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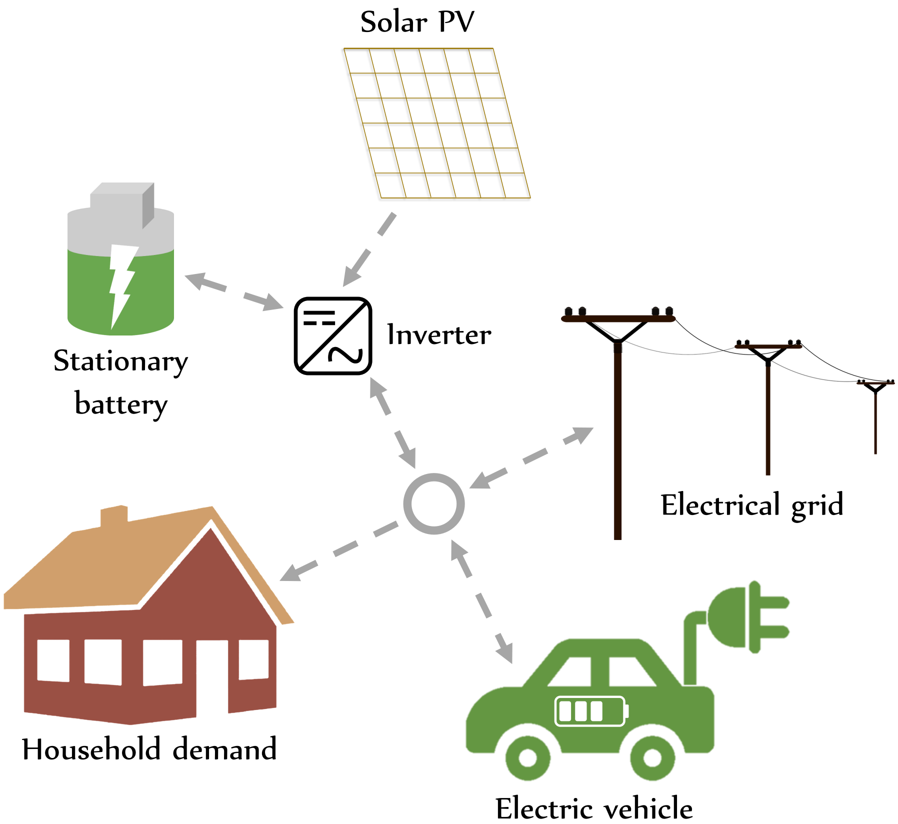


# Effect on household prosumers self-consumption and self-sufficiency when introducing an electric vehicle

## Modelling of residential households with solar PV and stationary battery

Master's thesis in Sustainable Energy Systems


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Department of Space, Earth and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

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Cover: Components in the modelled households electricity system and how electricity can be transferred between them.

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## Abstract

Electric vehicles introduces new possibilities for households with local generation of electricity to store this electricity, which can increase their self-sufficiency. The aim of this master thesis is to investigate the technical potential in using an electric vehicle as storage for residential households, with small scale electricity production from solar photovoltaics and in some cases stationary battery storage, and how the introduction of an electric vehicle can impact the demand for electricity from the grid for such households. A model has been developed to optimize the electricity system in households with the objective to maximize their self-sufficiency. Measured data on households electricity consumption, solar irradiation and, in contrast to existing literature, vehicle driving was used as input to the optimization model. In total 400 combinations of households and vehicles have been modelled over one year. Results from the model shows that introduction of electric vehicles to households increases their yearly mean self-consumption of in-house produced electricity with 19%. Also the mean self-sufficiency for all modelled households increases with 10%, despite the increased electricity demand for the households due to charging of the electric vehicle. The increase in self-sufficiency is more pronounced for larger solar panel sizes, while it decreases if the household already has a stationary battery installed. For households with larger solar panel systems (array-to-load ratio of 3-8) an electric vehicle can on average replace a stationary battery for storage of in-house produced electricity, and obtain the same self-sufficiency. Nevertheless, both storage possibilities complement each other and the highest mean self-sufficiency (42.5%) is obtained for households with both an electric vehicle and a stationary battery. The ability for electric vehicles to discharge stored electricity back to the household by vehicle-to-home technology is proven to be of importance for the electric vehicles ability to increase the self-sufficiency, the mean self-sufficiency is 8% higher if this technology is available. Several factors such as time at home by the electric vehicle and its share of total electricity demand for the household is found to be of importance for the results, and there are large variations (maximum 50 percentage points) in self-sufficiency between different combinations of households and electric vehicles.

Keywords: Residential household, prosumer, solar photovoltaic, electric vehicle, self-consumption, self-sufficiency, storage, battery, modelling

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David Gudmunds, Gothenburg, June 2018

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# 1

# Introduction

One of the major challenges for our society is climate change caused by increased levels of greenhouse gases (GHG) in the atmosphere (United Nations, 2018). As a way to reduce GHG emissions to mitigate climate change, the installed capacity of renewable energy sources such as solar photovoltaics (PV) and wind power have grown exponentially over the last decade (International Renewable Energy Agency, 2018). In addition to having low GHG emissions these sources also change the power generation system from being centralized, with a few large power plants, into a more distributed system consisting of several smaller power plants. The outermost example of this are consumers producing parts or all of their own energy needs, so called prosumers (Sioshansi, 2016). The fact that solar PV units are scalable down to a capacity of less than one kilowatt, in contrast to traditional power generation technologies such as coal or nuclear, has made it possible to install them in suitable sized modules, from large utilities down to private households. One barrier for installation of solar PV is further decreased by the possibility to install them on already existing buildings (Widén, 2009). In combination with decreasing prices of such modules and policy measures making them reach grid parity[1], this has paved the way for an exponential increase in new installed capacity. As an example the installed capacity of solar PV in Sweden was 65% higher at the end of 2017 compared to 2016 (Statistiska Centralbyrån, 2018*a*). However, solar energy is growing from an initial low level. In Sweden it accounted for only 0.13% of the annual electricity production during 2016, and globally the corresponding number during 2015 was 1% (Lindahl, 2017; World Energy Council, 2013).

One aspect of these renewable energy sources is the fact that they are intermittent, and thus cannot be dispatched in time. At the same time the electrical system requires instantaneous balance between supply and demand to maintain reliable operation (von Meier, 2006). A solution that can make a greater penetration of intermittent power generation possible is storage of electricity (Eurelectric, 2011). Storage technologies can both support the electrical system, and a prosumer who can utilize a larger share of locally produced electricity for own use, and thereby enhance their self-sufficiency (Nyholm et al., 2017).

[1]The stage of development where a technology is cost competitive with conventional grid-supplied electricity (Yang, 2010)

Another present trend in society is electrification of loads which traditionally have been supplied by other energy sources such as gas or gasoline (International Energy Agency, 2017*b*). One area where development on electrification is taking place is the transport sector, with introduction of vehicles partly or fully driven by electricity (International Energy Agency, 2017*a*). This provides an opportunity for the transport sector to lower its emissions if the electricity is produced by renewable energy sources (Coffman et al., 2017). At the same time electrification of vehicles also provides potential for improving local air quality and increased energy security for countries (Muratori, 2017). In Sweden the government has decided that emissions from domestic transport should be reduced by 70% until 2030, compared to the levels in 2010 (Regeringskansliet, 2017). Here electrification of vehicles is seen as one solution. The number of electric vehicles (EVs) in Sweden has grown by 61% the last 12 months (end of May 2018), to 54 000 (Elbilsstatistik.se, 2018). However, as for solar PV the increase is starting from low levels and EVs were in the end of April 2018 accounting for just above one percent of the total number of active passenger cars in Sweden (Statistiska Centralbyrån, 2018*c*).

This shift towards electrification of the transport sector links this sector with the electricity system in a way not seen before. To make it possible to incorporate these EVs' additional demand for electricity in the current electricity infrastructure new solutions are needed. Without such solutions EVs can have a negative impact on the power grid in terms of e.g. increased peak demand (van der Kam and van Sark, 2015). At the same time all these EVs with batteries can also provide storage capacity to the power system when being parked and connected to the electrical grid. This new connection enables innovative management strategies that can support the power grid or the individual household (White and Zhang, 2011; Yong et al., 2015). In parallel, stationary battery technologies are steadily improving and becoming cheaper, leading to a rapid growth (over 50% in 2016) in new deployment (International Energy Agency, 2017*a*). These trends in combination with increased installations of small scale electricity generation have the possibility to change how electricity is produced and consumed.

With the introduction of new control and communication technologies the concept of smart grid has been established, which can be defined as the vision to enhance the overall functionality of the power system. This can be done with respect to different factors such as minimizing the use of energy or lowering the costs for electricity, while ensuring reliability in the system all the way from production to end users (Gellings, 2009). In the same way it is possible to optimize the energy system in a household by using appliances that are connected to a control unit. One technology that can be used for such purpose is the so called vehicle-to-home (V2H) or vehicle-to-grid (V2G), where electricity can be transferred from the EV battery to the household or electrical grid (Briones et al., 2012). With such technologies, together with local small scale production, a single household can go from buying all electricity from the grid to being self-sufficient for many hours of the year. It also enables the consumers to take active part in the power system, which not only would impact the individual consumers but also the energy system on a regional level due to changes in load from these households (International Energy Agency, 2017*a*).

## 1.1 Aim and limitations

The aim of this master thesis is to investigate how the introduction of an EV to residential households, with small scale electricity generation from solar PV and both with and without stationary battery storage, can affect the electricity demand from the grid for these households.

More specifically the following research questions are to be answered:

- How does the introduction of an EV, with available battery capacity and additional demand for electricity, affect the self-consumption and self-sufficiency for households with in-house electricity generation from solar PV?
- Can an EV with its battery complement or alternatively replace a stationary battery for storage of electricity in households with in-house electricity generation from solar PV?

In the long term perspective, studies on how the introduction of EVs will impact the energy system on a regional or country level are of great interest. However, to find answers to such questions one first needs to know how the load from single households will be affected. By answering the specified research questions this thesis will provide a basis for such further studies. This will be done by modelling the electricity system in households with an EV, solar PV and for most cases also a stationary battery storage system.

The thesis will not include any economic aspects such as investment costs for the components or electricity prices on the market. Neither will sizes of the different systems in the model be optimized. Instead the model will be optimized with respect to minimizing the amount of electricity used from the grid, and the effect from introduction of an EV to the household electricity system will be analyzed.

## 1.2 Literature Review

A lot of studies and articles (e.g. Nyholm et al., 2017, Munkhammar et al., 2013 and Zhao et al., 2013) are available within the field of electricity management for residential households. These studies investigate different combinations of small scale PV generation, charging of EVs, in-house battery energy storage and for some studies (e.g. Erdinc, 2014 and Erdinc et al., 2015) also demand response options.

Nyholm et al. (2017) have investigated how installations of solar PV in combination with battery installations in Swedish households without demand response actions can increase the self-consumption of in-house PV generated electricity, and by this the self-sufficiency of the household.

When introducing load from charging of an EV to a residential household Munkhammar et al. (2013) have shown that the yearly total electricity demand for the household on average increases with over 35%, and that there is a mismatch in time between PV generation and charging demand. Even if the PV capacity is increased according to the load increase, the introduction of EV charging demand results in lower self-sufficiency for the household (Munkhammar et al., 2013). In the study by Munkhammar et al. the EV is assumed to be plugged in for charging as soon as it arrives at home. However, when and how to charge the EV can be varied. Zhao et al. (2013) have shown that using appropriate scheduling when charging EVs with respect to electricity prices, in this case in combination with small scale solar PV generation and storage possibilities for electricity, has benefits for both customers and utility companies. However, neither bidirectional power flow from the EV to the household, i.e. vehicle-to-house, nor vehicle-to-grid power flow is taken into account by Zhao et al. (2013).

Two studies that take demand response of parts of the household into account, in addition to small scale PV generation, local battery energy storage and EV charging demand, when evaluating smart household electricity management are Erdinc (2014) and Erdinc et al. (2015). In Erdinc (2014) only electricity produced by the PV array is assumed to be possible to sell back to the grid, while the EV battery and the stationary battery storage system only can be used to supply load internally in the household or EV. Erdinc et al. (2015) also includes the options for vehicle-to-home, vehicle-to-grid and possibilities to use the stationary battery for selling back electricity to the grid. Different combinations of these options have been investigated together with consumer preferences for charging of the EV, showing that the cost of electricity can be reduced by up to 65% if the consumers are willing to postpone the charging to periods with lower prices and all smart grid solutions available are implemented (Erdinc et al., 2015).

While most of the references mentioned uses real-life data regarding households' electricity consumption and PV generation, none of them uses measurements as basis for driving patterns of the EVs. Instead different assumptions are made regarding when the EVs are plugged in at home, their daily electricity consumption and how much energy there is left in the EV batteries when they arrive at home. In Munkhammar et al. (2013) a stochastic model is used to mimic different lifestyles, which generates both household load and driving together with charging pattern for the EV. Other references (e.g. Sundström and Krysander, 2015, Zhao et al., 2013, Wu et al., 2017 and Erdinc, 2014) have defined fixed times when the EV arrives home in the afternoon, and leaves in the morning. In these studies the time for plug-in at home varies from 17 to 20, while the time for plug-out is in the range of 06 to 07. These times are most likely based on general travel patterns with different travel surveys used as background, even though none of the studies refers to any specific survey. Some of these studies also have a defined energy level in the EV battery when the EV is plugged in (Erdinc, 2014; Erdinc et al., 2015; Wu et al., 2017). Sundström and Krysander (2015) instead uses randomly selected values of the EV battery energy level when the EV is plugged in, between fully loaded and empty. However, these sources have all defined that the EV battery should be fully charged when the EV is plugged out in the morning. This can be compared with Zhao et al. (2013) where different values of EV battery levels, both when arriving and leaving home, is used. The EV batteries are connected to the electrical grid and possible to charge (and in some studies discharge) during all hours when the EVs are plugged in, which makes room for different charging optimization strategies.

Only one study which uses GPS-based travel data from vehicles is found studying a similar research question as previously mentioned studies. However, this study does not consider electricity management in households specifically, instead it focuses on the role of being able to charge EVs at work (Wu, 2018). With that said, this thesis aims at filling the identified gap by using measured data on households' electricity consumption, small scale PV electricity generation and measurements of vehicles' driving patterns to answer the specified research questions.

# 2

# Theory

In this chapter the relevant theoretical background is presented in order to provide the reader with an adequate framework for understanding the rest of this thesis. The chapter includes basic theory about the electrical grid and distributed generation, solar PV and its potential in Sweden, and electric vehicles and how they can be integrated with the electrical grid to provide services both for the power system and the individual household.

## 2.1 Electrical grid

One of the central challenges in operation of the electric power system is the fact that electricity must be generated in the same moment as it is consumed, with rotational inertia as the only inherent storage capacity in the system. Due to this lack of possibility to store produced electricity in the grid, the system has to be controlled constantly to maintain stable operating conditions and real-time balance between supply and demand (von Meier, 2006). This also holds true for the electrical system in a residential household, where the amount of electricity consumed has to be balanced with the electricity bought from the grid or produced locally at all times.

Installed capacity of renewable power generation technologies is increasing as a way to reduce GHG emissions. This transition results in a more distributed generation system, caused by the fact that renewable power plants tend to be spread out, partly to manage the varying availability of these resources (Widén, 2009). Distributed generation is by Ackermann et al. (2001, p. 201) defined as *"...an electric power source connected directly to the distribution network or on the customer site of the meter."* Even though the costs for generation can be higher with smaller scale distributed generation, the overall cost can be reduced thanks to lower costs for transmission and distribution (Willis and Scott, 2000). Also the losses in the system can be reduced by this design (Ibid).

## 2.2 Solar PV

A solar PV system is made up of single solar cells, which are combined to modules. When exposed to solar radiation a voltage is created across the cell, which makes the current flow if the solar cell is connected to a load. By connecting these cells in series and parallel a sufficient power output can be obtained (Widén, 2009). Currently the most efficient solar panels available on the market has an efficiency of 22.5%, with the majority of panels lying between 14% to 16% in efficiency (Aggarwal, 2018). In laboratory scientists have managed to reach up to 44.5% efficiency for solar panels (Lumb et al., 2017).

The theoretical potential for solar energy as an energy source on Earth is substantial. The total annual solar radiation hitting the earth's surface is more than 6 000 times the annual primary energy used globally, which in 2015 was just above 150 000 TWh (World Energy Council, 2013; BP, 2017). Even though Sweden is located far north of the equator, there still is a big potential for electricity generation from solar PV. According to European Photovoltaic Industry Association (2012) the maximum output per kW installed PV capacity is 1050 kWh/year in Sweden, which can be compared to 1085 kWh/year in Germany where currently a considerably larger share of electricity is produced from solar PV. In addition, King et al. (2004) has shown that a colder climate can increase the efficiency of solar cells. Instead another challenge occurs on our northern latitudes, the fact that there is a negative correlation between electricity production from solar PV and residential power demand, both on daily and annual basis (Munkhammar et al., 2013).

The physical potential for the installation of solar PV in Sweden is large compared to the current installed capacity. According to Kamp (2013) there is 319 $km^2$ of roof area in Sweden where PV could be installed. This would correspond to almost 50 GW capacity, which could generate 49 TWh electricity per year. Also, the potential for installed PV capacity on unused cultivated land is substantial, corresponding to a potential of 126 TWh/year in electricity production according to Norberg et al. (2015). These numbers can be compared with the total electricity production in Sweden during 2017 which was 143 TWh (Statistiska Centralbyrån, 2018*b*). Even though it is not likely that all off these areas will be exploited, one can notice that the future expansion of electricity production from solar PV in Sweden is not hampered by available area. Nor will the capacity of the electrical grid be limiting at first, as shown in a study by Marklund (2015) the medium-voltage grid can handle up to 30% of the total electricity production coming from solar PV. Instead other factors such as profitability or distance to the closest transformer station might be limiting factors (Norberg et al., 2015).

For households with solar PV it is economically advantageous to consume this generated electricity in-house, since additional costs such as tax and grid fees that are added to the end-user price for electricity bought from the grid can be avoided (Munkhammar et al., 2013). Self-consumption of PV generated electricity is by

Luthander et al. (2015) defined as the share of locally generated electricity that is being consumed in-house, while self-sufficiency is defined as the share of total demand that is being supplied by in-house generated electricity.

## 2.3 Electric vehicles

Electric vehicles (EVs) refers to vehicles partly or fully propelled by one or more electric motors (Yong et al., 2015). In this thesis focus will be on passenger EVs, but the same technologies exists also for buses, motorcycles and lorries. Within the definition of EVs several types of technologies exist depending on their ratio of electrification. The least electrified type is the hybrid electric vehicle (HEV) where the internal battery is being charged by the combustion engine and regeneration of kinetic energy when braking, and there is no possibility for external charging of the EV battery. The next step in electrification is the plug-in hybrid electric vehicle (PHEV) which has both an electric motor and a combustion engine. Charging of the EV battery in a PHEV can be done from the electrical grid, by plug-in of the vehicle. Lastly the pure battery electric vehicle (BEV) exists, with energy storage only in a battery and propulsion all done by an electric motor. In addition to the advantages with EVs compared to vehicles with an internal combustion engine (ICE) mentioned earlier, vehicles propelled by electric motors are more energy efficient. In combination with low prices of electricity this leads to lower operating costs compared to traditional ICE vehicles (Yong et al., 2015). In this thesis a distinction is made between *EV* referring to electric vehicle, while the usage of *vehicle* refers to ICE vehicle.

Charging of EV batteries can be done everywhere where the EV can be plugged into the electrical grid, and the time it takes to charge the battery depends both on the size of the battery and the charging power. When charging at home or at work one normally uses charging power below 22 kW, while fast charging stations for example along highways can have higher power. Home charging of EVs can be done by both single-phase or three-phase connections, which give a charging power normally between 2.3 kW up to 11.0 kW. The time needed to charge the EV battery can approximately be calculated by dividing the battery capacity with the charging power, with some deviation due to the fact that the power is varied during charging to be more gentle to the battery (Energimyndigheten, 2018; Emobility.se, 2018). In Table 2.1 the approximate charging time for some different EV battery sizes and grid connections can be seen.

**Table 2.1:** *Approximate charging time in hours for charging of EV batteries from complete depleted to fully charged, depending on charging power.*

| Grid connection | Power [kW] | EV battery sizes 15 kWh [hours] | 25 kWh [hours] | 50 kWh [hours] | 75 kWh [hours] |
|---|---|---|---|---|---|
| 1-phase (AC) 230 V 16 A | 3.7 | 4.1 | 6.8 | 13.6 | 20.3 |
| 3-phase (AC) 230 V 16 A | 11.0 | 1.4 | 2.3 | 4.5 | 6.8 |
| Direct current 400 V 125 A | 50.0 | 0.3 | 0.5 | 1.0 | 1.5 |

Electricity flow between the household (or grid) and the EV can be both unidirectional, where electricity only can be transferred to the EV, and bidirectional where electricity also can be exchanged back from the EV battery to the household or electrical grid. During unidirectional connection the charging rate of the EV can be adjusted over the hours when the EV is being plugged in, so called smart charging. However, the most basic unidirectional charging strategy is when the EV is being charged with maximum power from immediately when it is arriving at home until the battery is fully charged. With bidirectional power flow vehicle-to-home (V2H) or vehicle-to-grid (V2G) technology can be used to also transfer electricity back from the EV to the household or electrical grid (Tan et al., 2016).

Smart charging can be realized by adding a controller which manages the charge rate. By such a setup the flexibility of the EV charging can be enhanced that can support the power grid operations. As an example charging of the EV can be postponed to hours with lower demand in the system, reducing the need for peak power generation in the system and at the same time lowering the costs of charging for the EV owner (Tan et al., 2016; Guille and Gross, 2009; Sundström and Krysander, 2015). By introducing bidirectional power flow EVs further can contribute to the system operation by also being able to feed back power during periods with high demand. This setup can also help the integration of intermittent renewable sources by the possibility to store excess electricity in EV batteries to hours with less production (Tan et al., 2016; Wang and Wang, 2013). Fattori et al. (2014) have shown that the benefits from V2G for the electrical system can be tangible when EVs accounts for around 10% of the vehicle fleet.

One technical drawback held against V2H and V2G technology is the fact that battery performance will deteriorate more quickly due to the increased number of charging cycles (Peterson et al., 2010). In contrary, Uddin et al. (2017) have shown that V2G can reduce the deteriorating of battery performance by decreasing the number of hours with really high or low battery level, which are associated with increased degradation. In addition, cultural and business barriers towards a large implementation of V2G exists (Sovacool and Hirsh, 2009). Among these the risk of having low battery storage level when needing the EV is a major concern. Another question is how much economic compensation one will get for enabling these service to the grid. On this topic White and Zhang (2011) have shown that there might be low economic incentives for individuals to provide peak reduction services by V2G, but a significant potential for financial return when providing ancillary services such as frequency response.

According to the definitions of self-consumption and self-sufficiency provided in Section 2.2, introduction of an EV to a household will provide possibilities to increase the self-consumption of PV generated electricity, while it both can increase or decrease the self-sufficiency. This is the case since the total electricity demand for the household increases due to EV charging demand, at the same time as the EV also might enable increased utilization of PV produced electricity.

# 3

# Methodology

A model over the electricity system in a residential household has been developed to be able to fulfill the aim of this thesis and answer the specified research questions. This model is presented in this chapter together with a description of the input to the model, the constraints and assumptions used and the different parameters that have been investigated.

## 3.1 Components of the household electricity system

The electricity system in the modelled households consists of electronic devices within the household (including heating in cases of electric based heating), a solar PV panel, a stationary battery and an EV with battery that can be plugged into the household. Some of these components generate an electricity demand, while others supply the system with electricity. The connection with the electricity grid is also included, which can be used for both transmission of electricity from the grid and back to the grid during hours with excess production from the PV panel. The stationary battery and PV panel are connected through an electrical inverter which converts direct current (DC) to alternating current (AC). These components and their connections can be seen in Figure 3.1.

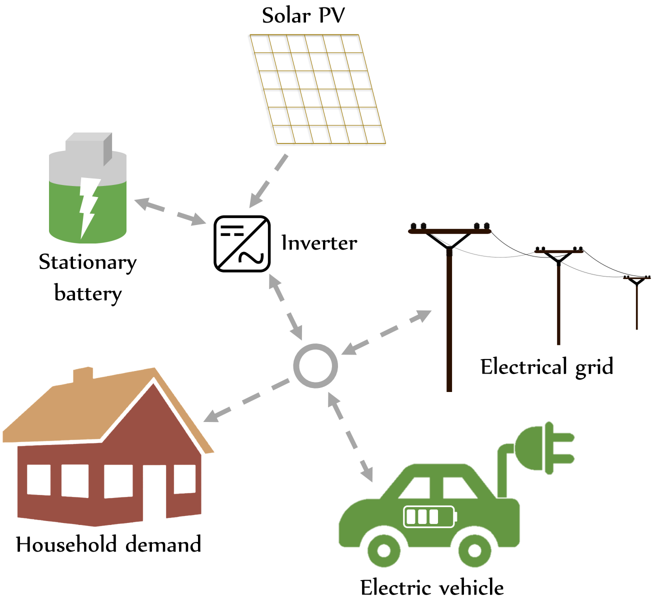


**Figure 3.1:** *Components in the household electricity system. The arrows indicates how electricity can be transferred between the components. Abbreviation used: PV = photovoltaics.*

## 3.2 The model of the household electricity system

The developed model is a linear programming model that consist of several equations that represent the household electricity system, and based on the model developed by Nyholm et al. (2017). Electricity demand from the household and EV, and the electricity production from solar PV are fixed and given as input to the model. Charging and discharging from the EV battery and stationary battery, and transmission from and to the electrical grid are variables that can be varied. The model is optimized with respect to minimizing the amount of electricity transmitted from the electrical grid, in order for the household to obtain as high self-sufficiency as possible. The software used for optimization is GAMS (general algebraic modeling system), and the code can be seen in Appendix A.

### 3.2.1 Equations and constraints

The main equation is the energy balance of the household that includes all components in the household electricity system, and can be seen in equation 3.1.

$$El_{householddemand}(t) = PV_{prod}(t) * PV_{cap} + P_{batt,discharge}(t) * \eta_{battery} - P_{batt,charge}(t)$$
$$+El_{fromGrid}(t) - El_{toGrid}(t) + EV_{pluggstatus}(t) * (P_{EV,discharge} * \eta_{battery} - P_{EV,charge}(t)) \quad (3.1)$$

$El_{householddemand}$ represent the electricity demand of the household, $El_{fromGrid}$ and $El_{toGrid}$ represent the amount of electricity transmitted from or back to the electrical grid. $P_{batt,charge}$ is the charging of the stationary battery while $P_{batt,discharge}$ represent the discharging back to the household from the stationary battery. $EV_{pluggstatus}$ is a binary parameter representing the plug-in status of the EV (if it is at home or not). Connected to this parameter is $P_{EV,charge}$ which represent the charging of the EV battery, while $P_{EV,discharge}$ represent discharging of the EV battery. Charging and discharging of the EV can only be done when the it is plugged in at home. The PV production is given as a fraction, $PV_{prod}$, of the installed capacity $PV_{cap}$, which combined gives generated electricity each hour. Both charging and discharging of the EV battery and stationary battery is constrained by limits on the maximum charging power. Connected to discharging of both the stationary battery and the EV battery is a battery efficiency $\eta_{battery}$.

An energy balance is formulated for both the stationary battery and the EV battery. The energy balance for the stationary battery is given in equation 3.2, where $E_{stationary}$ is the amount of energy stored in the battery. The capacity of $E_{stationary}$ is constrained to a maximum level.

$$E_{stationary}(t) = E_{stationary}(t-1) + P_{batt,charge}(t) * \eta_{battery} - P_{batt,discharge}(t) \quad (3.2)$$

Furthermore, equation 3.3 is the energy balance for the EV battery, where $E_{EV}$ is the amount of energy stored in the battery. As for the stationary battery the capacity of the EV battery ($E_{EV}$) is limited. Occasionally additional charging of the EV outside home might be needed, if the driven distance is too long before reaching home. If needed, this charging is represented by $P_{EVadditional}$.

$$E_{EV}(t) = E_{EV}(t-1) + P_{EVadditional}(t)$$
$$+EV_{pluggstatus}(t) * (P_{EV,charge}(t) * \eta_{battery} - P_{EV,discharge}) \quad (3.3)$$

As can be seen in equation 3.1, 3.2 and 3.3 the battery efficiency is taken into account both when charging and discharging the batteries, which combined gives the roundtrip efficiency. Regarding the efficiency of the inverter this is already considered when calculating the solar PV production, and thus included in $PV_{prod}$ (Norwood et al., 2014).

## 3.3 Input data and assumptions

The data used as input in the model is vehicle driving patterns, households electricity consumption and PV electricity generation. Worth to notice is the fact that the data on vehicle driving patterns and households electricity consumption is obtained from two separate studies, with different households included. This input data will be further described in this Section.

### 3.3.1 Vehicle driving pattern

The data regarding driving patterns of vehicles used in this thesis comes from *The Swedish car movement data project* (Karlsson, 2013). In that project all trips of over 700 privately driven vehicles were measured with GPS equipment for approximately two months each, between June 2010 and November 2012. The selection of vehicles in the study was done with constraints, limiting the sample to privately driven passenger vehicles, not older than from 2002 and registered in the west of Sweden. For the selected vehicles; position, velocity and time were measured for all trips during the specific period. In total over 450 vehicles, all powered by gasoline or diesel, were measured for more than 50 days. This data was further post-processed to repair missing data due to, e.g., malfunctioning GPS equipment (Karlsson, 2013). The data used as input in this thesis comes from 429 of these vehicles. Before the vehicle driving data were used in the model some further processing was performed, including locating home for each vehicle, and which hours the vehicles were parked at home during the measured period.

In the vehicle data, GPS coordinates for start and end location of each trip is available, but GPS coordinates for each vehicle's home is not provided. To find these locations the driving pattern of each vehicle was analyzed in a similar way as made by Wu (2018). In this thesis, the time the vehicle was parked at each location were used to decide the home location. For each vehicle a grid of 1x1 kilometer squares was generated based on the vehicle's outermost positions in each direction during the measured period. In this analysis only trips with less than one kilometer between the starting location and previous ending location were used. Trips with longer distance between these locations were not used since it indicates that the GPS system was not activated when the vehicle got parked or left the parking, implying an uncertainty regarding at which location the vehicle was actually parked. For trips with both end and start position within the same square, the parked time for these trips was allocated to this square. From this analysis each vehicle's home location was found by assuming it to be within the square were the vehicle had been parked the most number of hours.

In the input data to the model each EV is set as plugged in at home during one actual hour if the corresponding vehicle in the measured driving data is being parked at home for more than half of that actual hour. If the measured vehicle is not parked at all or parked for a shorter time than half of the hour within this square the EV is set as plugged out. The distance driven for each trip is allocated to the hour when the trip is finished, independent of if the trip ends at home or not. This gives the input data for each EV with hourly resolution as one binary parameter (1 if plugged in at home and 0 if not plugged in at home), and one parameter with total driving distance. In Table 3.1 an example of this data can be seen. Worth to notice is the fact that an EV can have recorded distance driven during hours where it is set as being plugged in, as can be seen for hour 260 in the Table. This is a consequence of the hourly resolution, where a vehicle can have been out driving for less than half of an hour and parked at home the rest of that hour, and therefore the EV is set as being plugged in the whole hour in the input data to the model.

**Table 3.1:** *Example of driving input data for EV 18.*

| **Hour of the year** | *254* | *255* | *256* | *257* | *258* | *259* | *260* |
|---|---|---|---|---|---|---|---|
| **Plug-in status** | 0 | 1 | 1 | 1 | 0 | 0 | 1 |
| **Distance driven [km]** | 11.88 | 0 | 0 | 0 | 4.96 | 0 | 5.13 |

To be able to use the data for a yearly simulation in the model the measured driving data was extrapolated from the original period (31-160 days depending on vehicle) to 12 months, which implies that the driving data for each vehicle is used repeatedly. This extrapolation was performed with respect to days of the week so that driving data was matched with household consumption and PV generation from the same weekday.

Energy consumption for an EV varies depending on several factors including the vehicle characteristics (e.g. vehicle mass, frontal area and drivetrain efficiency), road and weather conditions. As input in this thesis 0.18 kWh/km is used as energy consumption (including engine losses), based on Taljegard et al. (2017) but with an adjustment since Taljegard et al. calculates for highway driving and includes the battery efficiency which in this thesis is taken into account separately. This number is assumed to be constant, i.e., it is independent of travel distance and other factors such as season.

In this thesis it is assumed that the motorists would not change their travel behaviour if they switch from a diesel or gasoline driven vehicle to an EV. This is a necessary assumption to be able to use the data of driving patterns from Karlsson (2013) since the vehicles in their study are ICE vehicles. Due to this fact the variable $P_{EV additional}$, as seen in equation 3.3, is needed since the charging demand for all EVs cannot always be supplied at home. This additional charging can be fulfilled, e.g., during parking at work or the grocery store. It is further assumed that home chargers for EVs are available in every household in the model, with the same maximum charging power (11 kW) in all households.

### 3.3.2 Household electricity consumption

The input data regarding household electricity consumption used in this thesis is based on measured hourly load profiles from 2221 Swedish single-family houses. The data was measured by the electricity supplier E.ON during one year as a part of a Swedish household measurement project, from 1st of February 2012 to 31st of January 2013. Included households consists of both row-houses and detached houses, and the annual electricity demand varies from 1.76 MWh to 45.78 MWh. Several different types of heating systems are used in the houses, both electric-based (heat pump or direct electric heating) or non-electric (e.g. district heating) which affects if the heating system is part of the electricity demand or not. Worth mentioning is that the data regarding household electricity consumption is not statistically representative since the selection of these households was not based on a statistical selection. For additional information about the data see Nyholm et al. (2017).

The distribution of electricity consumption over the year for one of the households is presented in Figure 3.2. Similar curves with hourly data are used as input for all households in the model.

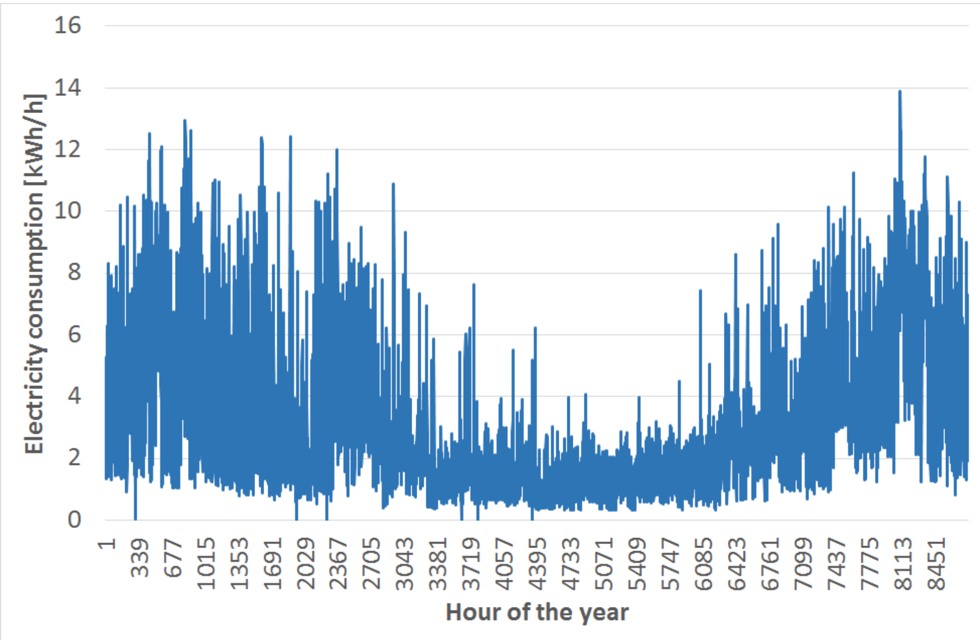


**Figure 3.2:** *Electricity consumption over the year for household 12.*

### 3.3.3 Selection of EVs and households

Among the 2221 available households, 20 were selected based on their annual electricity consumption and possible PV electricity generation. This selection was performed by first dividing the households into ten intervals depending on their yearly electricity consumption, from largest to smallest. The range of electricity consumption in each of these ten intervals were equally large, giving that not necessarily the same number of households were sorted into each interval. For each of these ten consumption intervals two new intervals were generated based on the yearly PV electricity generation by the households in each interval, from largest to smallest. Similarly as for the consumption intervals, the PV generation intervals were equally large in range of PV electricity generation. The households in each consumption interval were sorted into respective PV generation interval, and finally one household was randomly selected from each of these in total 20 samples. This approach was used to obtain as large variation as possible in selected households, with respect to both electricity demand and PV generation. The numbers regarding electricity consumption and PV electricity generation for the 20 selected households are presented in Figure 3.3.

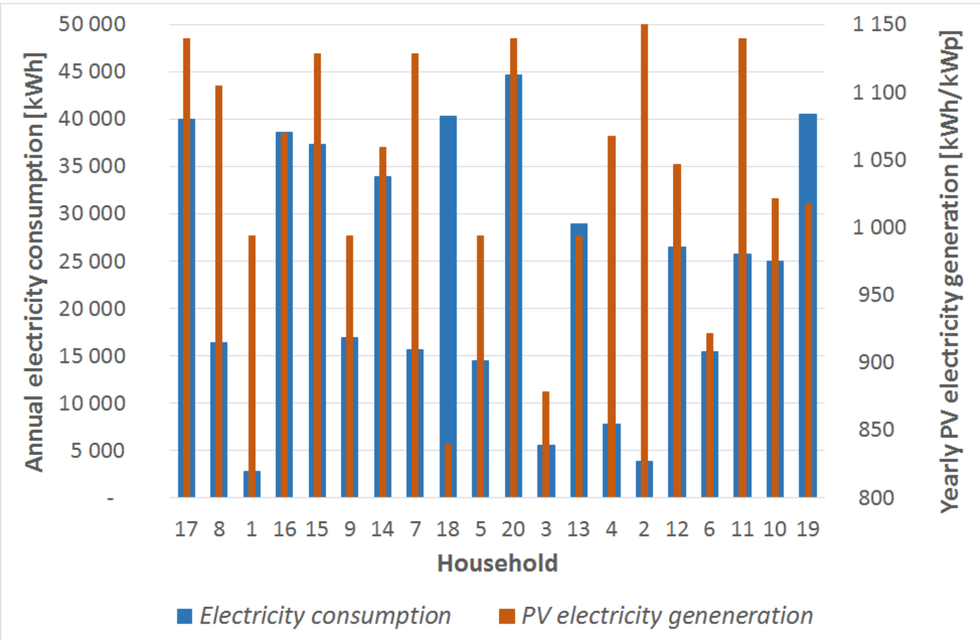


**Figure 3.3:** *Data on electricity consumption and PV electricity generation for the 20 households used as input to the model. The electricity generation is given in kWh per installed capacity of solar PV (kWp). Abbreviation used: PV = photovoltaics.*

In a similar way 20 EVs out of the 429 with measured data were selected based on the number of hours they were plugged in at home and total driving distance over the year. In this selection EVs where the corresponding vehicle were measured during summer (June - August) were excluded since their driving pattern most likely could differ from their normal driving behaviour due to e.g. vacation. First the EVs were divided into ten intervals depending on how many hours they were plugged in at home during the whole year. These ten intervals were equally large in number of hours, and ranging from the largest to smallest number of hours at home among all EVs. For each of these ten intervals two new intervals were generated based on the EVs' yearly driving distance, from largest to smallest. As for the intervals regarding number of hours at home, the distance intervals were equally large in range of distance. The EVs in each of the ten intervals regarding hours at home were sorted into their respective distance interval, and finally one EV was randomly selected from each of these in total 20 samples. Numbers for the 20 selected EVs regarding hours plugged in at home and annual driving distance can be seen in Figure 3.4.

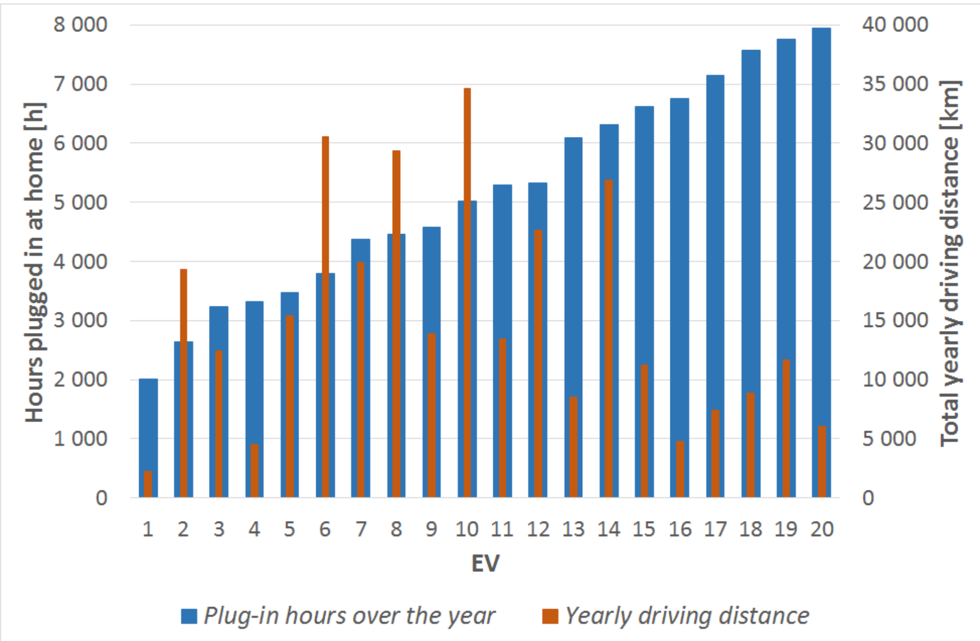


**Figure 3.4:** *Data on number of hours plugged in at home and total driving distance over the year for the 20 EVs used as input to the model.*

This selection of 20 households and 20 EVs were combined and gave 400 combinations of households and EVs as input to the model. The electricity demand for the households increases after introduction of an EV, due to the introduced charging demand from the EV. The increase in electricity demand depends on both the original household demand and charging demand from the EV, and varies from 0.8% increase to 224.1% increase in demand for different combinations of household and EV. With a larger battery in the EV a larger share of the trips is possible to supply by charging at home and less charging outside of the home is needed, which results in an increased charging demand at home. Due to this, the increase in electricity demand for households from charging the EV is larger when the size of the EV battery is increasing. The average increase in electricity demand goes from 16.1% increase at an EV battery size of 15 kWh to 20.6% increase when the EVs have a battery of 75 kWh.

Similarly the charging demand from the EVs that has to be fulfilled at home accounts for a varying share of the total electricity demand for the households (including EV charging), as can be seen in Figure 3.5. Also this share is affected by the EV battery size, since a larger EV battery results in an increased charging demand at home. Due to this, the demand for charging the EV make up a larger share of the total electricity demand for households when the size of the EV battery is increasing. With an EV battery size of 15 kWh the charging of the battery on average stands for 11.6% of the total electricity demand, which increase up to 14.0% when the EV battery size increases to 75 kWh.

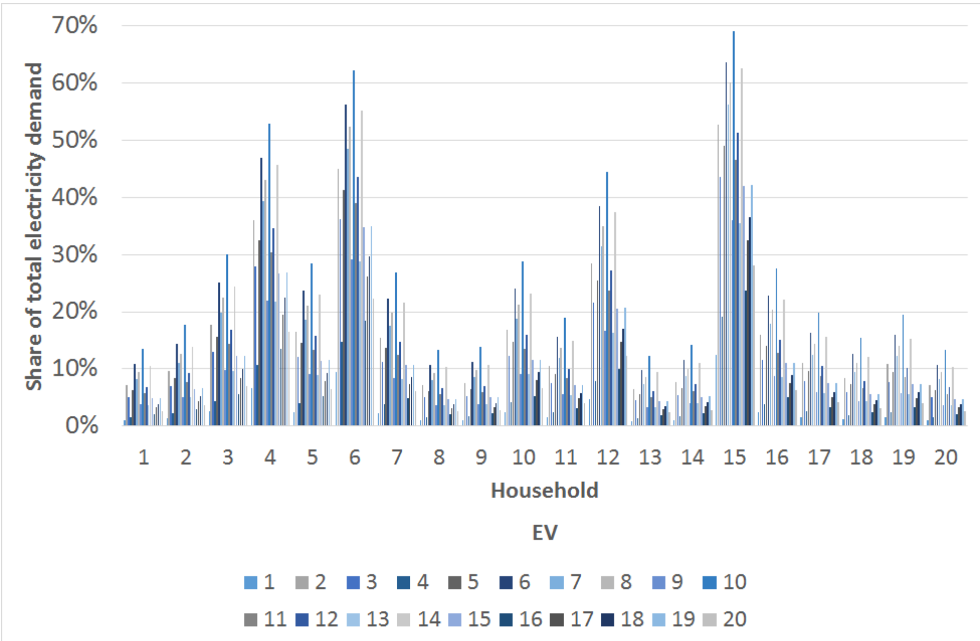


**Figure 3.5:** *Share of total electricity demand for the household including EV charging at home that the EV charging accounts for, for all combinations of households and EVs (with a 50 kWh EV battery).*

### 3.3.4 Solar photovoltaic electricity generation

Similarly as for the electricity consumption, data on possible electricity generation from solar PV during 2012 is available for all households. The solar PV panels are assumed to be tilted $31^o$ (representing the average house-roof tilt in Sweden), facing south and be polycrystalline silicon panels. The output of the installed PV systems are expressed in relation to the installed capacity for the households, and based on Norwood et al. (2014) and King et al. (2004). Meteorological data (temperature and solar radiation) with hourly resolution, from different sites in Sweden is used as input (Remund and Müller, 2011). To represent the lifetime degradation of the solar panels, a degradation efficiency is used. These input data are presented in Table 3.2.

**Table 3.2:** *Input data for PV systems used in the model.*

| **Input parameter** | **Input value** |
|---|---|
| Panel orientation | Due south |
| Panel tilt | $31^o$ (Kamp, 2013) |
| Degradation efficiency | 0.98 (Jordan and Kurtz, 2013) |
| Annual generated PV electricity (the range represents the different locations) | 839–1150 kWh/kW$_p$ (Norwood et al., 2014) |

The electricity generation from PV panels is presented in Figure 3.6, for one of the households during the year. Similar curves are used as input for all households in the model.

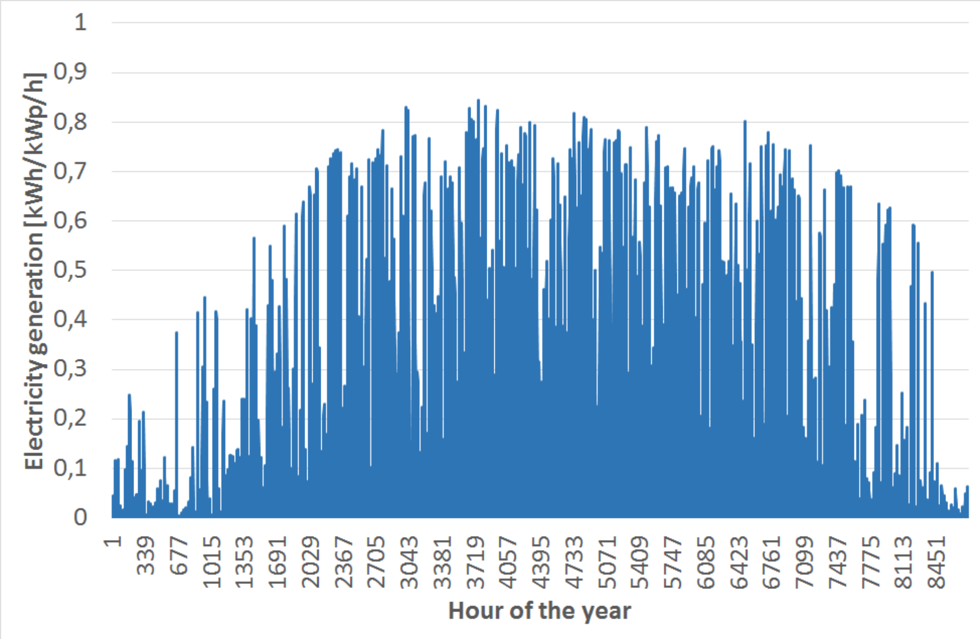


**Figure 3.6:** *PV electricity generation over the year for household 12, expressed as a ratio of the installed capacity (kWp).*

### 3.3.5 Batteries and inverter

For the electronic equipment included in the model, inverter and batteries, the data presented in Table 3.3 is used. The battery efficiency is used for both stationary batteries and EV batteries.

**Table 3.3:** *Input data for battery and inverter systems used in the model.*

| Input parameter | Input value |
|---|---|
| Inverter efficiency | 0.95 (Notton et al., 2010) |
| Battery efficiency (roundtrip) | 0.95 (0.90) (Battke et al., 2013) |

The energy balances for the batteries, as seen in equation 3.2 and 3.3 shows that a linear battery model is used. The maximum charging power is constant and not adjusted depending on the storage level in the battery, this applies for both the stationary battery and the EV battery. The battery sizes used in the model reflects the usable share of the installed batteries, which implies that no limits on depth of discharge are used. Both batteries are used solely to meet internal electricity demand in the household, and cannot be used for transmission to the grid to provide services such as demand response in the electricity grid.

### 3.3.6 Varied parameters

Several of the input parameters are varied within the model to evaluate their impact on the results. The parameters that are varied in this thesis are:

(i) Size of the solar PV panel
(ii) Size of the stationary battery
(iii) Size of the EV battery
(iv) Maximum charging power of the EV battery
(v) If vehicle-to-home technology is available or not
(vi) If a minimum available distance in the EV battery when being plugged in at home is required or not

The size of the PV panel system and stationary battery for each household is related to the demand for electricity in this actual household, in contrast to using the same actual size for all households independent on their consumption. By adjusting the size to each household results for different households become more comparable. According to this, the size of the PV panel system for each household is related to the average demand for electricity in this actual household. This is expressed as the so called Array-to-load ratio (ALR), defined by Widén et al. (2009), as in equation 3.4.

$$ALR = \frac{array\ size\ (W_p)}{average\ annual\ demand\ (W)} \tag{3.4}$$

By this, the actual size of the PV system varies from 0.3 kW to 5.1 kW for an ALR value of one, depending on household among the 20 selected households in the model. In the same way the size of the stationary battery is expressed as Battery-to-demand ratio (BDR) as in equation 3.5, defined by Nyholm et al. (2017).

$$BDR = \frac{battery\ energy\ capacity\ (Wh)}{average\ annual\ hourly\ demand\ (Wh)} \tag{3.5}$$

As for the PV system size, the installed battery capacity at a BDR value of one varies from 0.3 kWh to 5.1 kWh depending on household in the model. To relate the amount of electricity produced by the PV panel to the installed battery capacity, the concept of Relative battery capacity (RBC) is used. RBC is defined as in equation 3.6 by Nyholm et al. (2017).

$$RBC = \frac{battery\ energy\ capacity\ (Wh)\ \text{x}\ 1000}{annual\ generated\ PV\ electricity\ (Wh)} \tag{3.6}$$

The size of the EV battery is varied independent of electricity demand of the household and EV. This is done since the optimal battery size for an EV according to Kullingsjö et al. (2013) depends on several different factors, making it difficult to find one optimum for a fleet with large variations. Another factor is that sizes of EV batteries, in contrast to sizing of PV panel systems and stationary batteries, currently is set by the producers and not a parameter one can choose freely depending on personal preference. In this thesis some different sizes (in the range 15-75 kWh) are used to cover relevant battery sizes both for plug-in hybrid electric vehicles and pure battery electric vehicles. Despite the fact that EV battery sizes investigated in this thesis covers also relevant sizes for plug-in hybrid electric vehicles, the EVs in the model are driven by electricity only. EVs without possibility of charging from the grid are not included in this study.

The possible maximum charging power of the EV battery is fixed and depends on the electrical installation in the household. In this thesis two different values are included to analyze if the level of the maximum charging power has any effect on the results. The maximum charging power depends on the usage of single (3.7 kW) or three phase (11.0 kW) charger. A 16 ampere fuse is assumed in both cases.

In contrast to this, the maximum charging power of stationary batteries is variable and adjusted to the installed battery capacity. The maximum charging power is 1*E, where E is the capacity of the battery, which gives that a battery of 2 kWh corresponds to a maximum charging power of 2 kW.

The electricity exchange between the EV battery and the household electricity system is varied between unidirectional smart charging and bidirectional power flow where V2H can be used. Immediate maximum charging of the EV battery when arriving at home until the battery is fully charged is not modelled since this behaviour does not include any aspect of optimization.

A requirement on a minimum energy level in the EV battery, enough to drive a certain distance, when the EV is being plugged in at home is implemented for some model optimization. By this the EV battery always has at least a certain battery level when being at home to make shorter unplanned trips possible. At the same time it implies that not the whole EV battery capacity can be used for V2H.

In Table 3.4 all different values used in the model for the parameters presented in this Section are introduced.

**Table 3.4:** *Input values of varied parameters to the model.*

| Input parameter | Input value |
|---|---|
| PV panel ALR | 1, 2, 3, 4, 5 and 8 |
| Stationary battery BDR | 0, 1, 2, 3 and 4 |
| EV battery [kWh] | 15, 25, 50 and 75 |
| Maximum charging power of EV battery [kW] | 3.7 or 11 |
| Maximum charging power of stationary battery [kW] | Battery capacity [kWh] / h |
| V2H available | Yes or No |
| Minimum driving distance available in EV battery when vehicle being plugged in [km] | 0 or 50 |

When the size of PV panel systems reaches an ALR value of eight some of the households in the model produce more electricity on annual basis than they consume, and thus become net producers. According to the Swedish law a net producer has to pay fees that producers with less production than consumption are excluded from, which makes it desirable for a residential household to avoid being a net producer (Sveriges Riksdag, 2017). With the 20 households included in this thesis and the selected values of ALR, the actual sizes of PV panels varies between 0.32 to 36.93 kW, depending on household electricity demand. In the same way, the stationary battery sizes for the selected BDR values varies from 0 up to 20.34 kWh depending on household electricity demand.

# 4

# Results

In this chapter results from the model developed in this thesis are presented and explained, with focus on how the introduction of EVs affect self-consumption and self-sufficiency for the modelled households. For Sections 4.1 - 4.2, the EVs have the possibility to discharge electricity back to the households by V2H technology. In Section 4.3 three separate analysis of the impact on the results with respect to three parameters are presented; 1) Vehicles with the ability for vehicle-to-home (V2H) technology will be compared to vehicles without V2H; 2) Two levels of maximum charging power of the EV battery will be compared; 3) EVs with a requirement on the minimum available distance in the EV battery when they are plugged in at home will be compared to EVs without such a requirement.

## 4.1 Self-consumption

Introduction of an EV to a household can increase the self-consumption of solar PV electricity, or at worst keep it constant, due to the additional possibilities for utilization of the generated electricity in-house. The self-consumption can be seen in Figure 4.1, for each specific household in the model without EV (red dots) and each combination of household and EV (blue dots) for different EV battery sizes, together with the mean self-consumption for all households without EV (red line) and all combinations of household and EV (blue line). The self-consumption for households without EV is independent on EV battery size, and therefore the self-consumption for these households only is shown once, to the right in each subplot. Between the subplots in Figure 4.1 size of stationary battery systems is increased from left to right (higher value of BDR), while size of the PV panel systems is increased downwards (higher value of ALR). For clarity the Figure only shows some combinations of stationary battery sizes (BDR values) and PV panel sizes (ALR values), but all EV battery sizes for each combination. However, all PV panel sizes and stationary battery sizes are included in the analysis. The mean self-consumption is at most 21.2 percentage points higher for households with EV compared to without, this is seen in the case with ALR = 5, no stationary battery (BDR = 0) and EV battery of 75 kWh. The smallest difference of 0.8 percentage points occurs at ALR = 1, BDR

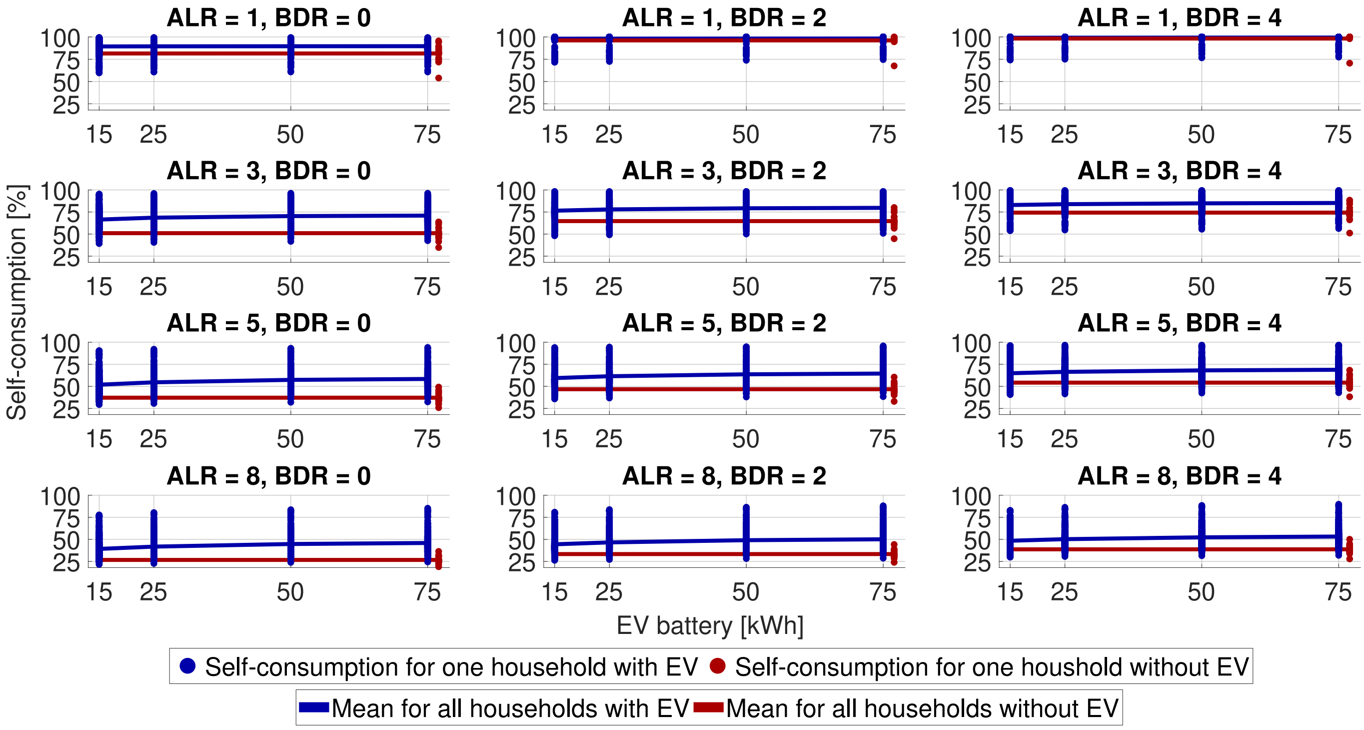


**Figure 4.1:** *Self-consumption for all households without EV (red) and all combinations of household and EV (blue), depending on EV battery size. The self-consumption for each household and combination of household and EV is represented by one filled circle (which together almost creates vertical lines), while the mean self-consumption for households with and without EV is indicated by the red and blue lines. Subplots for different sizes of PV systems (ALR increasing downwards) and stationary batteries (BDR increasing from left to right). Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

= 3 and EV battery of 15 kWh. When all combinations of different sizes of PV panel systems, stationary batteries, and EV battery sizes are summarized the mean self-consumption is 11.9 percentage points higher for households after introduction of an EV (corresponding to 19.4% increase).

The difference in self-consumption between households without EV and households with EV is greater for households with larger PV panel systems (ALR 3-8), as shown in Figure 4.1. In these cases households without an EV cannot exploit as much of the additional electricity generation, in comparison to if also an EV is available in the households.

On the contrary, larger stationary batteries (higher BDR values) decreases the difference in self-consumption between households with and without EV. As an example the mean difference in self-consumption when the PV panel systems have an ALR = 3, decreases from 18.1 percentage points when there is no stationary battery (BDR

= 0), to 9.9 percentage points at the same ALR but with the largest stationary battery (BDR = 4). The same impact on the difference in self-consumption cannot be seen for different EV battery sizes. This is most likely due to the fact that the EV batteries in comparison with the stationary batteries are large and already at the smallest EV battery size (15 kWh) can fulfill the required storage demand in most cases. Instead increased time at home for the EV would have a greater impact on the results. This trend with increasing self-consumption if the EV is at home a larger share of the year can be seen in Appendix B Figure B.1.

The trends that are seen in Figure 4.1 are on average for all households without EV, and combinations of household and EV. However, there are large variations in self-consumption between different households, which can be seen for both the blue and red dots in the Figure. Without EV the difference in self-consumption between different households is at most 41.6 percentage points, occurring for the smallest PV panel size and no stationary battery (ALR = 1 and BDR = 0). Between different households with an EV the difference in self-consumption reaches 61.6 percentage points when the EV battery is 75 kWh, PV panel size (ALR = 5) and no stationary battery (BDR = 0). This can partly be explained by the fact that different EVs are at home varying number of hours over the year. However, also for the same EV there is a substantial variation in self-consumption in combination with different households (as seen in Appendix B Figure B.1), which indicates that not only the number of hours that the EV is being plugged in at home has relevance. Instead also the correlation between the hours when the EV is at home, the electricity generation from the solar panels and the electricity demand from the household is of importance for the self-consumption.

## 4.2 Self-sufficiency

In the following Sections the main findings regarding how the self-sufficiency is affected by the introduction of EVs will be presented. In contrast to self-consumption the self-sufficiency can decrease after introduction of an EV to a household, since the total demand for electricity for the household will increase.

### 4.2.1 Impact from introduction of an EV

The difference in self-sufficiency for the modelled households is presented in Figure 4.2, where the difference for every modelled household with EV compared to without EV (blue dot) and the mean difference for all households (red line) for the different EV battery sizes can be seen. Between the subplots in Figure 4.2 the size of stationary batteries (BDR value) is increased from left to right, while size of the PV panel systems (ALR value) is increased downwards. It is evident that an EV both can increase and decrease the self-sufficiency for households, depending on if

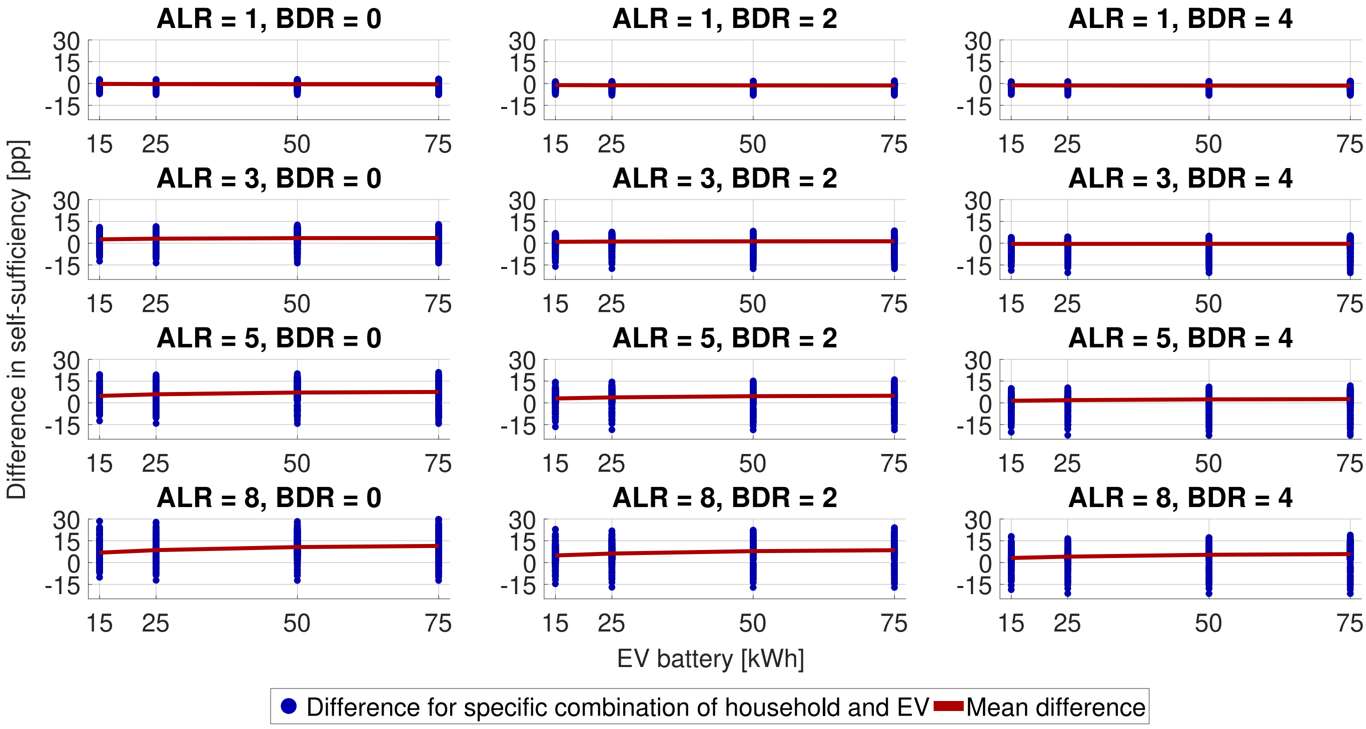


**Figure 4.2:** *Difference in self-sufficiency between households without EV and the same households with EV, depending on EV battery size. The difference is positive if the self-sufficiency for the household is higher with EV compared to without. Subplots for different sizes of PV systems (ALR increasing downwards) and stationary batteries (BDR increasing from left to right). Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

the possible increase in self-consumption can outweigh the additional electricity demand from the EV. At most the mean self-sufficiency increases with 11.5 percentage points, from 25.3% for households without EV to 36.7% for households with EV. This corresponds to an increase in mean self-sufficiency with 45.4% if an EV is introduced to the households, and occurs for households without stationary battery (BDR = 0), with the largest PV panel system (ALR = 8) and with an EV battery of 75 kWh. The largest decrease in mean self-sufficiency for households without and with EV is -1.5 percentage points (a 13.0% decrease) and occurs for an EV battery size is 75 kWh, the smallest PV panel size (ALR = 1) and the largest stationary battery (BDR = 4). When all combinations of different sizes of PV panel systems, stationary batteries, and EV battery sizes are summarized it can be seen that the mean self-sufficiency is 2.2 percentage points higher for households after introduction of an EV (corresponding to 9.9% increase).

With increased size of the PV panel system the additional possibility to consume the electricity in-house introduced by the EV has a positive impact on the self-sufficiency for the households, as can be seen in Figure 4.2. For households with a larger stationary battery a greater share of the generated electricity already can be stored in-house, thus the possibility to store electricity in the EV battery is not as beneficial for these households. Thus, if the presence of a stationary battery is sufficient to handle all potential excess PV generated electricity the introduction of an EV is not needed for storage purposes, and hence, the new demand is likely to at least partly lead to increased purchases from the grid. This can be seen in Figure 4.2 where the difference in self-sufficiency decreases if the stationary battery is increased (higher value of BDR) while the PV system size is kept constant.

Similarly as for the self-consumption, the size of the EV battery does not have a big impact on the self-sufficiency for different sizes of EV battery. However, this is more remarkable when it comes to self-sufficiency since the EV share of total electricity demand for the households increases with bigger EV battery sizes, as clarified in chapter 3.3.3. With a larger total demand resulting from the EV one could believe that it would have a negative influence on the self-sufficiency. Despite this the difference in self sufficiency is showing a slightly increasing trend for bigger EV batteries, for the cases with larger PV systems (ALR 5-8), which implies that the bigger EV battery cannot only make up for this additional electricity demand but also in addition increase the utilization of PV electricity even more.

The difference in self-sufficiency between different combinations of households and EVs shows large variations, as can be seen on the blue dots in Figure 4.2. This variation can depend on several factors such as how many hours the EV is plugged in, how large share of the total electricity demand that the EV accounts for or the correlation between hours with solar radiation and when the EV is plugged in. The increase in self-sufficiency when introducing an EV is greater if the EV is at home a larger share of the year. This is more distinct for increasing size of the PV system (higher value of ALR), while the increase is smaller, but still significant, for increasing size of the stationary battery (higher value of BDR) (see Appendix B Figure B.2). The result distinctly show a trend with a negative impact on the self-sufficiency if the EV accounts for a larger share of the total electricity demand in the household. In the opposite way, introduction of an EV accounting for a smaller share of the total demand have a positive impact on the self-sufficiency on average (see Appendix B Figure B.3).

When looking into the correlation between solar PV electricity generation and plug-in patterns of the EV, it is clear that not only the number of hours the EV is at home, but when in time the EV is plugged in has an impact on the influence from an EV on self-sufficiency for households. An EV that is at home during hours with more electricity generation does influence the self-sufficiency more positive, especially for smaller sizes of the stationary battery (see Appendix B Figure B.4). However, an apparent relationship between total number of hours at home for the EV and total PV generation when the EV is plugged in can be seen, i.e. more electricity is generated when the EV is plugged in if the EV is plugged in a larger number of hours. Nevertheless, this relationship does not apply for all EVs and households in the model. For some EVs the total electricity generation when they are plugged in at one household is as high as for another EV with twice the amount of hours at home at the same household over the year, as can be seen in Appendix B Figure B.5.

The amount of electricity that is being discharged from the EV batteries back to the households by V2H technology varies for different PV system sizes, stationary battery sizes and EV battery sizes. For most combinations of households and EVs the amount of discharged electricity from the EV to the household is lower than the total electricity demand from driving the EV. However, for some combinations of household and EV the amount of discharged electricity from the EV can reach levels above one time, up to almost seven times the amount of electricity that is needed to fulfill the driving demand. In these cases the EV batteries act more as batteries for the household than for the EV, since the largest share of the electricity charged into the EV battery is discharged back to the household again. Such utilization of the EV battery as storage is done to a greater extent for households without a stationary battery, and less when the size of the stationary battery increases. On average for all investigated PV panel sizes, stationary battery sizes and EV battery sizes the discharged amount of electricity is 0.45 times the driving demand (Appendix B Figure B.6).

### 4.2.2 Self-sufficiency with an EV compared to with a stationary battery

The mean self-sufficiency for households with different storage options can be seen in Figure 4.3, where the mean self-sufficiency for households without any storage option (black dashed line), households with stationary battery without EV (red lines) and households with EV without stationary battery (blue lines) is presented. Between the different red coloured lines, size of the stationary battery is varied, and in the same way size of the EV battery is varied between the blue coloured lines. This result shows that the self-sufficiency for households with EV without stationary battery on average can become as high as for households with a stationary battery without EV. This holds true for larger PV systems (ALR 3-8), where an EV has a greater positive impact on the self-sufficiency as stated before. The EV battery size also affects the level of self-sufficiency, and the difference between different EV battery sizes is increasing for larger size of the PV panel (higher value of ALR). Only at the largest PV panel size (ALR = 8) and the largest EV battery size (75 kWh) households with EV without stationary battery reaches the same mean self-sufficiency as households without EV with the largest stationary battery (BDR = 4). Thus, on average an EV does not offer the ability to replace a stationary battery and obtain the same self-sufficiency. However, for households with larger PV panel systems (ALR 3-8) an EV can on average entail the same self-sufficiency as a stationary battery.

To illustrate what size of stationary battery that an EV can replace, and at what size of PV system, one example can be used. At an ALR value of four, households with

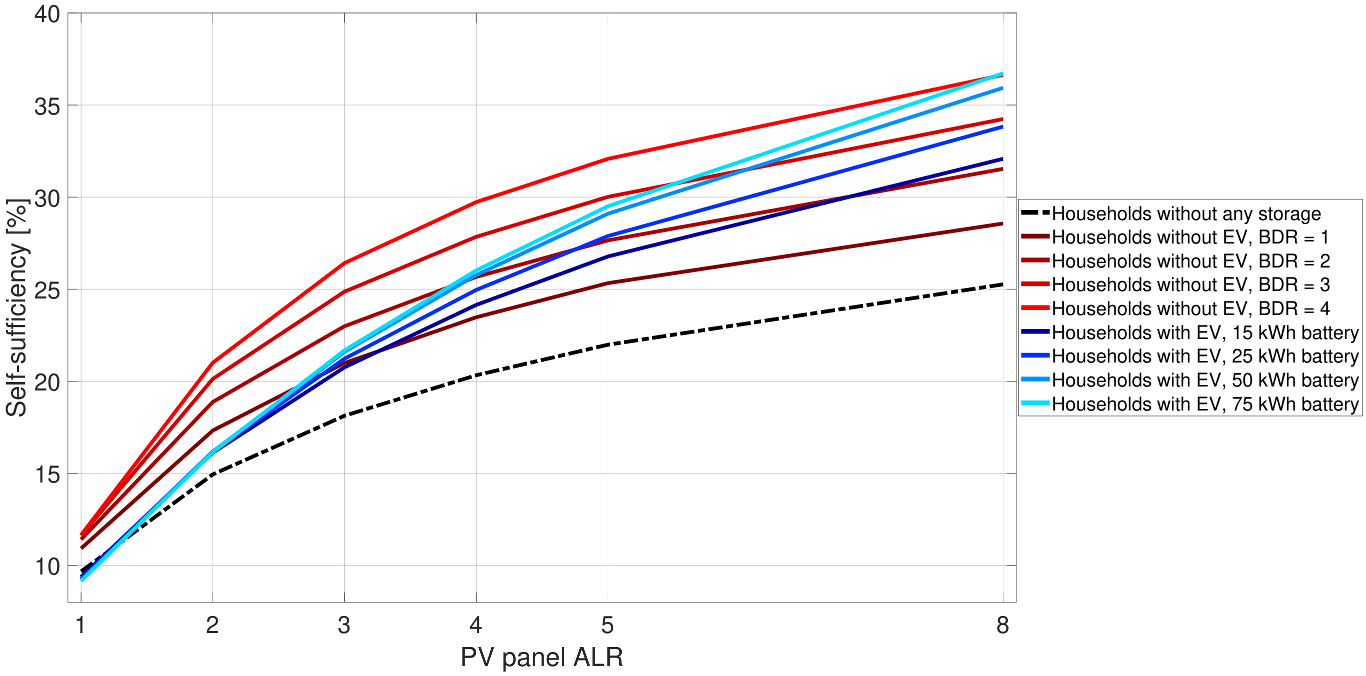


**Figure 4.3:** *Mean self-sufficiency for households without EV with and without stationary battery, compared to households with EV without a stationary battery. Both cases are modelled for different battery sizes of stationary battery or EV battery. Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

a stationary battery with BDR of two have almost the same mean self-sufficiency (0.1 percentage points lower) as if they instead have an EV with 50 kWh battery, as seen in Figure 4.3. These values of ALR and BDR corresponds to an average size for all 20 households of 10.9 kW PV panel and 5.5 kWh stationary battery.

The trends in Figure 4.3 are average trends, but the variation in self-sufficiency between different households and combinations of households and EVs is large. The variation for households with a stationary battery with a BDR value of two (red boxes) and households with an EV with a battery of 50 kWh (blue boxes) are shown in Figure 4.4. Both with and without EV the variation increases with larger size of the PV panel system. Nevertheless the variations are larger between households with EV, compared to without. As an example, at an ALR value of four the maximum variation between households without EV is 16.7 percentage points, while it for the same ALR is 31.7 percentage points between the outermost values in self-sufficiency for households with EV.

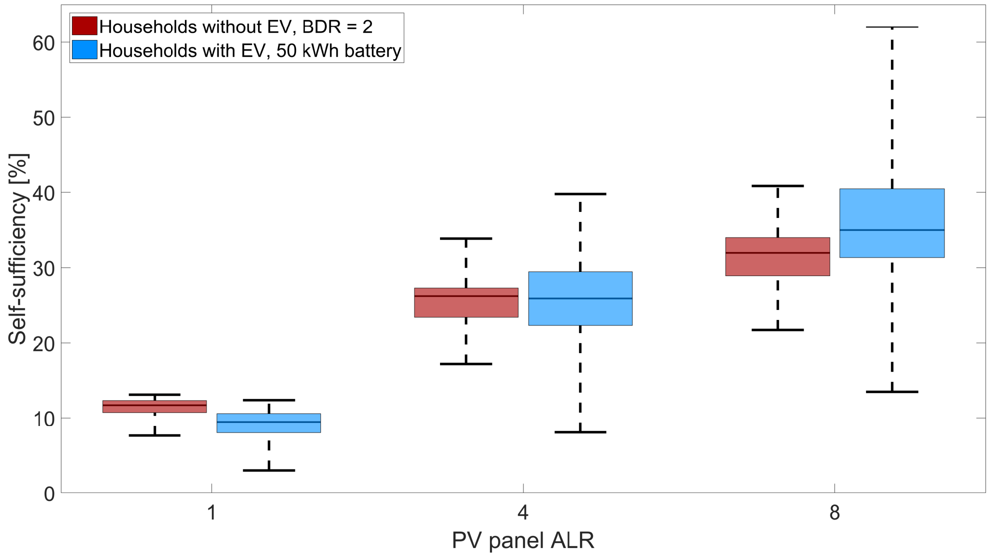


**Figure 4.4:** *Variations in self-sufficiency for households without EV with a stationary battery (BDR = 2), and households with EV (50 kWh battery) without stationary battery. The bottom and top edges of the boxes indicates the 25th and 75th percentiles, the central line indicates the median value while the whiskers indicates the most extreme values. Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

### 4.2.3 Effect from installation of a stationary battery

Installation of a stationary battery will increase the self-sufficiency, both for households with and without an EV. In Figure 4.5, the mean self-sufficiency for households with both EV and stationary battery (grey lines), households with only EV (blue lines), households with only stationary battery (red lines) and households without any storage (black dashed line) are shown. For clarity the Figure only shows the combination of stationary battery and EV battery size of 50 kWh, but combinations with stationary battery and all EV battery sizes are included in the analysis.

The two batteries can complement each other, even though a combination not necessary is the best option, as seen in Figure 4.5. Regardless of the size of PV panel system the self-sufficiency is higher if also a stationary battery is available, compared to only having an EV. On the other hand the self-sufficiency is higher for households with only a stationary battery, compared to the combination of stationary battery and EV, for smaller sizes of PV panels (lower ALR value). However, the highest mean self-sufficiency of 42.5% is obtained for the combination of EV (75 kWh battery) and stationary battery (BDR = 4). When having larger PV systems a combination of EV and stationary battery thus is proven to be best for most of the households.

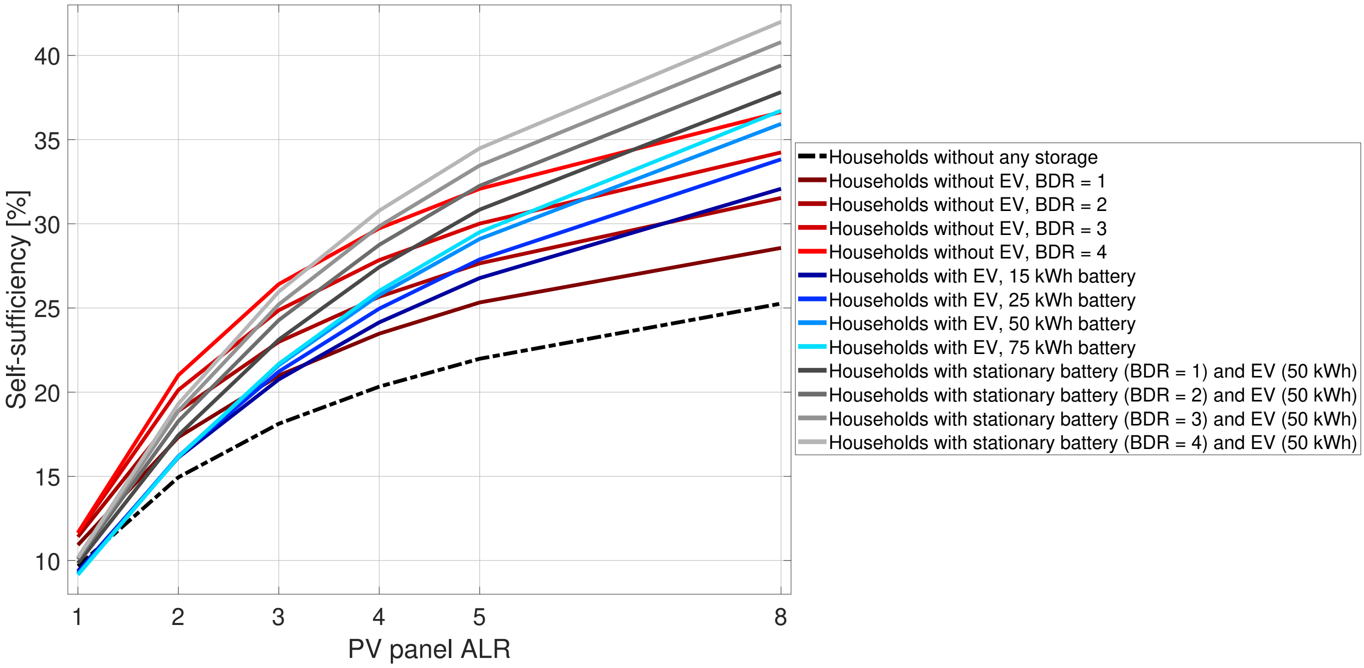


**Figure 4.5:** *Comparison of mean self-sufficiency between: households without any storage, households without EV with stationary battery, households with EV without stationary battery, and households with both stationary battery and EV. For the households with both stationary battery and EV only a 50 kWh EV battery is modelled, while the stationary battery size is varied. Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

From the grey lines in Figure 4.5 it can be seen that an increment in PV panel size (increased ALR value) has a bigger impact on the self-sufficiency for households with both stationary battery and EV compared to an increment in size of the stationary battery (a more light-grey line). For households with only a stationary battery (red lines) this trend only exists when the increment in PV panel size is from a low level.

The increase in self-sufficiency when installing a stationary battery is higher for households without EV compared to if the households have an EV, a trend that can be seen for all PV panel sizes but declines for the smallest PV panel size. Installation of a stationary battery has a somewhat bigger impact for the smallest EV battery (15 kWh), but the overall trend is the same independent on EV battery size (Appendix B Figure B.7).

The variations in self-sufficiency between different combinations of households and EVs are large. However, these variations are of the same magnitude when adding a stationary battery to households that already have an EV. As for all the results in Section 4.2 the EVs have the possibility for V2H (Appendix B Figure B.8). This indicates that EVs are the largest influencing factor on the variations in self-sufficiency between different households.

## 4.3 Impact on results from V2H availability, charging power and minimum distance requirement

Findings from an analysis on the model results with respect to three parameters are presented in this Section. The parameters included in the analysis are availability of V2H technology, charging power of the EV battery and a requirement on the minimum available distance in the EV battery when being plugged in at home. Each of these parameters are analyzed separately, meaning that for every analysis the other two parameters are kept constant. When one parameter is not analyzed, it has the same value as previously in this chapter. As an example, when analyzing the impact from charging power of the EV battery the power is varied between 11.0 and 3.7 kW, while no requirement on minimum distance is used and V2H is available.

### 4.3.1 Vehicle-to-home technology

When allowing the EV to discharge electricity back to the household the EV battery can act in the same way as the stationary battery, by storing additional solar PV electricity during hours with high production that later can be used in the household. Without V2H the EV is only an additional electricity load to the household, which strictly can store PV electricity for usage in the EV. However, charging demand from the EV is not fixed in time. Instead it sometimes can be moved to hours with PV electricity production, depending on the plug-in pattern of the EV. In Figure 4.6 the difference in self-sufficiency for every combination of household and EV between having V2H or not (blue dots), and the mean difference for all households and EVs (red lines) for the different EV battery sizes is presented. Between the subplots in Figure 4.6 size of stationary battery systems is increased from left to right, while size of the PV panel systems is increased downwards. On average for all modelled sizes of PV panel systems, stationary battery sizes and EV battery sizes the self-sufficiency is 1.9 percentage points higher if V2H is allowed, compared to having EVs without V2H, which is an increase in self-sufficiency with 8.4%. This can be compared to the 2.2 percentage points increase in self-sufficiency obtained for households if an EV with V2H is introduced, compared to not having an EV. The mean difference in self-sufficiency between households with an EV, with and without V2H, is highest when the PV system has the biggest size (ALR = 8), there is no stationary battery (BDR = 0) and the EV battery is 75 kWh, with 7.3% difference. On the contrary there is only a negligible difference (<0.1 percentage points) for several cases when the PV systems have the smallest size (ALR = 1).

V2H technology has a significant impact on the self-sufficiency for households with larger PV systems (higher values of ALR) since the EV battery in these cases is more important for utilization of the solar electricity production, as can be seen in Figure 4.6. As for the difference in self-consumption and self-sufficiency when introducing an EV the positive impact does decline when the household has a larger

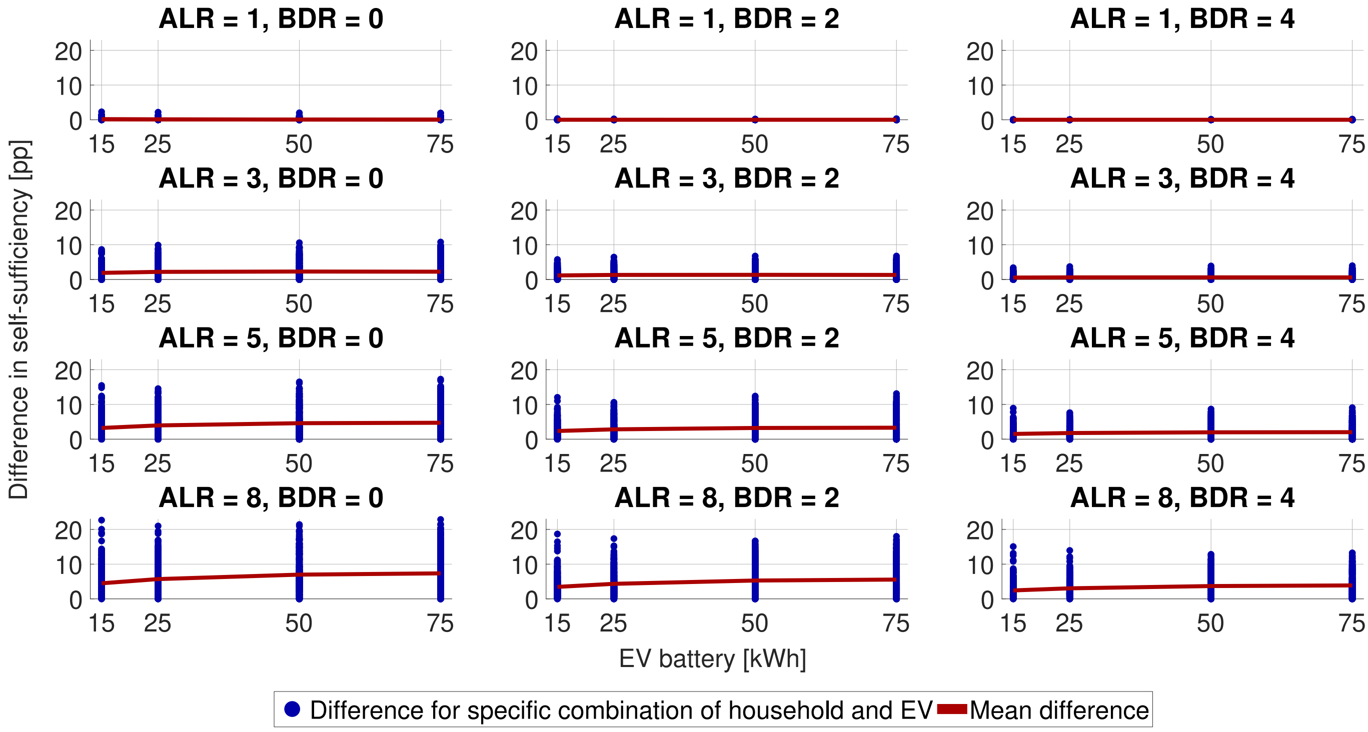


**Figure 4.6:** *Difference in self-sufficiency for households with EV, with and without V2H, depending on EV battery size. The difference is positive if the self-sufficiency is higher when V2H is allowed. Subplots for different sizes of PV systems (ALR increasing downwards) and stationary batteries (BDR increasing from left to right). Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

stationary battery installed (higher value of BDR). The variation in self-sufficiency between different combinations of households and EVs is smaller if V2H technology is not used, compared to when V2H is used (Appendix B Figure B.8).

The ability for an EV to replace a stationary battery as storage for households and obtain the same self-sufficiency is strongly affected by if V2H technology is used or not. Without V2H the average self-sufficiency for households with EV but without stationary battery is higher than for households without any storage (1.7 percentage points for ALR = 4). However, already for households with the smallest stationary battery (BDR = 1) installed and no EV the self-sufficiency is higher compared to if they instead have an EV without V2H and no stationary battery (1.5 percentage points at ALR = 4). Except from households with the largest PV panel system (ALR = 8) and an EV battery size of 50 or 75 kWh, where the self-sufficiency with EV can be slightly (0.6 percentage points) higher compared to with the smallest stationary battery, as seen in Appendix B Figure B.9. This can be explained by the fact that the EV batteries can be utilized to a greater extent when V2H is available. With V2H technology the EV can store PV electricity several days in a row, and discharge it during nighttime, while an EV without V2H only can fill up the battery once during each period at home.

Overall for all different sizes of PV panel systems, stationary batteries and EV battery sizes, introduction of an EV without V2H technology increases the mean self-sufficiency with 1.4% for households, compared to if the households have no EV. For households with larger PV panel systems (ALR 5-8) the increase is larger (at most 4.1 percentage points, corresponding to 12.9%), while the self-sufficiency on average decreases (at most with 1.8 percentage points, corresponding to -8.2%) for households with larger stationary batteries (BDR 3-4) and smaller PV panel systems (ALR 1-3) (Appendix B Figure B.10). The fact that introduction of an EV without V2H to households increases the mean self-sufficiency with 1.4% indicates that V2H technology is not necessary for EVs to be able to increase the self-sufficiency for households. At the same time, introduction of an EV can also decrease the self-sufficiency for households, both when V2H technology is available or not. But if an EV should be used instead of a stationary battery for households to obtain the same self-sufficiency, V2H technology is necessary.

### 4.3.2 Maximum charging power of the EV battery

The difference in self-sufficiency between a maximum charging power for the EV battery of 11.0 kW and 3.7 kW is presented in Figure 4.7, where the difference for every combination of household and EV (blue dots), and the mean difference for all households and EVs (red lines) for the different EV battery sizes is presented. Between the subplots in Figure 4.7 the stationary battery systems size is increased from left to right, while size of the PV panel systems is increased downwards. For clarity the Figure only shows some combinations of stationary battery sizes (BDR values) and PV panel sizes (ALR values), but all EV battery sizes for each combination. However, all PV panel sizes and stationary battery sizes are included in the analysis.

Overall for all modelled sizes of PV panel systems, stationary battery sizes and EV battery sizes the self-sufficiency is 0.4 percentage points higher with 11.0 kW charging power (an 1.6% increase). The mean difference is largest (3.1 percentage points) when the PV system has the biggest size (ALR = 8), the EV battery is 75 kWh and there is no stationary battery (BDR = 0). On the contrary the difference is -0.1 percentage points when the EV battery has the smallest size (15 kWh), the stationary battery has the largest size (BDR = 4) and PV ALR = 2. The negative difference for some combinations of household and EV is due to the fact that a larger share of the charging demand for some EVs can be supplied at home when a higher charging power is used. This additional demand for electricity might have a negative impact on the self-sufficiency for these households.

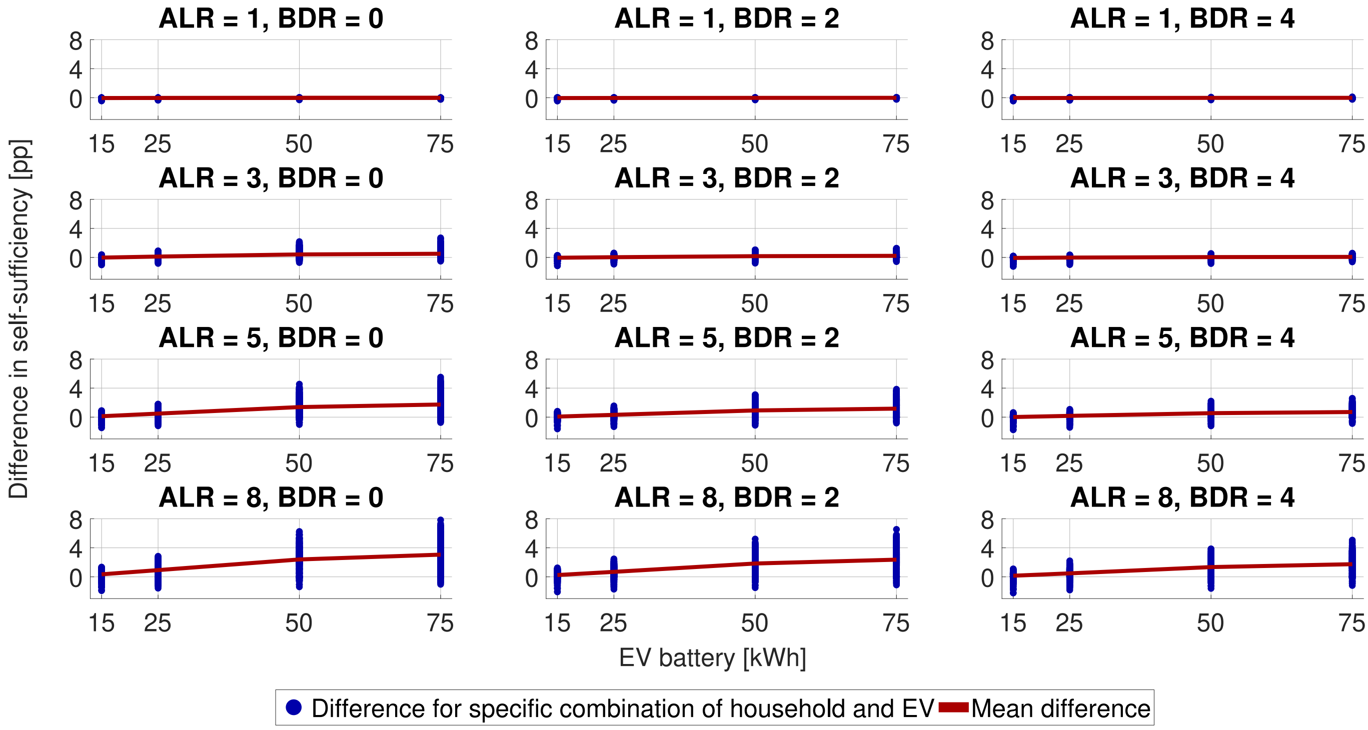


**Figure 4.7:** *Difference in self-sufficiency for households with EV, with different charging power (3.7 kW or 11.0 kW), depending on EV battery size. The difference is positive if the self-sufficiency is higher with 11 kW charging power compared to with 3.7 kW. For both cases V2H is available. Subplots for different sizes of PV systems (ALR increasing downwards) and stationary batteries (BDR increasing from left to right). Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

### 4.3.3 Requirement on available driving distance in the EV battery when plugged in at home

The requirement on the minimum available driving distance in the EV battery more specifically means that the EV battery at least needs to contain enough electricity for the EV to drive 50 km when the EV is plugged in at home. This setup makes spontaneous trips possible, but does at the same time take up a share of the EV battery that cannot be disposed for V2H in the same way as without such a minimum distance requirement. The difference in self-sufficiency due to such a requirement is presented in Figure 4.8, where the difference for every combination of household and EV (blue dots), and the mean difference for all households and EVs (red lines) for the different EV battery sizes can be seen. Between the subplots in Figure 4.8 the stationary battery systems size is increased from left to right, while size of the PV panel systems is increased downwards.

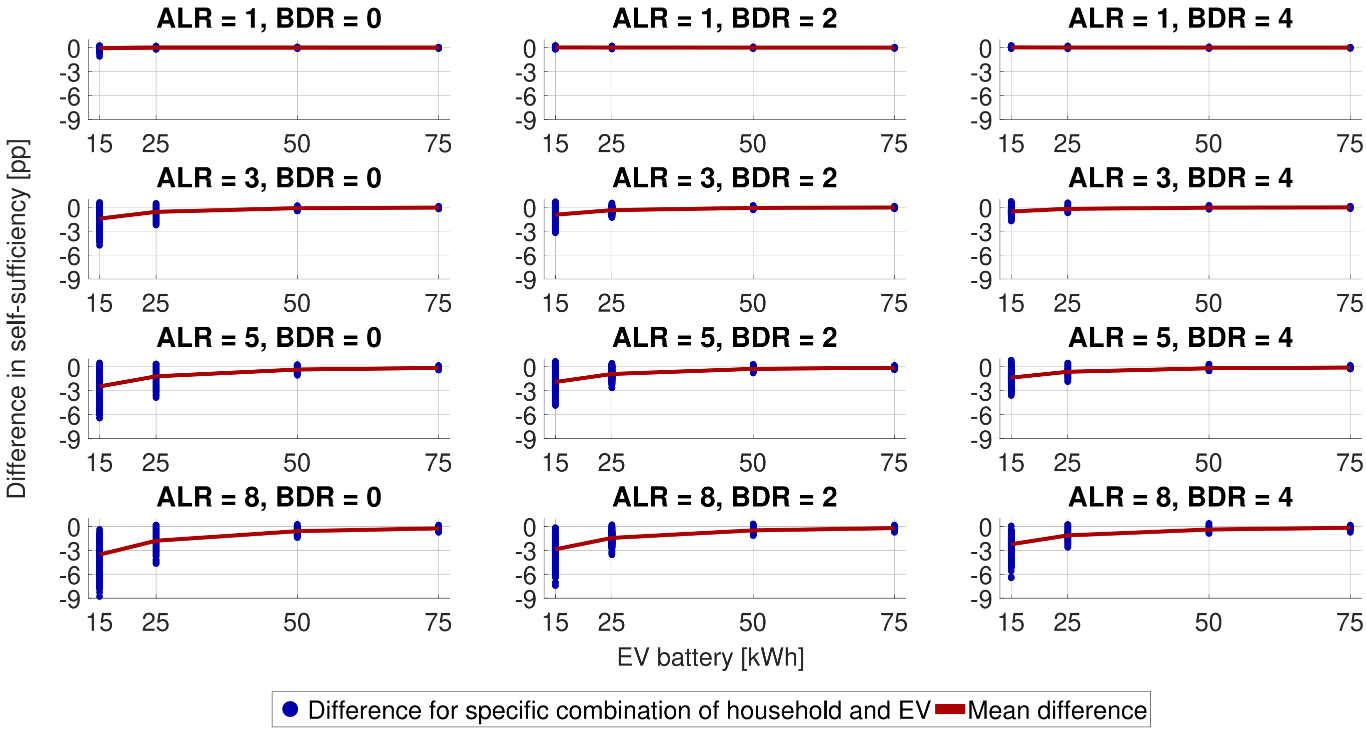


**Figure 4.8:** *Difference in self-sufficiency for households with EV, with and without a requirement on available distance in the EV battery when being plugged in at home. The difference is positive if the self-sufficiency for the households is higher with such a requirement compared to without a requirement. For both cases V2H is available. Subplots for different sizes of PV systems (ALR increasing downwards) and stationary batteries (BDR increasing from left to right). Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

The self-sufficiency for households is on average 0.5 percentage points lower (a decrease with -2.1%) when there is a requirement on the EV battery, compared to households with an EV without such a requirement, when all model runs for different PV panel sizes, stationary battery sizes and EV battery sizes are summarized. The influence on the self-sufficiency is greater for smaller EV batteries, as can be seen in Figure 4.8, since a distance of 50 km takes up a larger share of these batteries. With the data on energy consumption for driving an EV (0.18 kWh/km as defined in Section 3.3.1), a 50 km distance corresponds to 9 kWh battery capacity. For the 15 kWh and 75 kWh EV batteries this corresponds to 60% and 12% of the battery capacity, respectively. With the 15 kWh EV battery the self-sufficiency on average decreases with -5.2% when all investigated PV panel sizes and stationary battery sizes are summarized. The corresponding number is -2.3% for a 25 kWh EV battery, -0.7% for the 50 kWh EV battery and -0.3% for an EV battery of 75 kWh. Worth to notice is that an EV with a 15 kWh battery likely is a plug-in hybrid EV that thus also have a combustion driven engine. Therefore this type of requirement on minimum energy level is not necessary in the same way as for a pure battery EV.

The requirement on the available distance in the EV battery has a larger impact on the self-sufficiency for larger PV panel systems, since the EV battery is more utilized in these cases. Correspondingly the difference decreases if the households have larger stationary batteries since the importance of the EV battery declines. Furthermore, the requirement on a minimum distance impacts how large share of the charging demand that can be supplied at home for some EVs. The negative difference that can be seen for some combinations of household and EV in Figure 4.8 is due to this fact.

As anticipated the introduction of this requirement impact the energy level in the EV battery for the hours when the EV is plugged in at home. Nevertheless the charging pattern can be similar with and without the requirement, but with different energy level in the EV battery (Appendix B Figure B.11). Only during periods with a lot of electricity generation from the solar PV panels, is the EV battery equally full with and without usage of a requirement on minimum distance, to utilize the generated electricity in-house. During periods with less electricity generation from the PV panels, charging from the grid would have been needed for the EV to obtain the same energy level as with a requirement. If not needed, this is avoided by the model which makes the energy level in the EV battery lower for most hours when no requirement is used.

# 5

# Discussion

First in this chapter the results from the model are summarized and presented. This is followed by an analysis of the results and its implications in a broader context. Further, limitations in the developed model and the input data are discussed, and finally recommendations for further studies are presented.

## 5.1 Results summary

The difference in mean self-consumption and self-sufficiency for all combinations of households and EVs modelled, and for all investigated cases are presented in Table 5.1. It can be seen that the introduction of an EV raises both self-consumption and self-sufficiency for the modelled households. The increase in self-consumption and self-sufficiency is more pronounced if the EV uses V2H technology, compared to without V2H. Finally it can be concluded that a lower maximum charging power, and a requirement on a minimum distance in the EV battery when being plugged in does negatively influence the self-sufficiency.

**Table 5.1:** *Difference in mean self-consumption and self-sufficiency for all investigated cases. Positive difference indicates that the case on the left hand side of the Table has higher mean value in comparison with the case on top of the Table. Values are given both as percentage points difference and percentage increase.*

| | **Households without EV** | **Households with EV (without V2H)** | **Households with EV (with V2H), with lower charging power** | **Households with EV (with V2H), with requirement on minimum distance** |
|---|---|---|---|---|
| *Self-consumption* | | | | |
| **Households with EV (without V2H)** | 8.2 pp<br>13.4% | - | - | - |
| **Households with EV (with V2H)** | 11.9 pp<br>19.4% | 3.7 pp<br>5.4% | - | - |
| *Self-sufficiency* | | | | |
| **Households with EV (without V2H)** | 0.3 pp<br>1.4% | - | - | - |
| **Households with EV (with V2H)** | 2.2 pp<br>9.9% | 1.9 pp<br>8.4% | 0.4 pp<br>1.6% | 0.5 pp<br>2.1% |

## 5.2 Results analysis

The possibility for EVs to contribute to increased self-sufficiency for households is strongly affected by when and for how long the EVs are plugged in. Even though similar trends as the ones assumed in other studies, with EVs leaving in the morning and arriving home again in the evening, can be seen also from the measured driving data there are important differences. As one example always at least 36% of the 429 EVs, based on the measured vehicles, are plugged in at home independent of time of day over the week. At most 78% of the EVs are plugged in at home at the same time on weekly basis. Worth to notice is the fact that these numbers would increase if also plug-in at work or other charging stations would have been taken into account. As mentioned EVs can contribute with services to the electrical grid while being plugged in, which makes these numbers regarding how large share of the EV fleet that is plugged in of interest for the power system. However, no conclusions regarding this potential should be based on the results in this study.

Worth to notice when analyzing the charging behaviour of the EVs in this study is the fact that electricity prices for buying or selling electricity to the grid not are taken into account. Thus it does not matter if the EV is charged immediately when arriving home or in the middle of the night. If one instead would optimize with respect to minimizing cost for buying electricity, the charging patterns would be affected and the self-sufficiency would likely decrease for most combinations of households and EVs. In such a situation also feedback mechanisms on the electricity prices are of importance, for example that electricity prices would increase during hours when many EVs are charged. In the future, with a larger share of the vehicle fleet expected to be EVs, such mechanisms will have greater impact on the electricity prices. In this study with only focus on self-sufficiency these kind of feedback mechanisms have no influence on the results. Nevertheless, economic calculations would be needed to analyze if the investments in PV panels, stationary batteries or an EV can be justified from an economic point of view. For a deeper analysis regarding the potential of this result, also social aspects would be needed to be taken into account. In this thesis only technical aspects have been considered.

One aspect of interest is that introduction of EVs is more or less suitable for different households, depending on their driving patterns and number of vehicles in the household. According to Jakobsson et al. (2016) second cars in mutli-car households are better suited for switching to full electric vehicles, compared to cars in single-car households or first cars in multi-car households. In this thesis no deeper analysis regarding this has been conducted. However, among the EVs used in this thesis no relation between number of vehicles in the measured households could be seen, neither for number of hours at home, nor driving distance over the year by the EV. As stated in the results also when the EVs are plugged in affects the results, which might be influenced by the number of vehicles in the household. Therefore no conclusions regarding the influence from eventual other vehicles in the households can be drawn from this thesis. Nevertheless, interesting for the reliability of the results in this thesis is the fact that the selected 20 EVs on average both are at home less number of hours and driving slightly more on annual basis compared to all the 429 vehicles with measured data.

The input data regarding households electricity consumption and PV generation used in this thesis is measured in Sweden, which makes this study representative for regions with similar weather conditions. In regions with more solar radiation an EV might have the possibility to increase the self-sufficiency for households even more, since an EV in this study is shown to have a greater impact on the self-sufficiency for households with a larger electricity generation from PV panels. In warmer climates the correlation between electricity demand in households and solar radiation might be different, which also affects the self-sufficiency for households. However, for an EV to contribute to increased self-sufficiency it has to be plugged in during hours with solar radiation. Therefore, if EV batteries are to be used for storage of electricity from solar PV, opportunities for plug-in of EVs also at other locations where the EVs might be parked during daytime are of importance.

Usage of V2H technology has proven to be of importance for the ability for EVs to contribute to increased self-sufficiency for households. Interesting to notice is the fact that V2H can be used in different ways with the same result. Depending on which solver that is being used GAMS utilizes the EV batteries differently, as can be seen in Appendix B Figure B.12. Nevertheless, the self-sufficiency for the households is the same independent of solver, proving that there is multiple solutions for the same optimal value. However, this is the case since is does not matter when in time the households in the model uses electricity from the grid. If the market price for electricity was included and the model would be optimized with respect to minimizing the total cost for buying electricity, the charging patterns of the EVs would be more constrained and there would be less number of optimal solutions.

## 5.3 Model and data limitations

Largest influence on the results from the method used in this thesis is assumed to come from the processing of the vehicle driving data. Naturally exact GPS-coordinates of respective home parking would have been preferable, especially since the time at home for each EV is found to have great impact on the results. When converting this driving data to input data with hourly resolution there are likely both over and under representation regarding how many hours the EVs are plugged in. This could impact the results for a specific EV, but put over all 20 EVs in the model this should likely be leveled out. In contrast, the driving distance for each EV is the same as measured for each hour. Also different driving patterns over the year is missing, since only shorter periods of measurements are extrapolated. But patterns of separate weekdays are taken into account in the model. However, even with these limitations to this study the usage of measured data on vehicle driving provides a more realistic basis compared to made up assumptions as used in most other literature.

The behaviour of this model is affected by the fact that the model has so called perfect foresight, where it in advance knows the exact demand or supply from all input components over the whole year. With this knowledge the model can optimize the utilization of the batteries, and only charge the EV battery exactly as much as needed to fulfill the upcoming trips before arriving home again. Therefore, this study can be seen as an investigation of the potential in usage of an EV battery as storage for households. But in reality one likely would prefer to charge the EV battery differently. The investigation with a requirement on a minimum distance available in the EV battery can be seen as a way to analyze the potential with more realistic charging behaviour, where perfect foresight is somewhat restricted.

The selection of the 20 EVs and households naturally has an impact on the results. This selection was done in a way to include as large variations as possible in consumption and PV generation of the households, and driving and plug-in patterns of the EVs. Nevertheless, 400 combinations of households and EVs are used, which naturally is not representative for all of the Swedish population. The mentioned hourly resolution also has an impact on the results from another perspective. The electricity system requires balance in every moment, but in this model short peaks and valleys in electricity demand and generation are leveled out to curves with hourly resolution. By this setup there is no need for a power balance in every moment. However, this thesis looks at the households' electricity system on annual basis, where the amount of electricity produced and consumed are correct.

One assumption made in this study is that the data regarding driving patterns is valid for EVs, even though it is measured on ICE vehicles. For some EVs in the model additional charging outside home is needed to fulfill a number of trips. However, this is not a made up solution only for this model. Also in reality EV drivers uses charging stations away from home to fill up the EV battery. Therefore, this would most likely have been needed also if driving data was measured only on EVs. Charging stations are becoming more common at work places, grocery stores and along highways making this to a decreasing problem for most drivers and trips.

Data on household electricity consumption and PV generation from the year 2012 is used, which makes the results consistent but at the same time not fully representative for all years. Data on vehicle driving on the other hand is from 2010-2012, and have no connection with the households which implies that the EV can be set as being plugged out during hours with high household electricity consumption, and the other way around. If this lack of correlation has any influence on the results is hard to say, and is something that has to be investigated more in detail. Anyway, this behaviour with e.g. high demand at the same time as the EV is out driving could happen in reality, since there could be both several people living in the household and several vehicles coupled with it.

## 5.4 Recommendations for further studies

Further studies are of interest for deeper analysis of the abilities for EVs to influence the self-sufficiency for households, and how this might impact the electricity grid on a system level. One aspect of high interest is how the introduction of electricity prices in this model would affect the results, with the possibility to not only optimize self-sufficiency but also minimize yearly cost for electricity. First after such an analysis the economic potential in these results can be examined. Also an evaluation of the possibilities to enable additional services to the electricity grid, with this measured driving data as basis, would be of great interest. Finally more extensive studies with increased number of combinations of households and EVs are needed to be able to draw more far-reaching conclusions regarding which parameters that are of biggest importance for the possibilities for EVs to increase households self-sufficiency.

# 6

# Conclusion

This thesis has shown that there is a potential for usage of the battery in an EV for storage of in-house produced electricity to reach the same self-sufficiency for residential households with solar PV, as could be obtained with a stationary battery. This result is found if the PV system installed in the household is in the larger range (ALR 3-8) of investigated sizes. These findings are especially interesting since real-life measurements are used as input also for EV driving patterns, in contrast to existing literature in the field.

Introduction of an EV offer additional possibilities for the household to utilize locally produced electricity in-house. Correspondingly the results from the model shows that the mean self-consumption increases with 19.4% for the households after introduction of an EV. Despite the fact that charging of an EV implies additional demand for electricity for the household, the mean self-sufficiency for all modelled households increases with 9.9% after introduction of an EV. The increase in self-sufficiency is more pronounced for households with the larger PV panel sizes investigated (ALR 5-8), while it decreases if the household already has a stationary battery installed. Nevertheless, the combination of a stationary battery and an EV battery for storage are found to complement each other, and the highest mean self-sufficiency (42.5%) is obtained for households with both an EV and a stationary battery. Even though the stationary battery in most cases is smaller in size compared to the EV battery it has the advantage of always being available, while the EV is plugged out for several days of the year.

The possibility for the EV to discharge electricity back to the household by V2H technology is proven to be of importance for the ability to increase the self-sufficiency. The mean self-sufficiency for all combinations of households and EVs is 8.4% higher if V2H is available compared to without. If, for some reason, there is a limit on minimum energy level in the EV battery introduced for hours when the EV is plugged in at home, the results indicate that this influence the results to a greater extent for smaller EV batteries. For the smallest EV battery investigated (15 kWh) the decrease in self-sufficiency is -5.5% compared to when no such requirement is used, while the decrease for the largest EV battery modelled (75 kWh) is -0.3%. The charging power of the EV battery is found to be of minor importance, only a mean difference in self-sufficiency of 1.6% could be seen between a maximum charging power of 11.0 kW or 3.7 kW. However, this could be affected by the fact that hourly resolution is used in the model. If a higher resolution was used, the impact from another charging power could be greater.

Even if these trends are found on average for all 400 combinations of households and EVs, the variations between these different combinations are large. Several factors such as time at home by the EV and the EV's share of total electricity demand for the household is found to be of importance for the results. An EV that is at home a larger number of hours over the year, on average has a more positive effect on the self-consumption and self-sufficiency for households. On the contrary an EV that accounts for a larger share of the total electricity demand in the household has a negative impact on the self-sufficiency for households. Nevertheless, the variations are large and it is therefore only possible to draw general conclusions from this result, but these do not apply to all combinations of households and EVs.

# Bibliography

Ackermann, T., Andersson, G. and Söder, L. (2001), 'Distributed Generation: A Definition', *Electric Power Systems Research* (57), 195–204.

Aggarwal, V. (2018), 'What are the most efficient solar panels on the market?'. Accessed: 2018-02-07.
**URL:** *https://news.energysage.com/what-are-the-most-efficient-solar-panels-on-the-market/*

Battke, B., Schmidt, T. S., Grosspietsch, D. and Hoffmann, V. H. (2013), 'A review and probabilistic model of lifecycle costs of stationary batteries in multiple applications', *Renewable and Sustainable Energy Reviews* **25**, 240–250.

BP (2017), *BP Statistical Review of World Energy 2017*, 66 edn, BP p.l.c., London, UK.

Briones, A., Francfort, J., Heitmann, P., Schey, M., Schey, S. and Smart, J. (2012), 'Vehicle-to-Grid (V2G) - Power Flow Regulations and Building Codes Review by the AVTA', *U.S. department of Energy National Laboratory* .

Coffman, M., Bernstein, P. and Wee, S. (2017), 'Integrating electric vehicles and residential solar PV', *Transport Policy* **53**, 30–38.

Elbilsstatistik.se (2018), 'Laddbara fordon i Sverige'. Accessed: 2018-06-08.
**URL:** *https://www.elbilsstatistik.se/*

Emobility.se (2018), 'Grunderna i laddning'. Accessed: 2018-02-20.
**URL:** *http://emobility.se/startsida/laddinfrastruktur/elbilsladdning/*

Energimyndigheten (2018), 'Elfordon och laddning'. Accessed: 2018-02-20.
**URL:** *http://www.energimyndigheten.se/klimat–miljo/fossilfria-transporter/elfordon-och-laddning/*

Erdinc, O. (2014), 'Economic impacts of small-scale own generating and storage units, and electric vehicles under different demand response strategies for smart households', *Applied Energy* **126**, 142–150.

Erdinc, O., Paterakis, N. G., Mendes, T. D. P., Bakirtzis, A. G. and Catalâo, J. P. S. (2015), 'Smart Household Operation Considering Bi-Directional EV and ESS Utilization by Real-Time Pricing-Based DR', *IEEE Transactions on Smart Grid* **6**(3), 1281–1291.

Eurelectric (2011), *Flexible generation: Backing up renewables*, Union of the Electricity Industry - EURELECTRIC, Brussels, Belgium.

European Photovoltaic Industry Association (2012), 'Connecting the Sun - Solar Photovoltaics on the Road To Large Scale Grid Integration', (September), 1–120.

Fattori, F., Anglani, N. and Muliere, G. (2014), 'Combining photovoltaic energy with electric vehicles, smart charging and vehicle-to-grid', *Solar Energy* **110**, 438–451.

Gellings, C. W. (2009), *Smart Grid : Enabling Energy Efficiency and Demand Response*, Fairmont Press, Lilburn, GA, US.

Guille, C. and Gross, G. (2009), 'A conceptual framework for the vehicle-to-grid (V2G) implementation', *Energy Policy* **37**(11), 4379–4390.

International Energy Agency (2017*a*), 'Energy Technology Perspectives 2017 - Executive Summary'.

International Energy Agency (2017*b*), 'World Energy Outlook'.

International Renewable Energy Agency (2018), 'Trends in renewable energy (installed capacity)'. Accessed: 2018-01-25.
**URL:** *http://resourceirena.irena.org/gateway/dashboard/?topic=4&subTopic=16*

Jakobsson, N., Gnann, T., Plötz, P., Sprei, F. and Karlsson, S. (2016), 'Are multi-car households better suited for battery electric vehicles? - Driving patterns and economics in Sweden and Germany', *Transportation Research Part C: Emerging Technologies* **65**, 1–15.

Jordan, D. and Kurtz, S. (2013), 'Photovoltaic Degradation Rates—an Analytical Review', *Prog. Photovolt: Res. Appl.* **21**, 12–29.

Kamp, S. (2013), Sveriges potential för elproduktion från takmonterade solceller, Master's thesis, Uppsala Universitet.

Karlsson, S. (2013), 'The Swedish car movement data project Final report'.

King, D. L., Kratochvil, J. A. and Boyson, W. E. (2004), 'Photovoltaic array performance model', *Sandia National Laboratories* **8**(December), 1–19.

Kullingsjö, L. H., Karlsson, S. and Sprei, F. (2013), 'Conflicting interests in defining an 'optimal' battery size when introducing the PHEV?', *World Electric Vehicle Journal* **6**(4), 1021–1028.

Lindahl, J. (2017), *National Survey Report of PV Power Applications in Sweden 2016*, Swedish Energy Agency, Eskilstuna, Sweden.

Lumb, M. P., Mack, S., Schmieder, K. J., González, M., Bennett, M. F., Scheiman, D., Meitl, M., Fisher, B., Burroughs, S., Lee, K. T., Rogers, J. A. and Walters, R. J. (2017), 'GaSb-Based Solar Cells for Full Solar Spectrum Energy Harvesting', *Advanced Energy Materials* **7**(20), 1–9.

Luthander, R., Widén, J., Nilsson, D. and Palm, J. (2015), 'Photovoltaic self-consumption in buildings: A review', *Applied Energy* **142**, 80–94.

Marklund, J. (2015), Potential för storskalig anslutning av solel i landsbygdsnät, Master's thesis, Uppsala Universitet.

Munkhammar, J., Grahn, P. and Widén, J. (2013), 'Quantifying self-consumption of on-site photovoltaic power generation in households with electric vehicle home charging', *Solar Energy* **97**, 208–216.

Muratori, M. (2017), 'Impact of uncoordinated plug-in electric vehicle charging on residential power demand - supplementary data', *Nature Energy* .

Norberg, I., Pettersson, O., Gustavsson, A., Kovacs, P., Boork, M., Ollas, P., Widén, J., Lingfors, D., Marklund, J., Larsson, D., Ingman, D. and Jältorp, H. (2015), 'Solel i lantbruket - realiserbar potential och nya affärsmodeller', *JTI, Lantbruk & Industri* (433), 1–66.

Norwood, Z., Nyholm, E., Otanicar, T. and Johnsson, F. (2014), 'A geospatial comparison of distributed solar heat and power in europe and the US', *PLoS ONE* **9**(12), 1–31.

Notton, G., Lazarov, V. and Stoyanov, L. (2010), 'Optimal sizing of a grid-connected PV system for various PV module technologies and inclinations, inverter efficiency characteristics and locations', *Renewable Energy* **35**(2), 541–554.

Nyholm, E., Odenberger, M. and Johnsson, F. (2017), 'An economic assessment of distributed solar PV generation in Sweden from a consumer perspective – The impact of demand response', *Renewable Energy* **108**, 169–178.

Peterson, S. B., Apt, J. and Whitacre, J. F. (2010), 'Lithium-ion battery cell degradation resulting from realistic vehicle and vehicle-to-grid utilization', *Journal of Power Sources* **195**(8), 2385–2392.

Regeringskansliet (2017), 'Det klimatpolitiska ramverket'. Accessed: 2018-02-19.
**URL:** *http://www.regeringen.se/artiklar/2017/06/det-klimatpolitiska-ramverket/*

Remund, J. and Müller, S. C. (2011), 'Solar radiation and uncertainty information of meteonorm 7', *26th European Photovoltaic Solar Energy Conference and Exhibition* **7**(November 2011), 4388–4390.

Sioshansi, F. (2016), *Future of Utilities - Utilities of the Future: How Technological Innovations in Distributed Energy Resources Will Reshape the Electric Power Sector*, Academic Press, Cambridge, MA, US.

Sovacool, B. K. and Hirsh, R. F. (2009), 'Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition', *Energy Policy* **37**(3), 1095–1103.

Statistiska Centralbyrån (2018*a*), 'Antal solcellsanläggningar och installerad effekt (MW), efter region. År 2016 - 2017'. Accessed: 2018-04-09.
**URL:** *http://www.statistikdatabasen.scb.se*

Statistiska Centralbyrån (2018*b*), 'Elförsörjning 2017'. Accessed: 2018-01-29.
**URL:** *http://www.scb.se/hitta-statistik/statistik-efter-amne/energi/tillforsel-*

*och-anvandning-av-energi/manatlig-elstatistik/pong/tabell-och-diagram/elforsorjning*

Statistiska Centralbyrån (2018*c*), 'Fordonsstatistik januari 2006–maj 2018'. Accessed: 2018-06-08.
**URL:** *www.scb.se/hitta-statistik/statistik-efter-amne/transporter-och-kommunikationer/vagtrafik/fordonsstatistik/pong/tabell-och-diagram/fordonsstatistik/*

Sundström, C. and Krysander, M. (2015), 'Smart energy usage for vehicle charging and house heating', *IFAC-PapersOnLine* **48**(15), 224–229.

Sveriges Riksdag (2017), 'Ellag (1997:857)'. Accessed: 2018-05-09.
**URL:** $https : //www.riksdagen.se/sv/dokument - lagar/dokument/svensk - forfattningssamling/ellag - 1997857_sfs - 1997 - 857$

Taljegard, M., Göransson, L., Odenberger, M. and Johnsson, F. (2017), 'Spacial and dynamic energy demand of the E39 highway – Implications on electrification options', *Applied Energy* **195**, 681–692.

Tan, K. M., Ramachandaramurthy, V. K. and Yong, J. Y. (2016), 'Integration of electric vehicles in smart grid: A review on vehicle to grid technologies and optimization techniques', *Renewable and Sustainable Energy Reviews* **53**, 720–732.

Uddin, K., Jackson, T., Widanage, W. D., Chouchelamane, G., Jennings, P. A. and Marco, J. (2017), 'On the possibility of extending the lifetime of lithium-ion batteries through optimal V2G facilitated by an integrated vehicle and smart-grid system', *Energy* **133**, 710–722.

United Nations (2018), 'Climate change'. Accessed: 2018-01-25.
**URL:** *http://www.un.org/en/sections/issues-depth/climate-change/*

van der Kam, M. and van Sark, W. (2015), 'Smart charging of electric vehicles with photovoltaic power and vehicle-to-grid technology in a microgrid; a case study', *Applied Energy* **152**, 20–30.

von Meier, A. (2006), *Electric Power Systems*, John Wiley and Sons, Inc., Hoboken, NJ, US.

Wang, Z. and Wang, S. (2013), 'Grid power peak shaving and valley filling using vehicle-to-grid systems', *IEEE Transactions on Power Delivery* **28**(3), 1822–1829.

White, C. D. and Zhang, K. M. (2011), 'Using vehicle-to-grid technology for frequency regulation and peak-load reduction', *Journal of Power Sources* **196**(8), 3972–3980.

Widén, J. (2009), 'Distributed Photovoltaics in the Swedish Energy System', *Model Development and Simulations, Licentiate Thesis, Uppsala universitet* p. 89.

Widén, J., Wäckelgård, E. and Lund, P. D. (2009), 'Options for improving the load matching capability of distributed photovoltaics: Methodology and application to high-latitude data', *Solar Energy* **83**(11), 1953–1966.

Willis, H. L. and Scott, W. G. (2000), *Distributed Power Generation*, Marcel Dekker Inc., New York, NY, US.

World Energy Council (2013), *World Energy Resources*, World Energy Council, London, UK.

Wu, X. (2018), 'Role of workplace charging opportunities on adoption of plug-in electric vehicles – Analysis based on GPS-based longitudinal travel data', *Energy Policy* **114**(December 2017), 367–379.

Wu, X., Hu, X., Teng, Y., Qian, S. and Cheng, R. (2017), 'Optimal integration of a hybrid solar-battery power source into smart home nanogrid with plug-in electric vehicle', *Journal of Power Sources* **363**, 277–283.

Yang, C. J. (2010), 'Reconsidering solar grid parity', *Energy Policy* **38**(7), 3270–3273.

Yong, J. Y., Ramachandaramurthy, V. K., Tan, K. M. and Mithulananthan, N. (2015), 'A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects', *Renewable and Sustainable Energy Reviews* **49**, 365–385.

Zhao, J., Kucuksari, S., Mazhari, E. and Son, Y. J. (2013), 'Integrated analysis of high-penetration PV and PHEV with energy storage and demand response', *Applied Energy* **112**, 35–51.

# A

# GAMS code

In this Appendix the GAMS code is presented. The code includes loading of input data, definition of variables and equations, solving of the model and finally saving output data.

```

************************** Input data **************************

* All data is generated into GDX files in Matlab.


* ------------------------ Loads sets --------------------------

Sets

$GDXin SetDef_HouseholdEV_fixed.gdx

* Hours in the simulated year
hour 'hours in a year'
* /1*8784/
$loaddc hour

* The housholds that are modeled
household 'the households that are to be modeld'
* /H234, H432/
$loaddc household

* The vehicles that are modeled
vehicle 'the vehicles that are to be modeld'
* /V234, V432/
$loaddc vehicle


```

```
* ------------------------ Load parameters ---------------------

Parameter

$GDXin inParMatlab_household_fixed.gdx

* Data for the output generation of PV
data_PV(household,hour) share of installed kWp PV that is utilized each hour
$loaddc data_PV

* Electricity demand profile for each household
demand_profile(household,hour) 'electricity demand for houses [kWh/h]'
$loaddc demand_profile


$GDXin inParMatlab_household_varying.gdx

* PV panel size for each household
PV_panel_size(household) size of PV panel (kw)
$loaddc PV_panel_size

* Installed battery capacity for each household
battery_cap_installed(household) installed battery capacity in household [kWh]
$loaddc battery_cap_installed

* Stationary battery maximum charging power for each household
battery_power_cap(household) maximum battery charging power [kw]
$loaddc battery_power_cap


$GDXin inParMatlab_EV_fixed.gdx

* EV driving distance each hour for each vehicle
EV_distance(vehicle,hour) driving distance for each vehicle [km]
$load EV_distance

* EV plug-in status each hour for each vehicle
EV_plugstatus(vehicle,hour) plug-in status for each vehicle
$load EV_plugstatus


* ------------------------ Load scalars ------------------------

Scalar

$GDXin in_scalars_EV_varying.gdx

* EV battery maximum charging power
EV_charge_cap maximum charging power EV battery [kW]
$loaddc EV_charge_cap

```

```
* EV battery minimum available battery level
EV_SOC_min minimum SOC EV battery
$loaddc EV_SOC_min

* EV battery capacity
EV_battery_cap maximum EV battery capacity [kWh]
$loaddc EV_battery_cap
$GDXin in_scalars_household_fixed.gdx

* Battery efficiency
battery_eff battery efficiency
$loaddc battery_eff


$GDXin in_scalars_EV_fixed.gdx

* Energy consumption from driving
EV_driveconsum 'energy consumption from driving [kWh/km]'
$loaddc EV_driveconsum


************************** Variables ***************************

positive variables
Grid_buy(household,vehicle,hour) Amount of electricity bought from grid [kWh]

Grid_sell(household,vehicle,hour) Amount of electricity sold to grid [kWh]

store_added_battery(household,vehicle,hour) amount added to internal storage each hour [kWh]

store_removed_battery(household,vehicle,hour) amount removed from internal storage each hour [kWh]

stored_battery(household,vehicle,hour) amount in internal storage each hour [kWh]

store_added_EV(household,vehicle,hour) amount added to EV storage each hour [kWh]

store_removed_EV(household,vehicle,hour) amount removed from EV storage each hour [kWh]

stored_EV(household,vehicle,hour) amount in EV storage each hour [kWh]

additional_EV(household,vehicle,hour) amount of additional energy needed to fullfill EV driving [kWh]
;

free variable
tot_el_bought Total amount of electricity bought from grid [kWh]
;


```

```
*************************** Equations ***************************

equations
Grid_balance(household,vehicle,hour)
store_filling_battery(household,vehicle,hour)
maxBattery_charge(household,vehicle,hour)
maxStore_cap_battery(household,vehicle,hour)
store_filling_EV(household,vehicle,hour)
maxEV_charge(household,vehicle,hour)
maxStore_cap_EV(household,vehicle,hour)
minSOC_EV(household,vehicle,hour)
Min_bought
;


* Household energy balance
Grid_balance(household,vehicle,hour)..
Grid_buy(household,vehicle,hour) + data_PV(household,hour)*PV_panel_size(household) + store_removed_battery(household,vehicle,hour)*battery_eff - demand_profile(household,hour) - Grid_sell(household,vehicle,hour) + store_removed_EV(household,vehicle,hour)*EV_plugstatus(vehicle,hour)*battery_eff - store_added_EV(household,vehicle,hour)*EV_plugstatus(vehicle,hour) =e= store_added_battery(household,vehicle,hour);

* The filling of the stationary battery storage, with round trip efficiency to take energy losses into account
store_filling_battery(household,vehicle,hour)..
stored_battery(household,vehicle,hour--1) - store_removed_battery(household,vehicle,hour) + store_added_battery(household,vehicle,hour)*battery_eff =e= stored_battery(household,vehicle,hour);

* Maximum power when charging stationary battery
maxBattery_charge(household,vehicle,hour)..
store_added_battery(household,vehicle,hour) + store_removed_battery(household,vehicle,hour) =L=  battery_power_cap(household);

* Maximum storage capacity in stationary battery
maxStore_cap_battery(household,vehicle,hour)..
stored_battery(household,vehicle,hour) =L= battery_cap_installed(household);

* The filling of the EV battery storage, with round trip efficiency to take energy losses into account
store_filling_EV(household,vehicle,hour)..
stored_EV(household,vehicle,hour--1) - store_removed_EV(household,vehicle,hour)*EV_plugstatus(vehicle,hour) + store_added_EV(household,vehicle,hour)*EV_plugstatus(vehicle,hour)*battery_eff - EV_distance(vehicle,hour)*EV_driveconsum + additional_EV(household,vehicle,hour) =e= stored_EV(household,vehicle,hour);

```

```
* Maximum power when charging EV battery
maxEV_charge(household,vehicle,hour)..
store_removed_EV(household,vehicle,hour) + store_added_EV(household,vehicle,hour) =L»
= EV_charge_cap;

* Maximum storage capacity in EV battery
maxStore_cap_EV(household,vehicle,hour)..
stored_EV(household,vehicle,hour) =L= EV_battery_cap;

* Minimum storage level in EV battery
minSOC_EV(household,vehicle,hour)$(EV_plugstatus(vehicle,hour) = 1)..
stored_EV(household,vehicle,hour) =G= EV_battery_cap*EV_SOC_min;


* Objective function maximise self-sufficiency, through minimizing the amount of ele»
ctrcity used from the grid. Including additional_EV to minimize the amount of chargi»
ng outside home, and Grid_sell to transmit overproduction of electricity to the grid»
 that is not possible to store. Grid_sell is multiplied with a number below one (exa»
ct number not of importance, in this case 0.9 is used) to make it more desirable for»
 the model to store the electricity than to transmit it to grid. But this term is ne»
eded in the objective function to force the model to transmit generated electricity »
that is not possible to utilize in-house. In the same way additional_EV is multiplie»
d with a number greater than one (exact number not of importance, in this case 2 is »
used) to force the model to only charge exactly as much as needed outside home.
Min_Bought..
tot_el_bought =e= sum((household,vehicle,hour), Grid_buy(household,vehicle,hour) - G»
rid_sell(household,vehicle,hour)*0.9 + additional_EV(household,vehicle,hour)*2);


************************* Model solver ***********************

MODEL House_Energyhub
/
Grid_balance
store_filling_battery
maxBattery_charge
maxStore_cap_battery
store_filling_EV
maxEV_charge
maxStore_cap_EV
minSOC_EV
Min_Bought
/;

House_Energyhub.optfile = 1;
option threads = 0;
SOLVE House_Energyhub using lp minimizing tot_el_bought
;


************************* Saving output **********************

execute_unload '%output_path%Results.gdx';
```

# B

# Supplementary figures

Supplementary figures, in addition to the results presented earlier in the thesis, are presented in this Appendix.

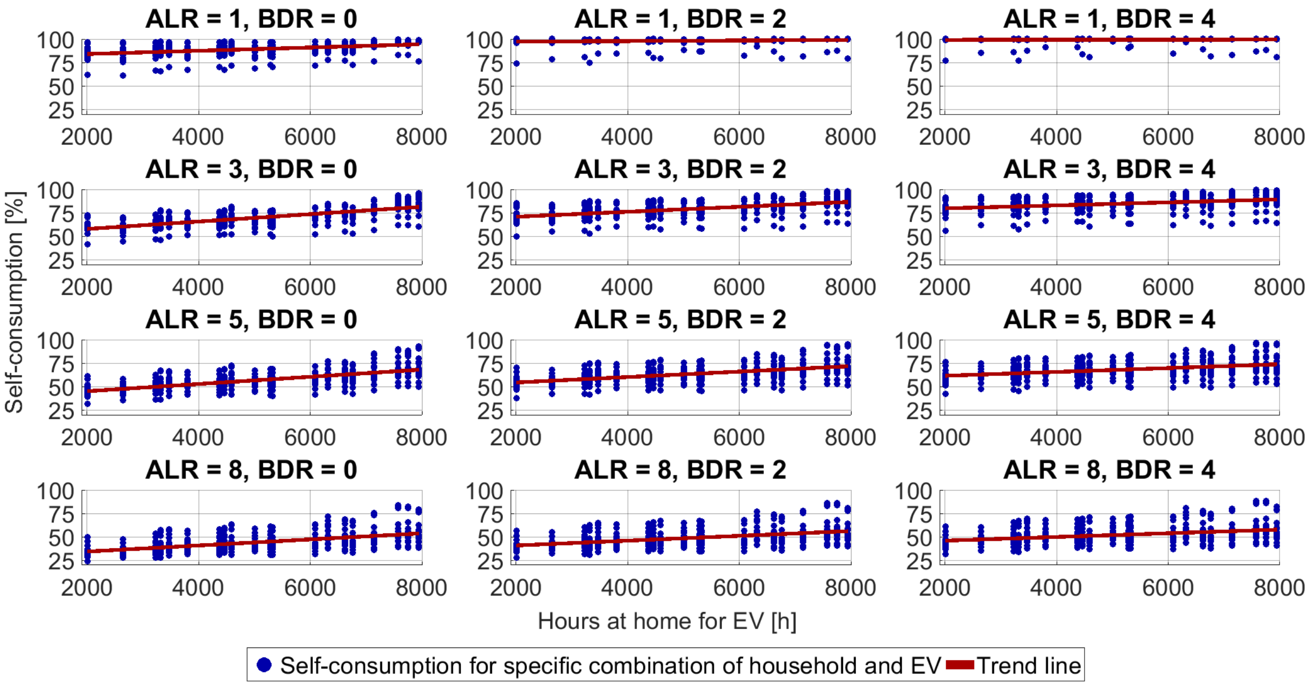


**Figure B.1:** *Self-consumption depending on number of hours that the EV is plugged in at home, for an EV battery size of 50 kWh. Subplots for different values of PV ALR and stationary battery BDR. Each vertical line of blue dots represents the same vehicle in combination with the 20 different households. Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

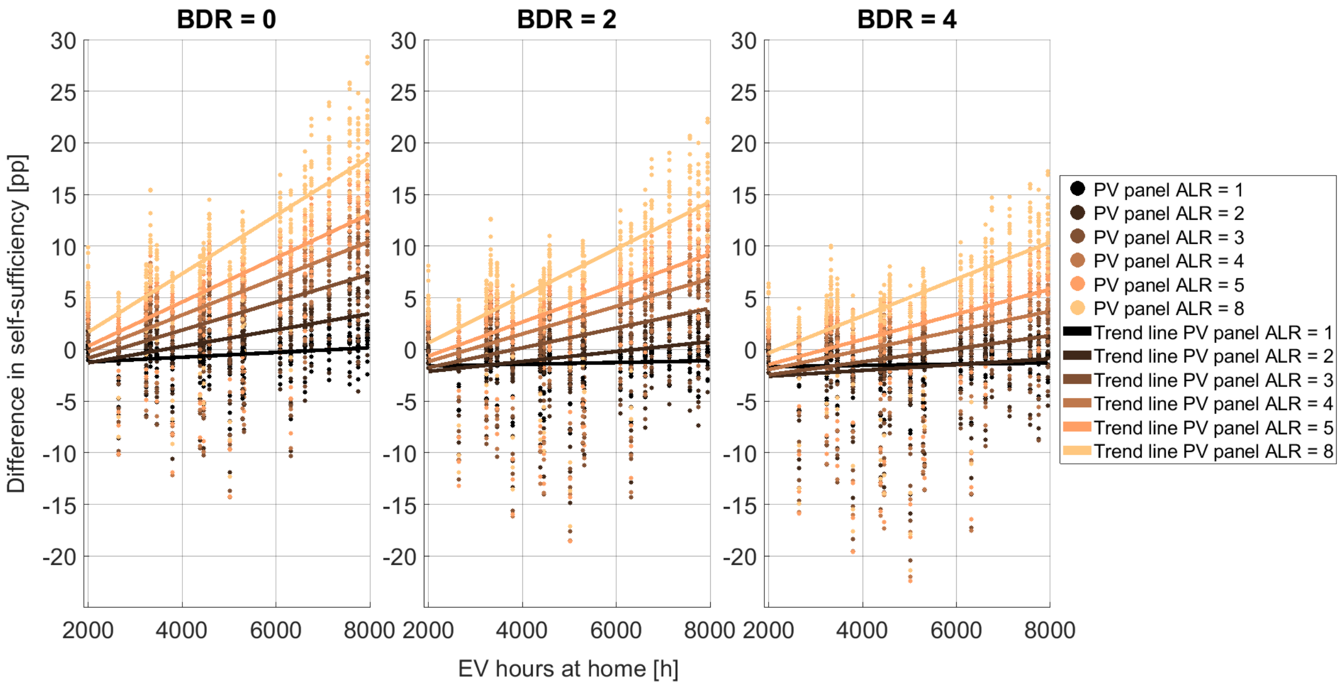


**Figure B.2:** *Difference in self-sufficiency between households without EV and the same households with EV, depending on number of hours that the EV is plugged in. The difference is positive if the self-sufficiency for the household is higher with EV compared to without. The plot is for an EV battery size of 50 kWh, with subplots for different stationary battery BDR values. Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

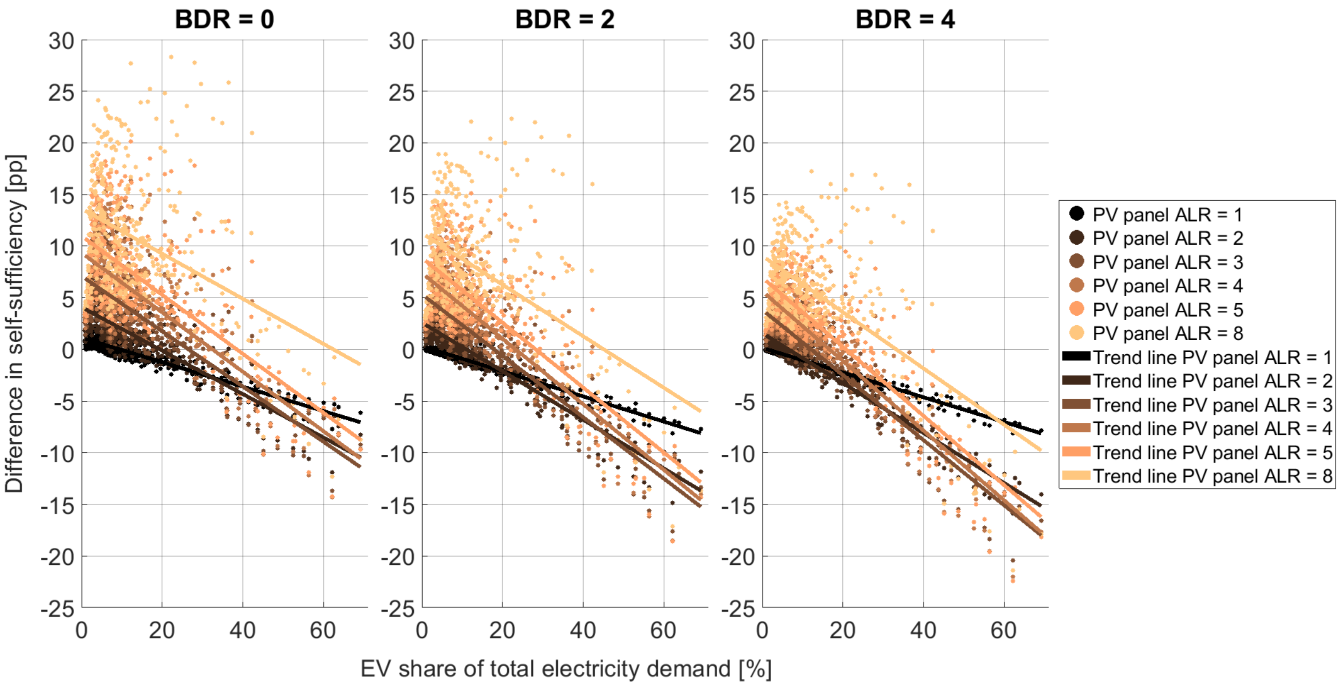


**Figure B.3:** *Difference in self-sufficiency between households without EV and the same households with EV, depending on how large share of the total electricity demand for the household including EV charging that the EV represent. The difference is positive if the self-sufficiency for the household is higher with EV compared to without. The plot is for an EV battery size of 50 kWh, with subplots for different stationary battery BDR values. Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

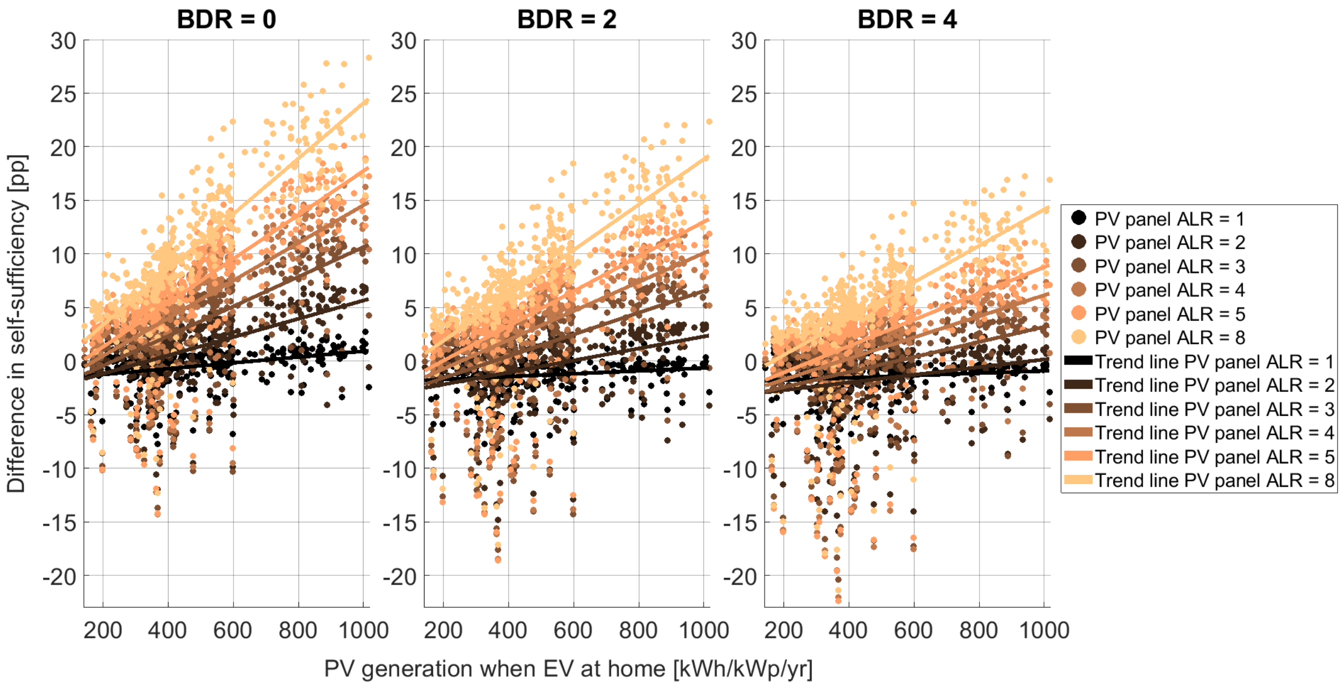


**Figure B.4:** *Difference in self-sufficiency depending on the correlation between solar PV electricity generation and hours when the EV is plugged in at home. On the x-axis is the total annual electricity generation per installed kW of PV panels (kWp) during hours when the vehicle is plugged in at home. This correlation is calculated for each combination of household and vehicle, and plotted against the difference in self-sufficiency for the household after introduction of an electric vehicle to the household. The difference is positive if the self-sufficiency for the household is higher with EV compared to without. Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

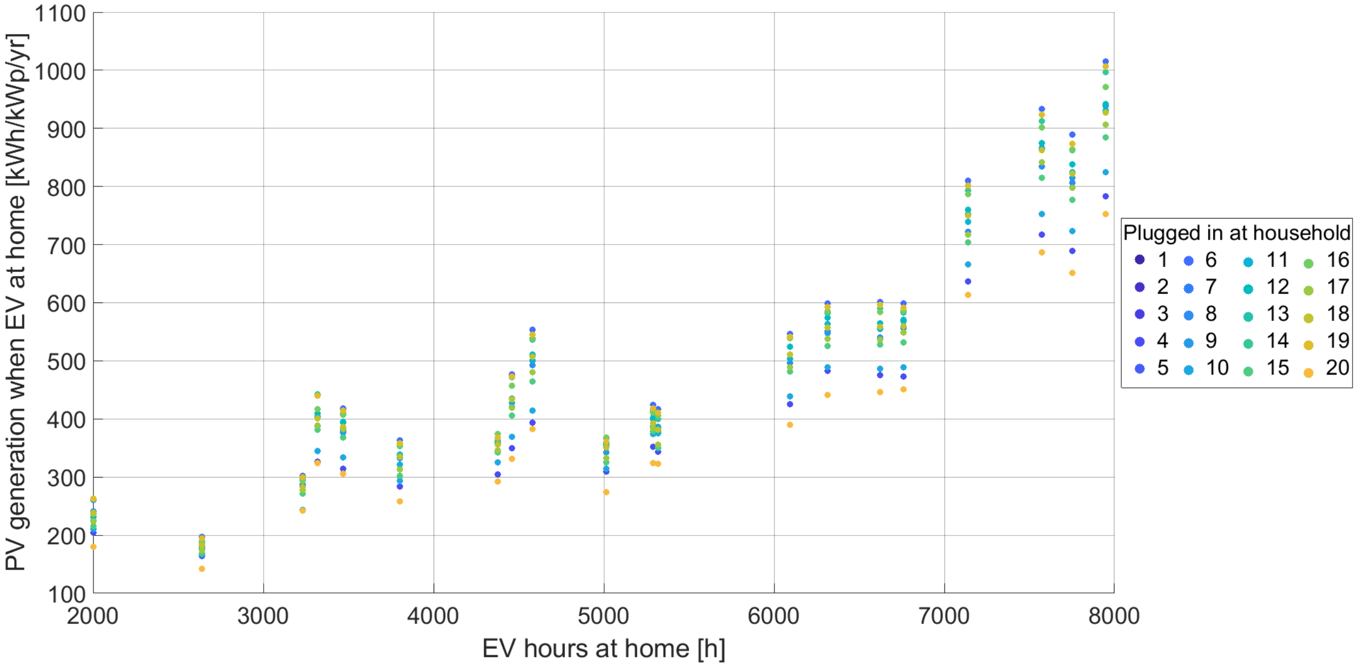


**Figure B.5:** *Correlation between annual PV electricity generation when the EVs are at home, and the total number of hours that the different EVs are at home. On the y-axis is the total annual electricity generation per installed kW of PV panels (kWp) during hours when the EV is plugged in at home. This correlation is calculated for each combination of household and EV. Abbreviations used: EV = electric vehicle and PV = photovoltaic.*

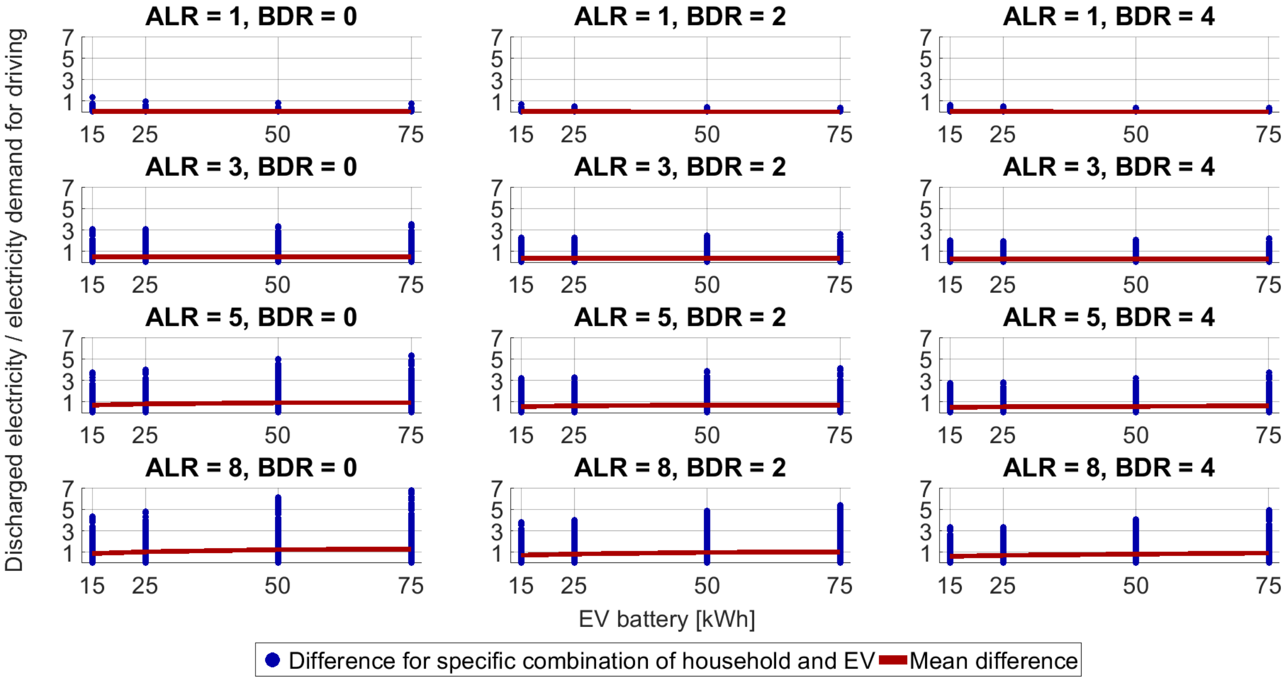


**Figure B.6:** *Total discharged electricity from the EV back to the household in relation to the total charging demand for the EV, depending on EV battery size. Subplots for different sizes of PV systems (ALR increasing downwards) and stationary batteries (BDR increasing from left to right). Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

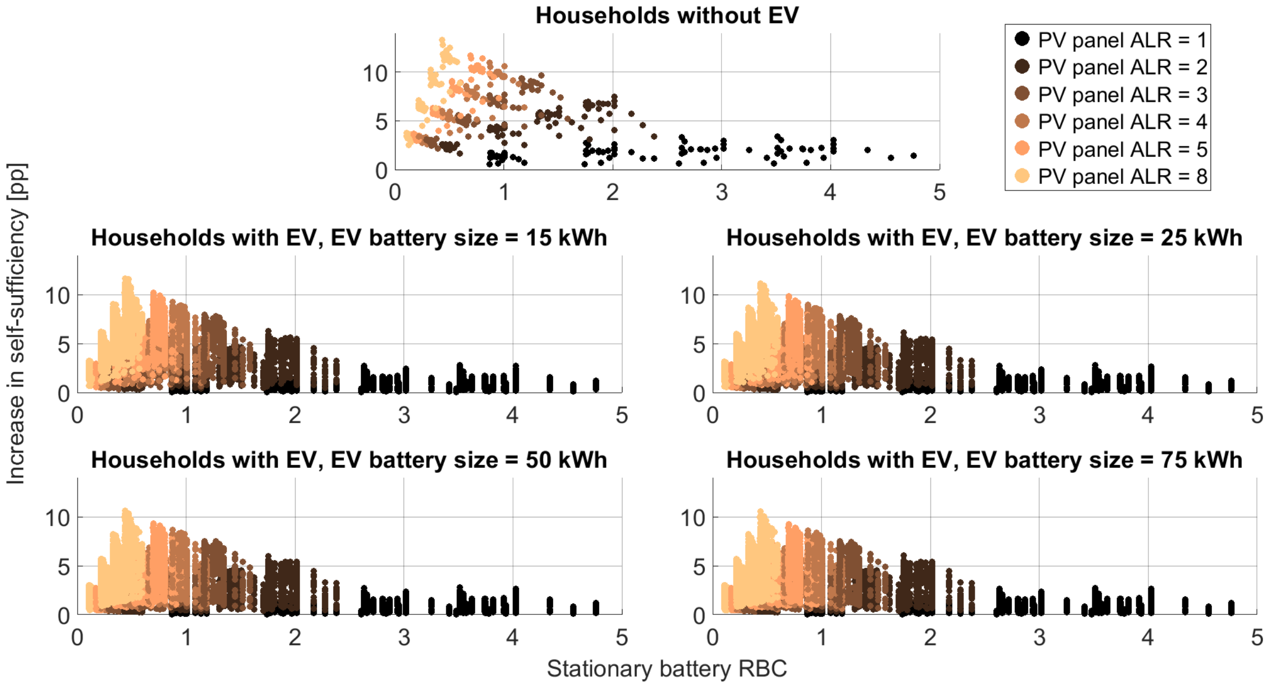


**Figure B.7:** *Increase in self-sufficiency when installing a stationary battery, depending on PV panel size, and size of the installed stationary battery in relation to the amount of electricity generated by the PV panels (as indicated by stationary battery RBC). Comparison between households without EVs and households with an EVs, subplots for all different EV battery sizes. Abbreviations used: ALR = array-to-load ratio, EV = electric vehicle, PV = photovoltaics and RBC = relative battery capacity.*

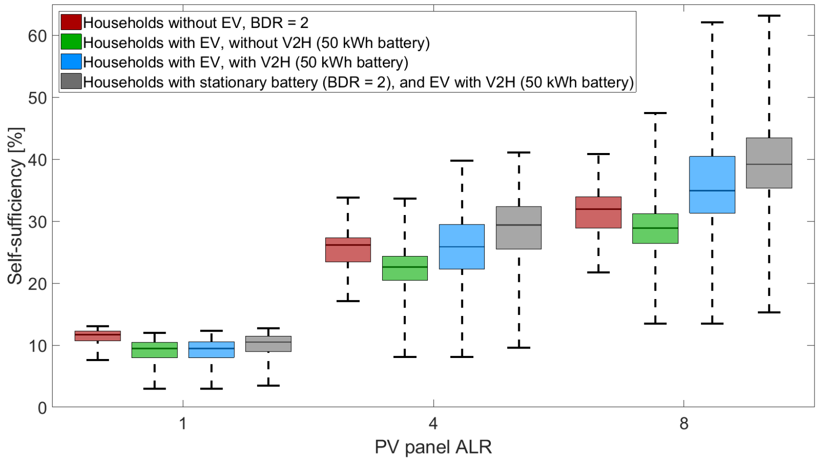


**Figure B.8:** *Variations in self-sufficiency for households without EV with a stationary battery (BDR = 2), households without stationary battery but with EV with and without V2H technology (50 kWh battery), and finally households with both stationary battery (BDR = 2) and EV with V2H (50 kWh battery). The bottom and top edges of the boxes indicates the 25th and 75th percentiles, the central line indicates the median value while the whiskers indicates the most extreme values of self-sufficiency. Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

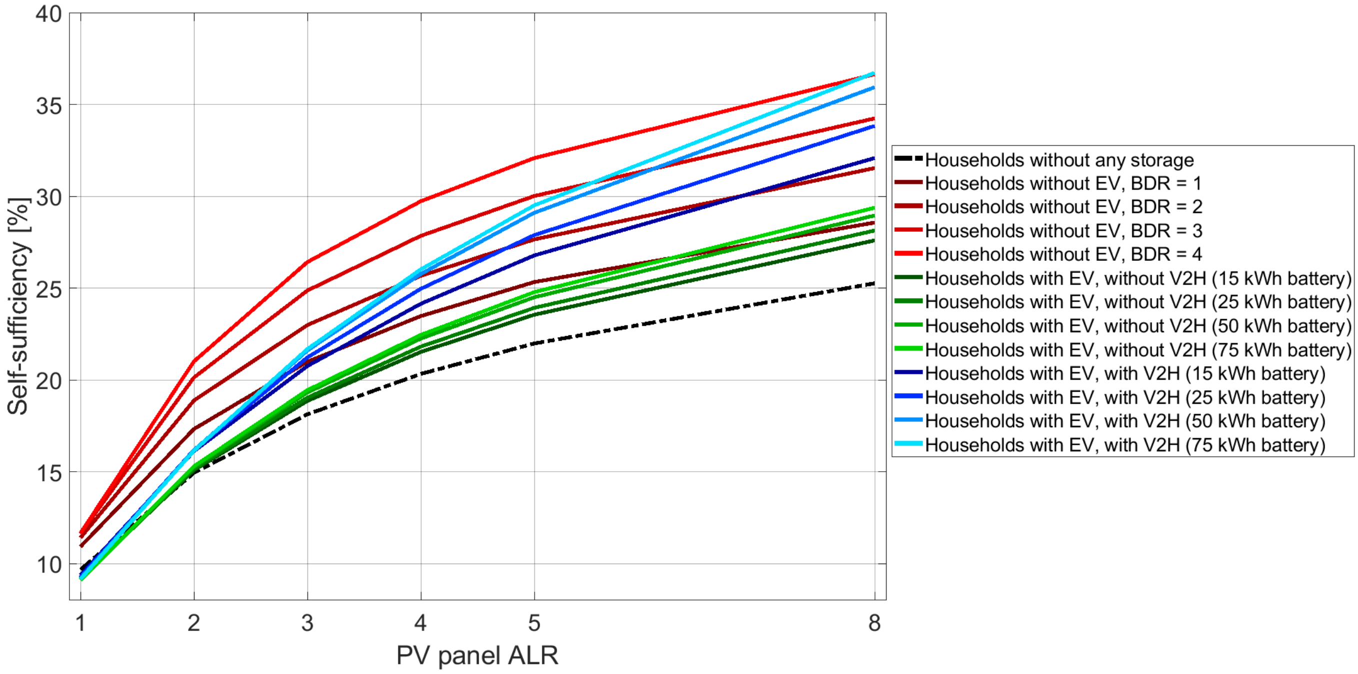


**Figure B.9:** *Self-sufficiency for households without storage, households with stationary battery without EV, and households with EV, with and without V2H, without a stationary battery. All three cases are modelled for different battery sizes of stationary battery or EV battery. Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle, PV = photovoltaics and V2H = vehicle-to-home.*

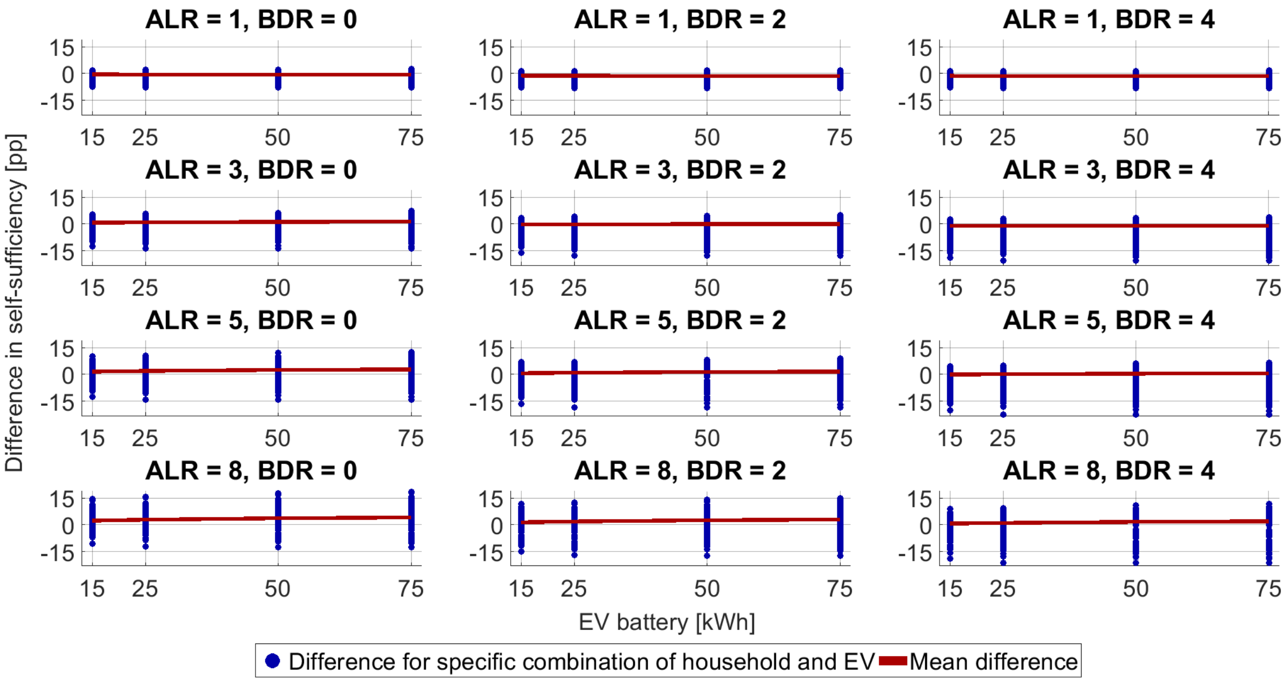


**Figure B.10:** *Difference in self-sufficiency between households without EV and the same households with EV, depending on EV battery size. In this simulation the EVs do not have the ability for V2H. The difference is positive if the self-sufficiency for the household is higher with EV compared to without. Subplots for different sizes of PV systems (ALR increasing downwards) and stationary batteries (BDR increasing from left to right). Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

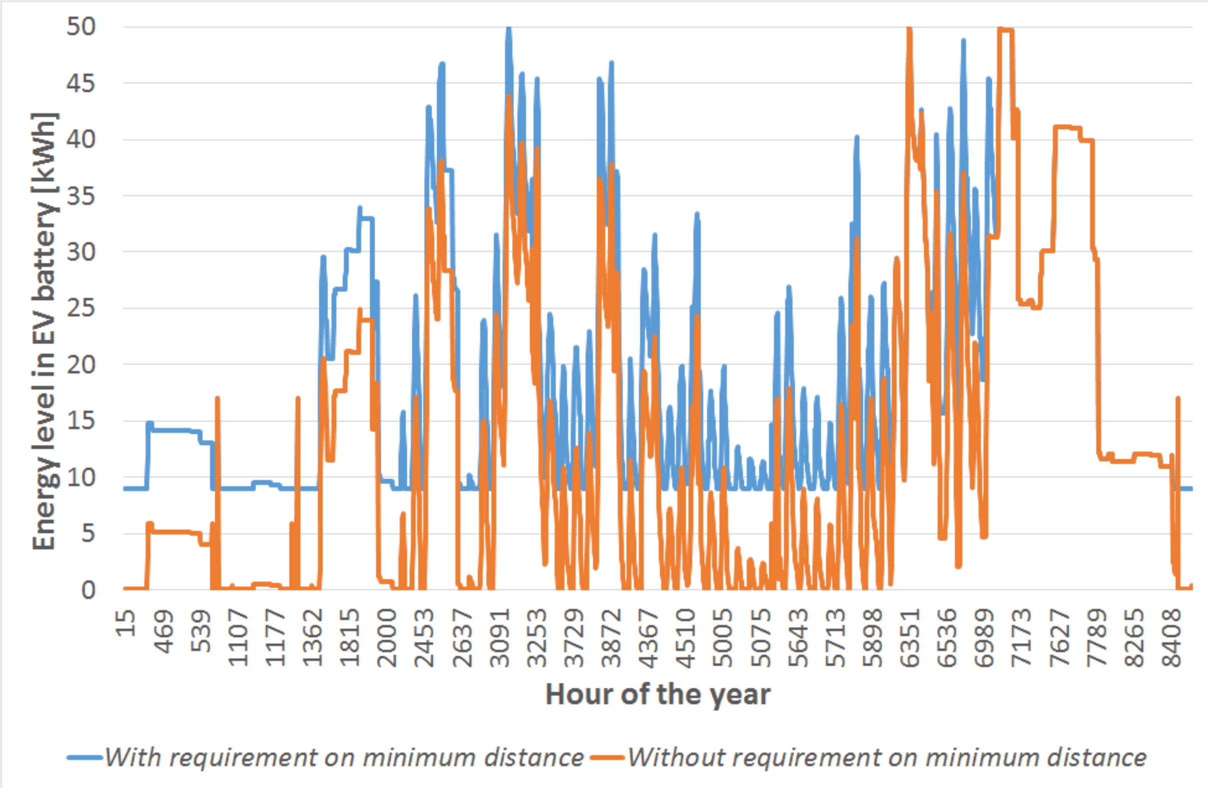


**Figure B.11:** *Energy level in the EV battery during hours when the EV is plugged in at home, with and without a requirement on a minimum driving distance available in the EV battery. In this graph the combination of household 7 and EV 1 is shown, and values for PV and stationary battery size used are ALR = 5 and BDR = 0. Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio, EV = electric vehicle and PV = photovoltaics.*

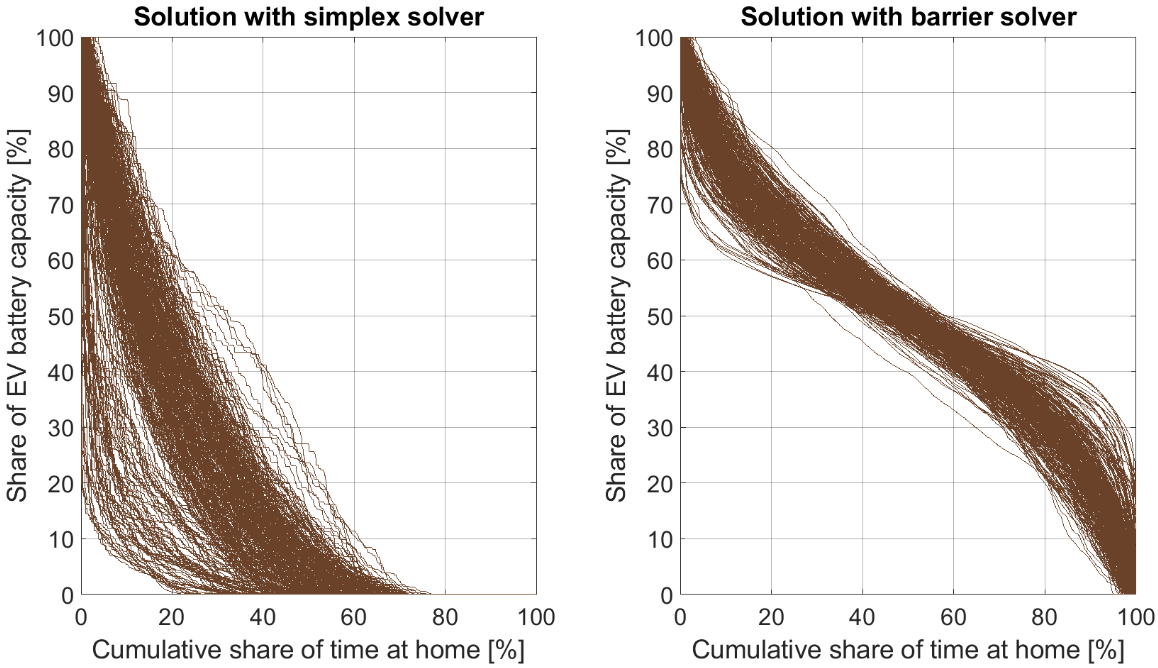


**Figure B.12:** *Comparison of the utilization of the EV battery depending on GAMS solver. A duration diagram over the energy level in the EV battery during hours when the EVs are plugged in at home is presented for both solvers, where each line represent the energy level in one EV in combination with one household. Values used for this comparison are ALR = 3, BDR = 2 and the EV battery size is 50 kWh. Abbreviations used: ALR = array-to-load ratio, BDR = battery-to-demand ratio and EV = electric vehicle.*