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RELEVANT – Realize efficient charging of electric cars with user-centred smart technology - A Swedish test pilot

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Summary

A Swedish test pilot for smart charging of electric vehicles is currently running where data is collected from ten households, some with solar panels. There are several research questions that are addressed regarding technology, user behaviour, costs, and values. Preliminary results are presented in this paper.

Keywords: smart charging, EV (electric vehicle), PHEV (plug in hybrid electric vehicle), BEV (battery electric vehicle), user behaviour

1 Background

The roll-out of rechargeable vehicles can be accelerated by the expansion of solar cells and other renewable electricity production. When prosumers[1] generate their own electricity, there is a potential incentive to store self-produced electricity locally in the house instead of sending the surplus online [1] There may be financial incentives for this but also motivations to be self-sufficient and contribute to sustainability [2][3]. Rechargeable vehicles can be recipients of the rechargeable electricity, together with any local battery stores, water heaters and other electricity consumers [4].

Today, both charging infrastructure, electric vehicles and smart home solutions are built according to each player's own perception of what is a good solution and a suitable customer offering. However, the overall picture and understanding is lacking [5][6] which can result in solutions where e.g., plugs are triggered, unnecessarily high costs, no charge and poor customer experience. Even more important for society is that poor solutions will hinder the development towards fossil-free rather than accelerate it. There is often an expectation for households to actively participate in and influence their electricity use [7], but at the same time there is a lack of knowledge about how smart technology should be designed and implemented to fit into people's everyday lives [8][3]. The solutions are often driven by a dominant technical focus based on ideal use cases rather than on the users' complex everyday situation, actual needs, and social context [6]. Vehicle manufacturers need to understand the evolution to be able to prepare future generations of vehicles with smart charging functionality [9] with a good user interface, and in the long run also understand the possibilities in the prosumer's ecosystem. Energy producers and grid owners need to understand how to avoid or keep down new investments in the electricity production system and grid due to an increased number of rechargeable cars. Electricity trading companies need to understand the opportunities and difficulties that arise with self-generation of electricity and rechargeable vehicles. Manufacturers of charging equipment, solar cells and control systems need to know what requirements are placed on each system.

To increase the knowledge about smart charging of rechargeable vehicles, a Swedish pilot has been set up with Volvo Cars, RISE, Halmstad University, Vattenfall, Skellefteå Kraft and Kraftringen Energi. The project started on the 1st of November 2019 and is planned to end after three years and hence is still on-going. The project is entitled RELEVANT - Realize efficient charging of electric cars (EVs) with user-centred smart technology.

In the RELEVANT project, different setting options of charging for customers will be evaluated, e.g., charge as cheaply as possible, as fast as possible or when only green electricity is available. The main hypothesis in the project is that users have different charging preferences and expectations of smart charging that develop over time, and it is included that both quantitatively (through measurements) and qualitatively (through ethnographic methods, interviews and questionnaires) understand these better. Today's charging function, which means charging as fast as possible when the plug is inserted, will be expanded with an AI-based scheduling algorithm, to be able to charge in a more intelligent way based on customer preferences and thereby contribute to new charging behaviours for a more sustainable society. The scheduling algorithm will be built up of mathematical models and will learn consumption patterns based on historical use of the home's energy consumers in combination with customer-specified input data, e.g., charging preferences and predictions of e.g., solar intensity. This will minimize the risk of plugs triggering, keep costs down, and provide a better customer experience. In addition, the chances of fossil freedom increase with attractive customer solutions.

This paper will explain the main results of the RELEVANT project so far. It will shortly describe the project set-up in the next section, followed by the preliminary results.

[1] https://www.energy.gov/eere/articles/consumer-vs-prosumer-whats-difference

2 Method – project set-up

The RELEVANT project is studying 10 households (whereas four of them already have their own generation of electricity through solar cells) and rechargeable cars with equipment for regulating systems in the home for a period of just over a year. During that time, the project will evaluate how the interaction between the home and the rechargeable car with the help of AI-based regulation can be improved in terms of energy consumption, network impact, costs, and user attractiveness. As the focus of the project is to understand how a smart charging algorithm works in people's everyday lives and how it could be developed with a user centric focus, the main qualitative approach is selected to deeply study the complexities and evolvement of different users in the households, household set-ups, rechargeable cars, user interfaces and charging algorithm.

Maximum 10 households were chosen to be the limit and still provide a huge amount of qualitative data that was possible to analyse. The quantitative design ethnographic approach [10] is used as support to provide usage data from the households to follow up the changes in energy usage, input to the qualitative interviews and input to simulations of future scenarios for energy usage.

In the first phase, which has been passed, the project is established, hardware and software as well as measurement methodology are developed, and users have been recruited. Through an initial ethnographic study of users with rechargeable vehicles in smart households, current and important aspects of vehicle charging preferences and expectations have been captured and considered in the development of technology and the user interface. Thereafter, a starting position will be developed through measurements and user activities, in the case where no smart charge is made, and this will serve as a reference case against which we later make comparisons.

In the second phase of the project, which is currently on-going, such different versions of co-regulation of home and car will be iteratively tested and evaluated through measurements and user activities to capture the users' change in preferences and expectations linked to e.g., the development of the technology solution, seasonal changes, or the users' knowledge development.

In the final phase of the project, which is expected to be done later this year, the results will be analysed and a description of how future collaboration between smart homes and rechargeable cars could be made.

Figure 1 visualizes the connections between the system components and the exchanged information:

- There is a cloud platform (shown in the upper right side of the figure) to which every car is connected. This platform is owned and developed by Volvo Cars. Data is collected from the vehicle and wallboxes and the charging schedule is downloaded to the car.
- There is a household cloud platform (shown in the upper left side of the figure) to which the house is connected. This platform is owned and developed by Vattenfall. Data is collected from the house and the energy management for the house is calculated based on sensor data and upcoming energy prices as well as predictions on future energy demand for devices in the house (like the car, heat pump if it exists and so on). The energy management function can be seen as an energy broker since it decides the schedule for the controlled devices in the household fulfilling the user preferences in the household. Uncertainties in information means that some decisions must be based on historical data and predictions of future data giving rise to the need for AI in the energy management/broker functionality. It is part of the project to develop and evaluate this functionality based on the user experience in the households. There is also an IT-platform in the house (shown as a computer in the middle of the house in the picture), which mainly handles the low-level communication between the house electricity meter, the solar panels and the wallbox.
- The household users interact with the system by a user display/apps (shown in the figure as a display in the lower left part of the house).
- There are interactions between the cloud platform of the car and the household and all the devices. The Application Program Interfaces (APIs) and exchange of information between the system will be defined in the project.

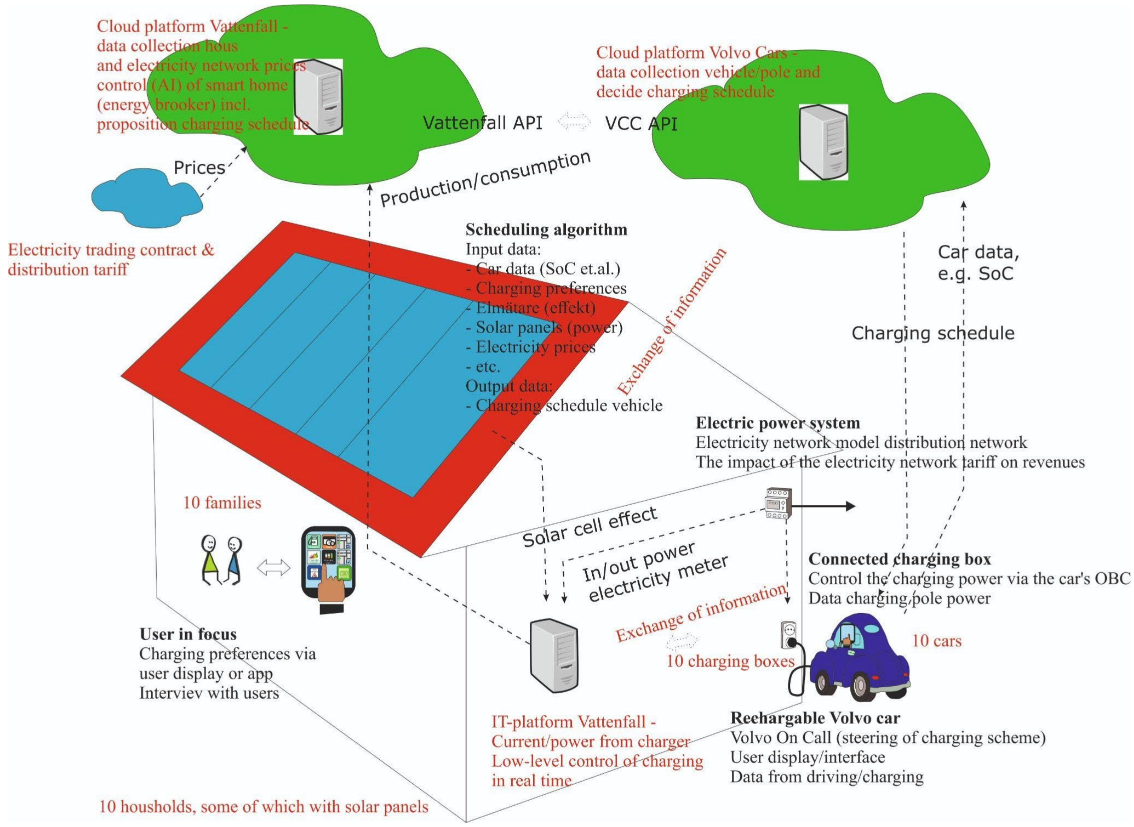

Figure 1: A schematic view visualizing the connection of the different systems forming a system-of-system needed to make smart charging in the households.

3 Method – project set-up

The project is still on-going, but the following preliminary results are obtained, divided into technology, user behavior, grid impact and cost analysis.

3.1 Technology

The baseline of the RELEVANT technical system is built up by following entities, see also Figure 1:

- A chargeable car with cloud connectivity;
- A remotely controllable wallbox installed in the houses;
- User preferences inputs (through app);
- Power meters measuring the main power flows from usage and production sources;
- Communication gateway enabling remote control of charging events and household data monitoring readouts;
- Algorithm for charging management as well as load balancing in the household environment.

By the systems approach it is made possible to manage and control charging of a set of individual cars connected to individual households equipped with wallboxes.

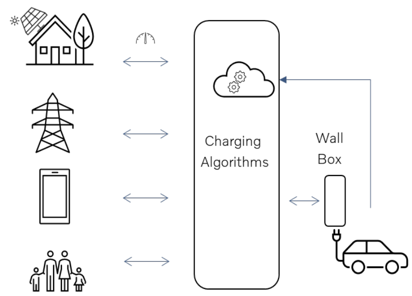

Figure 2: A principal sketch of the RELEVANT charging ecosystem.

The developed energy management solution comes with two main functionalities, explained further in the following:

1. Fuse protection
2. Cost optimised charging

Fuse protection

The fuse protection control uses real-time load measurements of the point of common coupling (grid connection) of the household and regulates the maximum current set point of the wallbox, so that the fuse limit will not be exceeded by additional EV charging.

Cost optimised charging

For cost optimised charging, following additional inputs are taken into consideration:

- Measurements from the vehicle (e.g. state of charge (SOC), connection status);
- User preferences (e.g. desired SOC, estimated time of departure);
- Day-ahead hourly electricity prices;
- Structure of the grid tariff;
- Forecast of the household electricity load based on historical measurements and additional; parameters, such as the weather forecasts.

Based on these inputs, an optimisation algorithm computes the charging schedule that is associated with the minimum costs while meeting the requirements and preferences set by the user. The value of the first hour of the charging schedule is translated into a current set point on the wallbox. The full charging schedule is additionally made available to the user and visualised in an app.

The electricity load forecast used in the smart solution will improve over time as more and more historical data of the household electricity consumption becomes available. The main hypothesis of the project is that each user has their own charging preferences and expectations that also will develop over time. Gaining a better understanding of these, both qualitatively and quantitatively, is included in the project goals. Hence, the project is not only built on hypothetical situations, but is based on real life situations where the user gets to experience the results of their decisions and can therefore contribute with important input to the research and future development.

So far, the technology has been installed and debugged and the steering algorithm has been tested with good results, showing good opportunities for cost savings and increased user comfort, see Figure 3.

Figure 3: Optimiser results (Nordpool[2] SE3[3]) for a household with solar production. Top figure shows the dynamic power delivered to the household. Middle figure shows the charging occasions considering the lowest price tariff. Bottom figure shows the price tariff (Nordpool SE3).

3.2 User behaviour

In this project, the understanding of the end-users evolving experience of how rechargeable cars integrate into their home energy system will be followed through both a qualitative and quantitative approach. So far, the first results have been generated from the qualitative ethnographic study done through three sets of interviews with participants from the households.

The first set of interviews were done in the early start-up phase with the participants from the households before they had any equipment for smart charging installed in their homes. Most of the participants were at this point new to rechargeable cars. The first interviews focused on the experience of going from fossil fuel cars to rechargeable cars, routines for mobility needs and home energy management (car routines, awareness about energy cost, current use of smart appliances in households or anticipation of what smart technology might provide in the future). Main findings from the first set of interviews showed:

[2] Nord Pool is the Nordic electricity exchange that was started in 1996 by Sweden and Norway. Today, there are several member countries in Europe.

[3] Sweden is today divided into four electricity areas from the electricity area Luleå (SE1) in the north to the electricity area Malmö (SE4) in the south.

- the transition from fossil cars to electrified cars to be more than only exchanging gasoline with electricity. The participants found the experience of driving on pure electric as a "good feeling", not only by the smoother, more silent and fume free experience, but also as it provided a more guilt free mobility.
- although the transition to fully electric cars felt natural or inevitable, which you had to adapt to by learning new habits and routines, there was a lot of anxiety or frustration in the charging of electric vehicles and how they connected to all new services around charging.
- refuelling a fossil car were seen as a very tangible and analogue experience through paying for fuel a at well-known places through your credit card, whereas charging where seen as a digital, much more complex and abstract experience in where to find charging, how much it costs, how to pay and what to use the electric energy for.
- knowledge about the households energy usage and cost were low and electric energy was taken for granted to be always available to meet the needs of the household.
- cost was often mentioned as a rational argument for investing in specific type of cars or home appliances, however getting a detailed understanding of if choices actually made any savings were difficult to calculate.

The second set of interviews were done approximately a half year into the project after all ten households had their wallbox and fuse protection charging algorithm enabled. These interviews also had to be done through video meetings with the participants due to the pandemic. The themes for the second set of interview questions circled around; changes in the household that might have impacted energy and mobility usage since last time; their charging experiences of their rechargeable cars so far; new learnings about energy and EV usage since last time; and what they anticipated next about experiences around charging and energy. Main findings from this set of interviews exposed:

- Life is not static - People do lots of changes which impact their energy usage during a quite short duration of time. During these six months some of the households had for e.g.: changed their plug-in hybrid to a full EV, some had changed household main fuse size from 20A to 25A. Some had dramatically changed their working habits due to the pandemic. Some had a new office location closer to home, and some had children that got a scooter which enabled them to reduce to one car in the household.
- New routines of charging - Most of the households had got a charging routine to mostly charge at home due to convenience and cheapest price. Most of them also charged directly to 100% except for the BEV owners. However, most every day trips was done on pure electric for the short range of plug-in hybrids. Most of the households plugged in and left the cable connected to their cars while at home.
- What is Smart charging? - The participants anticipated smartness in EV charging as: Something to make the complexity in finding, paying, pricing, avoiding power peaks, energy management, while charging by managing charging effortlessly. However, some saw it as difficult for an algorithm to be smart enough to predict households' needs or changing priorities. "Does smartness have to be that complex?". Also interesting is the future anticipation of being able to prioritise charging speed vs. household appliances. "Possibility to speed up charging?". The possibility for the technology to adapt over time without maintenance was also seen as smart.
- Learning from EV life - All households found that driving on pure electric EV felt very nice both from a practical and hedonic perspective. However, it felt as if it was cheaper to drive on electric, the actual running costs were seen as untransparent as it was difficult to find and calculate the cost for used energy. Many of the households had also learnt that energy and power is limited, when they realised that fuses sometimes blew while charging their cars or the discussion in society that there's sometimes a lack of power in the grid locally. As private household owners, solar panels and EV's felt as a natural future solution to reduce their dependence on energy providers, pricing and to become more sustainable.

The third set of interviews were done more than a year into the project when most of the households had their first introduction to the smart charging algorithm and the first basic version of the smartphone app interface to monitor charging status and set charging preferences. Most of the households had during this time also been provided the opportunity to change to pure EVs and 7 out of 10 households EVs. The third-round interviews were divided into two parts where the first one focused on what the participants had learned and experienced since last time regarding energy prices, becoming fully EV owners or other changes in life that had impact on their energy consumption. The second part provided an interactive demo of a smartphone app with speculative content that could be implemented in future versions of the real smart charging app. The participants were encouraged to try-out and speak out loud about their anticipation of the value of different content in the demo-app. These are some of the preliminary findings from the third set of interviews:

- Since the last round of interviews the spot energy price peaks during the autumn 2021 increased dramatically which also had made the participants in the households more concerned about understanding their energy usage for household and mobility.
- The participants that had recently shifted from plug-in hybrids to EV's learned a different behavior that charging was not necessary every day for their commute, however most tended to plug-in the cable anyway. Charging at work was no longer needed for EV owners, however some tried to charge at work when spot prices to charge at home were too high. Charging at home was still seen as the most convenient solution and mentioned as one of the arguments against going back to a fossil car and having to go to a gas station to refill.
- Interest in solar panels had increased among most households and one of the households had recently installed solar panels since last time.
- The high spot prices and uncertainties of the energy market had also made two households temporarily change back to a fixed price tariff.
- The demo of the smart charging app exposed different perspectives on the value of what "smart" charging meant for the participants, also within a household. Examples of this were: the value in understanding the capabilities and the logic of the smart charging algorithm in order to be able to use it in a smart way, others wanted more to be "guided" by the algorithm in order for them to know how they should assist and make smart choices.
- Transparency of the algorithm was seen by all participants as important in order to learn and trust to use it. Showing the forecast when charging was planned and the history of when it was done was both seen by some participants as good examples of information for understanding the logic of the smart charging function.
- Overriding the algorithm in an easy way was also seen as necessary in order for the participants to feel in control to prepare for trips, shared usage of car, shared usage of wallbox or cost optimisations (longer than the spot price forecast) that the algorithm was not seen as being able to detect and plan for.
- Showing the value of using the app was also seen as an important aspect to be included in the smartphone app. The value was mostly mentioned to be expressed in cost, but some also wanted to know the change in impact on the environment.
- Understanding the split between household energy and car charging was also seen as an important aspect as now their car usage ended up on the household energy bill.

From the three sets of interviews done so far, the following findings can be summarized:

- Finding #1 - Value for all: It's not all about saving money with smart charging, it is also about the feeling of making smart choices and becoming more independent. The value of smart charging could be seen differently by users within the same household. If not all within the same household see a positive value of "smart" technology it will risk creating friction rather than smartness. Smart is acknowledging the diversity of anticipations and fears in a household and enabling the collaboration and merging of interests, values and routines.
- Finding #2 – Trust for all: Smart automation is often seen as something that is doing its job without need for the users to worry or think about it. However smart charging becomes very entangled into everyday lives of several people in a household. Users have different interests and knowledge about how smart automation works and in order to create trust and understanding the smart technology needs to be transparent enough for users to be able to learn how to integrate technology in everyday lives. It's not the amount of algorithms and sensors that is used that creates smartness, it's the easiness for people to embed the technology into their everyday lives.
- Finding #3 – Control for all: Smart automation to reduce complexity and the need to monitor, remember and do routines feels valuable when and where it makes sense. However, to fully automate things and remove humans in the process was not seen as the end-goal, as people know their everyday best and a well performed human-technology collaboration is probably the smartest. Users sharing a household have different needs for control, which bring implications for the technology to provide different possibilities for control.
- Finding #4 - Adaptation over time: The transition to electrified cars is a (fast) chain reaction and people might be faster to adapt and integrate EV's into everyday life than expected. When making the change, and as people share their experiences and anticipation with friends and family, being at the tipping point for EV's, few want to invest in old fossil fuel technologies that might be obsolete in near future. EV's are not only about exchanging drivetrains, but they also provide new values that fossil fuel cars are lacking, such as the possibility of becoming energy storage. Also, there is a digital eco-system around the EV, the charging and home energy consumption that needs to be considered. Therefore, smart charging technologies must be flexible and possible to evolve with the users changing everyday context and eco-systems. Failing to do so, smart charging will quickly become an "unsmart" obsolete technology.

3.3 Grid impact

As the system has been running for a short time, a mock-up simulation with similar optimization but with perfect forecast has been implemented to indicate possible hazards related to distribution grid impact. The system is based on local optimization of EV charging but assuming two tariffs, one energy based, and one peak power based. To indicate the electric distribution system impact, the grid impact is evaluated through distribution system modelling, see Figure 4a. Each connection point is indicated with a number, whilst each customer has an added arrow attached. As an example, in Figure 4a, **3** is a connection point without load, and **5** is a load connection point with an EV and household load). Power flow studies, where standard charging (uncontrolled charging at arrival) has been compared to the charging patterns introduced by the proposed system given different tariff structures. Simulations show in Figure 4b that smart charging shifts the energy to low-cost hours at night. However, for the overall grid, an allocation of energy is shifted that simultaneously occurs, creating a larger peak at night with the local optimization.

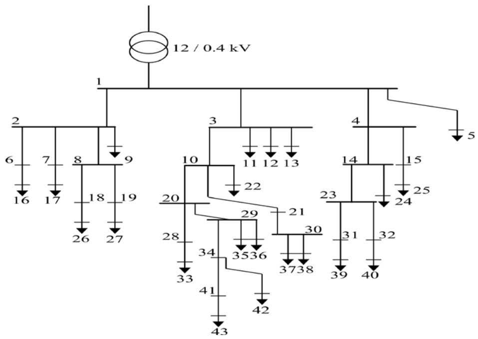

Figure 4a: Distribution grid model used in analysis.

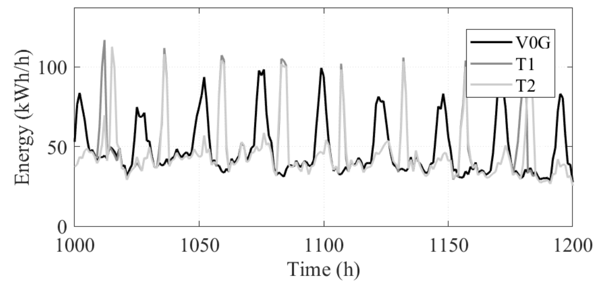

Figure 4b: Energy flow through transformer given 2 various tariffs as input to optimization compared to V0G, i.e., charging on arrival.

From the energy flow in Figure 4b, it can be seen that a local optimization concentrates the energy consumption to the hours at cheaper prices. This could in reality impact the operation of the grid in a negative way. For the case with a peak sensitive tariff (T2) the peak is reduced slightly. Similar but higher peaks were visible for the case of 11 kW charging power. Local optimizations of this type can therefore cause larger issues than V0G (i.e., charging on arrival) since it inherently has a more distributed power peak to the plug-in time of the EV.

3.4 Cost analysis

The ability for users to save costs is likely an important factor for the acceptance of smart charging in a mass market setting. In this project cost saving from smart charging will be estimated by comparing electricity costs from smart charging activated versus not activated. Charging behaviour ex-ante smart charging will be used to form a baseline, that subsequently will be compared to the actual behaviour and associated costs with smart charging activated. The baseline period consists of approximately 8 months of charging data from the 10 participating households. An average baseline charging profile (e.g. preferred start of charging and charging power) will be computed for the households during the summer/fall of 2022. The baseline charging profile will be applied to the actual cost context (spot prices) once smart charging is activated. The focus on actual user behaviour and its cost consequences is one novel contribution of this project.

Preliminary findings confirm the results in previous studies (e.g. [11]), that users without smart charging capabilities in general tend to initiate charging in the late afternoon. The charging data reveals that most of the users by default charge at maximum power, thus up to 11 kW. As a consequence, the vehicles will in many cases be fully charged before midnight and then remain idle for the remaining hours of the night. This use pattern is not ideal from a cost perspective, electricity prices are often peaking in the late afternoon and drop during the night. Albeit it needs to be acknowledged that some of the users are on a fixed monthly electricity price plan and are thus not exposed to hourly price changes. Once smart charging is activated the algorithm controls the charging patterns to occur at times with lower electricity prices, which in normal circumstances occurs at night. Charging power preferences does however remain the same, full power (up to 11 kW) is applied once prices are low. Often the charging session will be complete around 3-4 AM. This control setting is certainly cost optimizing for the individual household given a price model without peak power tariffs. It is however clear that vehicle charging yields the highest household peak power number for a majority of the households and could also cause possible local grid problems in scenarios with high EV penetration in an area. Another related finding is the change in household load profile due to change from a PHEV to a BEV. Although vehicle energy demand goes up slightly (likely due to increased electrical km driven) there is an even larger increase in peak load for the households. The

PHEV:s in this study have a peak charging power of 3,7 kW compared to 11 kW for the BEV:s. This is an interesting preliminary finding that will be further analysed in the project.

4 Conclusions

The technology for smart charging in 10 households is debugged and up and running, and qualitative and quantitative data is collected. Preliminary results indicate that smart charging is more complex than just saving money. People are a little sceptical about letting the decisions be made by an energy management system, so it will be interesting to see if that is true later in the project as well. The smart charging affects the grid, sometimes in a negative way.

Acknowledgments

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