but not necessary.

3.4 Financial incentive

All graphs presented in this chapter show the combined results for both the groups with and without financial incentive. Though we can see some differences between them, there are no clear differences that can logically be traced back to the financial incentive. Therefore, it can be concluded that the financial incentive had no observable influence on the network load. The results of the behavioral research provide further information on this aspect.

3.4.1 Participants on financial incentives

In the two surveys eight statements were presented about a financial incentive in relation to charge management, such as, "A financial incentive makes it more attractive for me to make my electric vehicle available for charge management" and "I do not need to receive a financial incentive for my contribution to a stable electricity network." To measure whether the participants' attitude would change, these questions were posed both before and after charge management was applied. The average score of 5.4 on a scale from 1 (negative attitude) to 7 (positive attitude) shows a predominantly positive attitude towards the financial incentive. The difference in this score between the first and second survey is negligible.

Of the 48 respondents who received a financial incentive and completed the second survey, 23% (11 respondents) indicated they had taken the financial incentive into account when considering whether to use the override function or not. Eight of these respondents indicated that they did not use the override function during the pilot.

Respondents were also asked what they thought of the level of financial incentive (N=48). 27% indicated that the level of financial incentive was too low, while 69% indicated that they thought the level of financial incentive was good. 4% thought the level was too high.

When the respondents from the experimental groups with a financial incentive were asked how they prefer to receive this financial incentive, most chose the option of receiving a monthly amount, based on the offered flexibility (chosen by 24 respondents). Estimates of the amount that respondents wanted to receive ranged from €4.50 to €100 per month. Respondents found an average remuneration of €26 to be appropriate. The second most chosen option for financial compensation was a discount on network operator costs (18x). On average, respondents found an amount of €12 suitable for this discount. Some also selected the options for a fixed amount per month (13x) and a discount on the Maxem (HEMS) subscription (12x). Donations (4x) and gift cards (3x) were chosen the least. Four respondents explicitly stated that they do not need a financial incentive.

Notably, 10 out of 20 interviewees mentioned they do not expect a financial incentive if charge management is applied to all users.

3.5 Willingness to continue charge management in the future

There is strong willingness among the participants to continue with charge management: 84% (75 respondents) stated that they want to (continue to) use it in the future, and 81% (72 respondents) would recommend using charge management to other EV-drivers.

Finally, respondents were given the following information in the survey: "By charging your EV at home, your total energy demand increases. To meet this demand, your grid connection may have to be reinforced. This could lead to extra costs. A variable capacity connection where energy consumption is spread more during the day can save costs." Subsequently, questions were asked on willingness to switch to a variable capacity connection. The willingness to switch to a variable capacity connection is highest when it is offered at a lower cost: 81% (72 respondents) indicate that they are willing to use a variable capacity connection. Fewer participants (55%/49 respondents) were willing to switch to a variable capacity connection at current cost. The willingness to switch to a variable capacity connection at higher costs is the lowest: only 15% (13 respondents) indicate that they are willing to do this.

4. Conclusion

Significant peak load reduction with negligible inconvenience to end users

At the start of the research, the main question was formulated as "To what extent can grid operators lower the peak load of the low-voltage electricity grid by controlling the charging of electric vehicles at households, and how do consumers experience this?" In this pilot study, reductions up to 40% have been achieved by applying charge management, showing that charge management can successfully be operationalized using a HEMS at households. The possibility of using the override function plays an important role in the attitude of households towards charge management and their experience. Participants are willing to continue using charge management and have a positive attitude towards this concept. Given that EVs have a connection time of between eight and twelve hours on average, they provide a large potential for flexibility. Applying charge management (preferably with a dynamic profile) can significantly reduce the grid impact of charging EVs.

Up to 40% reduction in peak load

Using (dynamic) charge management can substantially reduce the peak load of a low-voltage grid. This pilot study achieved a reduction up to 40%. This conclusion is valid for electricity grids with a high penetration of home charge points. Other changes in the household's electricity consumption (e.g. heat pumps) were not considered in this pilot study.

A concept with static charge management, as operationalized in this pilot, proved not to be useful: it shifted the peak load to a later point in time without reducing its magnitude. Furthermore, a concept with a financial reward for customers for providing flexibility (in this case by not overriding the DSO charging profile) had no observable effect on the degree of peak load reduction.

Charge management successfully operationalized using OSCP

At the start of the pilot, OSCP was selected as protocol to establish communication between the DSO and the aggregator because it (generally) matched the project requirements. This choice had implications for the technology and the operationalization of charge management. Charge management was operationalized practically by sending maximum limits from the DSO to the aggregator and influencing charging sessions of households via the HEMS device Maxem. The forecasts sent to the households were based on historical data and weather predictions.

Despite successful operationalization, some obstacles occurred. One of the practical obstacles was that a situation that "did not happen" had to be measured to determine the impact of charge management. Therefore, a method was developed for calculating the actual avoided usage. The resulting calculation of avoided usage is not accurate in all scenarios and must be considered an estimate. Furthermore, available protocols such as OSCP or OpenADR have to be adapted to be used in a specific case such as this pilot. An adaptation had to be done for OSCP to be able to communicate energy data. Currently, none of these protocols both exactly matches the use case and is widely accepted or used by a large part of the industry.

Additionally, some measurement errors were found, which led to some data not being usable for research purposes. While such errors are inherent in initiating an innovative project, it is important to take them into consideration when introducing the technology on a larger scale. Moreover, since many of the current charge points adhere to the Mode 3 / IEC 61851-1 standard, they need a minimal current of 6A to start a charging session. The lower limit of a control signal was therefore fixed to 6A in the pilot, to prevent charging sessions from stopping. This put an additional constraint on the charge management algorithm and limited the amount of control bandwidth. Furthermore, for the metering data, the researchers decided to send aggregated household usage from the aggregator to the DSO. Aggregated data was used primarily for privacy reasons, because metering data can be disclosed only to the aggregator under current privacy regulations and laws.

Participants have a positive attitude and are willing to continue charge management

In general, participants have a predominantly positive attitude towards charge management. Results show that participants are willing to continue using charge management. We can also conclude that charge management via a HEMS has a minimal effect on the attitude and experience of participants. There is hardly any difference between the attitude towards charge management before and after charge management was executed.

In addition, there is no significant difference in attitude between the static and dynamic signal research groups. Nevertheless, slightly over half of the participants noticed when charge management was active. This means that charge management cannot be applied unnoticed. Additionally, although actual data shows that participants have not used the override function frequently, most participants describe having the override function as important – some even describing it as "essential". Most participants used the override button out of curiosity or to test its function. It was only rarely used for practical reasons such as problems or because participants needed the EV to charge as quickly as possible.

In addition to that, we can conclude that the existence of a financial incentive did not seem to influence participants' attitude and experience towards charge management in this pilot. Data shows that participants who were rewarded with a financial incentive do not have deviant charging behavior. However, we did not investigate what the effect would be if the financial compensation would have been higher or whether this result has to do with the specific characteristics of this research group. This requires further research. Participants did indicate that they find financial incentives attractive and hold a positive attitude towards them.

Side notes

When interpreting these conclusions, it is important to take the following side notes into consideration:

- This research concerns the charging of EVs at home charge points. Approximately two-thirds of the respondents indicate that their EV is connected to their home charge point for an average of eight to twelve hours a day. This offers leeway for shifting the charge times and power load without further consequences.
- A large portion of the participants usually start their charging session outside peak hours when no charge management is applied. Furthermore, 80% of the participants indicate they have a day-and-night energy tariff at home, which possibly explains this timing of charging. Subsequently, these participants are likely to experience minimal impact from charge management.
- It is important to note that the research group of this pilot has a specific profile and is not necessarily representative of future EV-drivers. For example, we suspect that this group of users has a high willingness and interest in innovation, technology and sustainability, which contributes to their positive attitude towards charge management. Whether or not future EV-drivers (early majority) will have the same attitude needs to be investigated further.
- More than three-quarters of the participants drive a Tesla (Model S and Model X). This is an EV with a large range (over 400 kilometers). The large range could imply that drivers are less likely to experience problems due to charge point management.
- Finally, the participants in this research seem to be affluent. This might indicate that participants are not sensitive to the relatively small financial incentives used in this research.

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5. Recommendations

This pilot study shows that charge management can be operationalized among households. At the same time, it suggests some topics for future research. These can be categorized in terms of technology, behavior and scalability.

Technology

In this pilot study, OSCP was chosen beforehand as the protocol for communicating between the grid operator and the aggregator controlling the Maxem. Although it has been shown that charge management can be operationalized using OSCP, it is recommended to try alternatives and focus on the communication and data exchange between parties. The OCPP protocol for communication between charge stations and their backends also includes a functionality that can be used for charge management. OCPP 2.0 adds use cases with a HEMS, which can offer greater standardization in terms of communication between a charge station and a HEMS.

Furthermore, this pilot involved the development of a method for calculating the avoided usage by applying charge management. As part of this calculation, during a charging session, every 15 minutes a new reference current was determined by shortly releasing the setpoint and letting the EV charge without constraint for one minute. Further research is necessary to determine whether this short release of the setpoint would impact grid stability for large numbers of home charge stations and EVs. It is also recommended that the calculation method is studied in greater detail and compared to existing calculations to work towards an accurate, standardized calculation of the impact of charge management.

Moreover, heat pumps were ultimately not included in the pilot study because of the variety of types and lack of a standardized communication protocol. For future research, it is recommended to replicate this study and integrate heat pumps, to study the combined flexibility of EVs and heat pumps and determine how a standardized protocol can be created.

Behavior

The behavioral research conducted under this pilot study revealed that people have a positive attitude towards charge management. The results from the surveys show that although the override function is rarely used, participants value this function as it gives them a sense of control. In future research, it is recommended to study this override function in more depth, in order to gain insight into why people value it. A recommendation is to include direct user-interaction to shed light on why the override function is used. The surveys identified some of the reasons (e.g. to test the system) but only afterwards. It is also suggested to conduct more research on the provision of information, as some participants indicated that they would have appreciated more information on topics including the charge profile of their vehicle with active charge management.

Participants also indicated that they had a positive attitude towards charge management, but valued a financial benefit in return. A suggestion for future research is to study different customer propositions to determine whether people are willing to allow more charge management for an (extra) financial benefit in return. Also, the groups of participants were relatively small, with an average of 34 households per group. As a result, not all differences could be explained, because they were sometimes caused by a single outlier. For future research, it is recommended to consider a larger pilot group and, if possible, a more diverse group and different household compositions.

Scalability

The intended result of the pilot was to create a scalable solution for controlling large energy consuming appliances at households. With 138 participating households, this pilot study has achieved the largest scale of charge management via a HEMS within the domain of households so far in the Netherlands. However, more research is necessary on the harmonization and standardization of an eventual solution that is not dependent on a specific DSO or aggregator.

Moreover, this pilot study used the ELMO system to predict capacity and leftover room for flexible loads. To introduce this solution at more households, further in-depth research needs to be conducted on the prediction of capacity and the actual implementation. The extent to which capacity was predicted in this pilot was sufficient for the number of households, but might fall short when scaling up to a larger group. Furthermore, HEMS devices have proven to lend themselves as suitable system for entering the domain of households. Therefore, it is advisable for DSOs to get an idea of where these systems will arise and within which timespan.

An interesting follow-up is to consider the development of such devices and the quantities and locations in which they are expected to be adopted. To create a scalable solution, it is also necessary that there are aggregators that are willing to enter this market. A suggestion is therefore to consider the business case for parties and preconditions for parties to step in.

This project is an initiative of Enexis Netbeheer, Enpuls, ElaadNL en Maxem.