DTU Wind

Vehicle-to-grid services for prosumers in Denmark

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DTU Wind and Energy Systems is a department of the Technical University of Denmark with a unique integration of research, education, innovation and public/private sector consulting in the field of wind and energy. Our activities develop new opportunities and technology for the global and Danish exploitation of wind energy. Research focuses on key technical-scientific fields, which are central for the development, innovation and use of wind and energy and provides the basis for advanced education.

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Approval

This bachelor thesis has been submitted to the Technical University of Denmark Wind and Energy Systems Department in partial fulfilment of the requirements for acquiring a bachelor degree in Design of Sustainable Energy Systems at the Technical University of Denmark.

Under the supervision of Mattia Marinelli and Jan Engelhardt this work has been carried out between March and June 2023 at the Department of Wind and Energy Systems of the Technical University of Denmark. The thesis was set to be 17.5 ECTS for each of us and we have contributed equally.

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Abstract

The growing focus on climate change has led to an increased need for renewable energy sources, where residential photovoltaic systems are attractive for consumers wishing to contribute to the green transition. Alternative transportation forms, such as electric vehicles have also gained momentum, however with increased grid tariffs, smart charging has become increasingly more important.

This thesis aims to investigate how the addition of an electric vehicle will influence a prosumer's power exchange with the electricity grid. It explores the potential benefits of using smart charging strategies and how these may provide added value to a prosumer. Moreover, the influence of the prosumer's driving habits and the charger's power rating on the technical and economical results are assessed.

MATLAB-Simulink was used to model the controllers using a set of heuristic rules. The first four controllers are uni-directional and build on the previous one, whereas the fifth is a bi-directional controller. The controllers investigated were: (i) Dumb charging without a smart charger, (ii) V1H charging during low grid tariffs, (iii) V1HS charging utilizing more PV, (iv) V1HSD aiming at reduced degradation, and (v) V2H vehicle-to-home discharging during peak and high grid tariffs.

The basic system setup consists of an 11 kW smart charger and a 62 kWh EV that drives six times a week for a total of 315 km. All algorithms were assessed on the technical performance with regard to key metrics such as self-consumption, self-sufficiency, energy loss, average SOC and number of battery cycles. The economic assessment showed the largest improvement in total electricity bill was from Dumb to V1H with a difference of 4413 DKK achieved from shifting the charging start time from when the vehicle returns home to midnight. The improvement from uni-directional charging to bi-directional charging was 458 DKK.

An additional driving pattern was tested, where the prosumer drives four days a week for a total of 225 km. This increased the utilization of PV production and led to a higher self-consumption and self-sufficiency in V1HS, V1HSD and V2H from the first driving pattern. The prosumer also benefited economically as the price for total consumption of both house and EV could be covered by the sale of PV with a surplus of 282 DKK in V2H.

The power difference between PV production and household consumption was seen to lie predominantly between -3 kW and 3 kW, so a 6 kW and a 3 kW charger were investigated for the first driving pattern. A substantial decrease in energy loss was seen in V2H, with a reduction of 71% from the 11 kW to the 3 kW charger. This resulted in a surplus of 2 DKK for the 3 kW charger, an improvement of 460 DKK from the 11 kW charger in V2H.

Further investigation could include scaling to vehicle-to-grid applications or using day-ahead electricity prices in optimization algorithms to determine the charging and discharging of the vehicle based on the total electricity price, instead of just grid tariffs.

Acknowledgements

We would like to thank our supervisors Mattia Marinelli and Jan Engelhardt for taking the time to support and guide us through this project.

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List of Acronyms

AC	Alternating current
DC	Direct current
EV	Electric vehicle
PV	Photovoltaic
SOC	State of charge
V1H	Vehicle-to-home (uni-directional)
V1HS	Vehicle-to-home-sun (uni-directional)
V1HSD	Vehicle-to-home-sun-degradation (uni-directional)
V2H	Vehicle-to-home (bi-directional)
VAT	Value added tax

List of Symbols

η The efficiency of the smart charger

E_{cap} The capacity of the EV, which is 62 kWh

P_{max} The charger power rating

E_{level} Energy level of the electric vehicles

$E_{throughput}$ The energy throughput of EV

P_C Power consumed by the household

$P_{drive,Saturday}$ Power used for driving on Saturday

$P_{drive,weekdays}$ Power used for driving on each of the weekdays

P_{EV} Power input to the EV and power output of the EV

P_{grid} Power to and from the grid

P_{int} Internal power of the electric vehicle

P_{loss} The amount of power lost hen charging and discharging

P_{PV} Power produced by the photovoltaic

Contents

1 Introduction

In the last decade, the awareness of the climate crisis and the potential impacts of global warming and climate change has skyrocketed and laid a newfound focus on reducing greenhouse gas emissions. With the signing of the Paris Agreement in 2015 [1], signifying an international effort in combating climate change, many countries have begun to look for alternative forms of energy to replace conventional fossil fuels [2].

The main contestants in the Danish renewable energy market consist of wind and solar power. According to a study conducted by EnergiNet Denmark wind and solar covered 59.3% of the total electricity consumption in Denmark in 2022 [3], contributing in large part to the Danish governments goal of being carbon neutral by 2050 [4]. This has been achieved by installing a large number of off-shore wind parks and solar farms. However, in recent years residential photovoltaic (PV) installations have gained momentum, which allows individuals to produce and consume self-generated power, thus partaking in the green transition as prosumers.

With the increase in renewable energy well under way, the Danish government has now also begun to electrify the transportation sector, by setting a goal to increase the total number of electric vehicles (EVs) to 775,000 by 2030 [5]. Due to low charging costs, increased driving distance and decreased charging times [6] [7] of electric vehicles, more Danes are choosing EVs over conventional fossil fuel driven cars in line with reducing their carbon footprint. However, as more vehicles are added to the system, charging methods become increasingly important for grid security [8] [9]. The cost of transporting electricity in the Danish grid increased in 2023 [10], in order to shift consumption from peak hours, which currently lie between 17 and 21, to off-peak hours. The increase in grid tariffs further motivates EV owners to implement smart charging solutions, to avoid paying the high tariff prices [11].

As electric vehicles become more popular and the technology is further developed new opportunities arise for prosumers [12]. Vehicle-to-home applications have become possible with the introduction of bi-directional chargers that allow for electric vehicles to be used for energy storage. The connection between electric vehicles and a prosumer's home offers flexibility to the system and allows for the EV to be charged with solar power and discharge into the household as needed. These applications can be beneficial to the prosumer and reduce their interaction with the grid if proper control mechanisms are implemented.

1.1 Objectives

This project aims to evaluate the technical and economic performance of a Danish household with a number of domestic appliances, a 6 kW photovoltaic installation and a 62 kWh electric vehicle. The main question to be be answered throughout this thesis is:

How does an electric vehicle influence a prosumer's interaction with the electricity grid?

To answer the question above, sub-questions were made to find the objectives of this thesis:

- What charging strategies can be applied to the system?
- How much are the savings through smart charging?
- How much is the added value of bi-directional charging compared to uni-directional charging?
- How will different prosumer behavior impact the value of smart charging?
- How does the power rating of the smart charger influence the electric vehicle's performance?

These questions will be investigated by simulating the system using MATLAB Simulink. The thesis is structured in the following chapters:

- **Chapter 2** provides a description of the system, including the system set-up and properties of the electric vehicle, price data and driving patterns.
- **Chapter 3** models the system in Simulink and presents the input data required to run the simulations, as well as, the outputs obtained from the EV model.
- **Chapter 4** introduces the heuristic rules for the control algorithms and how they are modeled in Simulink.
- **Chapter 5** discusses the results obtained from the three investigations performed; the comparison of the algorithms, the impact of the prosumer's driving pattern and the influence of charger size.
- **Chapter 6** concludes on the findings and presents points for further investigation.

2 System Description

The system to be investigated in this thesis consists of a household located in Roskilde, Denmark. The household has a number of domestic appliances that together define the household consumption. The house also has a solar photovoltaic (PV) installation mounted on the roof and an electric vehicle (EV), charged using a smart charger. It is assumed that when the EV is home it is always connected to the house-grid-PV system. A schematic of the house-grid-PV-EV system setup can be seen in Figure 2.1.

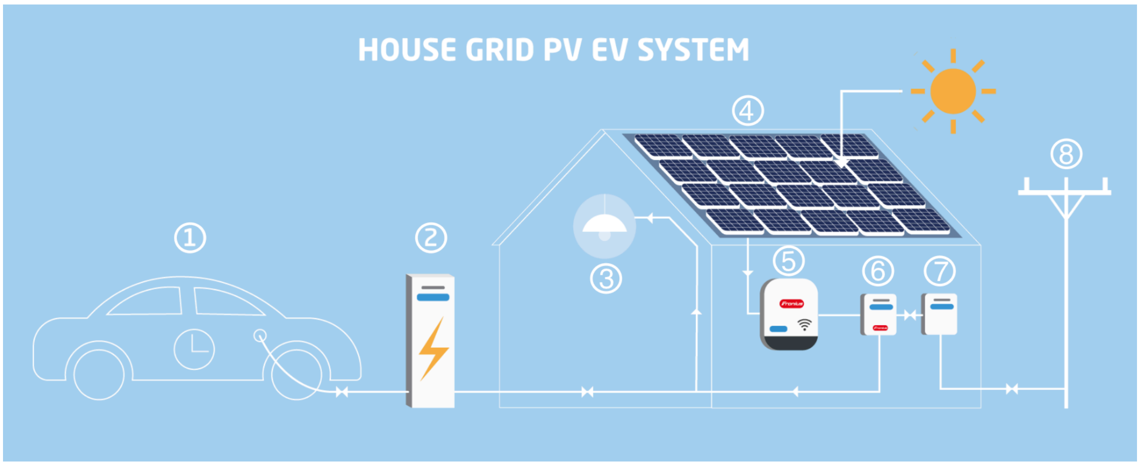

Figure 2.1: Schematic diagram showing the physical system investigated in this thesis. The components used are (1) EV, (2) smart charger, (3) household consumption, (4) PV installation, (5) inverter, (6) smart meter, (7) energy supplier meter and (8) grid. The arrows show the possible directions of the power flows. Adapted from [13]

The photovoltaic installation has a maximum power capacity of 6 kW, which can be used to supply renewable energy to the household and the EV. The power produced by the PV system will initially be used to cover household consumption, and in cases of excess production it can be used to charge the EV, when it is home. The PV system is connected to an inverter, which converts the PV production from direct current (DC) to alternating current (AC). The inverter is compatible with the household appliances and the smart charger and collects data regarding PV production and relays it back to the cloud.

The inverter communicates PV production to the smart meter, which also receives consumption data. PV production and consumption data is provided from January 2020 to December 2020. The smart meter manages energy import and export from the grid, based on PV production, as well as, household consumption and EV charging needs, creating either a surplus or deficit in the system. The smart meter measures the power flow between the household and the grid, as well as, current and voltage. The smart meter is placed directly before the energy supplier meter to ensure that both meters relay similar data to the prosumer and energy supply company respectively.

2.1 Electric Vehicle and Smart Charger

The electric vehicle integrated in the system has an energy capacity of 62 kWh and is charged with an 11 kW bi-directional smart charger. The use of a bi-directional charger allows for electricity flows in both directions, both from grid to EV and from EV to grid, whereas conventional uni-directional chargers only allow electricity flow from the grid into the EV. By implementing bi-directional charging, additional flexibility is given in the system, as the EV can be used as a battery to store energy for later use.

To prolong the lifespan of the EV, some constraints are set so that the EV does not fully charge daily. To minimize the battery degradation, it is important to avoid a high average state of charge (SOC) [14]. Therefore, the maximum state of charge for the battery is set at 85%. A minimum SOC value is also appointed to the EV and is set at 35% SOC to maintain battery health [15]. By implementing a minimum state of charge, enough energy is still stored in the vehicle to drive approximately 120 km, keeping the vehicle operational for emergency driving situations.

The EV is controlled using a smart charger that determines when the EV charges and discharges. The minimum power required to charge the EV is 1% of the charger's power rating. Hence, a minimum PV production of 110 W is required to charge the vehicle using only PV power for an 11 kW charger.

2.2 Price

When evaluating the performance of an electric vehicle integrated in the house-grid-PV-EV system, one of the important aspects is cost. Therefore, electricity prices needs to be considered. The electricity price is made up of three parts; the spot price, grid tariffs and VAT. The spot price is determined by the supply and demand of electricity in the market. The grid tariff is the price of transportation of electricity in the grid, where the price varies depending on what time of day electricity is consumed. VAT is a tax paid to the Danish government equal to 25% of the combined tariff and spot price.

The high share of renewable energy production in Denmark heavily influence the spot price. The PV production data is provided for 2020, however, the electricity spot prices were extremely low in 2020 due to COVID-19. To maintain the weather effect on spot prices for 2020 it is chosen to scale the spot prices. In 2022 electricity spot prices peaked as a response to the energy crisis and are not expected to represent future energy price levels. Therefore, the 2021 spot price levels are chosen to best constitute future electricity prices. The 2020 spot prices are scaled with a factor equal to the 2021 average spot price divided by the 2020 average spot price [16]:

$$k = \frac{653.78 \text{ [DKK]}}{211.73 \text{ [DKK]}} = 3.0878 \tag{2.1}$$

This method may result in some uncertainties regarding negative electricity prices, as they become three times more negative. However, upon further analysis there are very few hours in 2020 that have a negative electricity spot price, and when present, they lie quite close to zero. It is therefore concluded that these negative prices will have a negligible impact on the overall analysis. The scaled prices are seen in Figure 2.2.

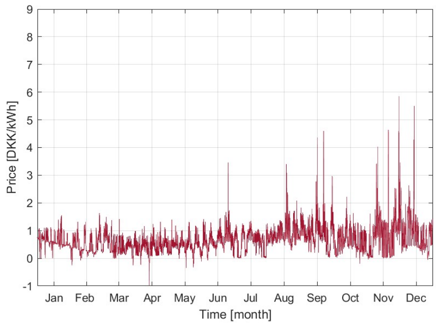

Figure 2.2: The spot prices for 2020 scaled by a factor of k.

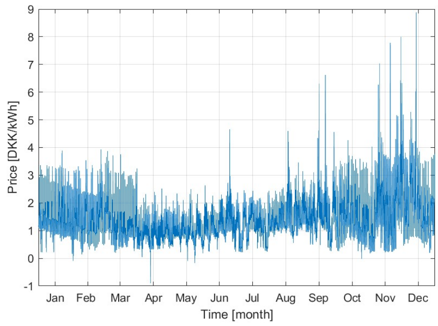

Figure 2.3: The overall electricity price, consisting of the spot price scaled by a factor of k, grid tariffs and VAT.

Excess PV production can be sold to the grid by the prosumer at spot price, while purchasing electricity from the grid is at the overall electricity price, where grid tariffs and VAT are also included, as seen in Figure 2.3.

In 2023, the grid tariffs on electricity were increased and three different tariff levels were implemented, issuing low, high and peak values depending on what time of day electricity is being consumed. The tariffs were set differently for the summer months, April to September, and winter months, October to March, and are shown in Table 2.1.

Table 2.1: The grid tariffs for 2023 [17].

	Time	Winter [DKK]	Summer [DKK]
Low	00-06	17.78	17.78
High	06-17 & 21-24	53.34	26.68
Peak	17-21	160.03	69.35

The overall electricity price is calculated by adding the 2023 tariff prices to the scaled 2020 spot prices, and then multiplying by the 25% VAT.

2.3 Driving Pattern

To determine the impacts of using an EV in this system, a driving pattern is required, as it is assumed that the vehicle is also used for transportation, and will occasionally be disconnected from the system. While public chargers are mainly used during the day [18], home charging typically occurs during the evening, when the car owners return to their homes. In this section two driving patterns are introduced for a home charging system.

Driving pattern 1 is based on the average Danes working hours during the week, which means the EV is away between the hours of 8 and 17 and drives a distance of 45 km per day. During the weekend people often need to go to family gatherings or other activities, and it is therefore chosen that the EV is away from 9 to 16 on Saturdays and drives a distance of 90 km. On Sunday it is assumed that the EV is home and plugged in all day. The driving pattern is summarized below:

- Weekdays: EV not home: 08-17, distance: 45 km
- Saturday: EV not home: 09-16, distance: 90 km
- Sunday: EV always home

When using this driving pattern the prosumer will drive six days a week resulting in 315 km per week. This is equivalent to an average driving distance of 45 km per day, which corresponds to the weighted average driving distance per day in Denmark [19].

After COVID-19, more people are choosing to work from home once or twice a week, hence the EV may not be in use all five weekdays. Therefore, it is chosen to analyze a second driving pattern, where the prosumer works from home every Wednesday and Friday. This allows for the EV to be connected to the house-grid-PV system more often. Driving pattern 2 is defined below:

- Monday, Tuesday and Thursday: EV not home: 08-17, distance: 45 km
- Saturday: EV not home: 09-16, distance: 90 km
- Wednesday, Friday and Sunday: EV always home

When using driving pattern 2 the prosumer will drive four days a week resulting in 225 km per week equivalent to an average of 32.1 km per day. This driving pattern represents a similar daily distance to the average European driving distance per day, which was estimated to 31 km per day [20].

For both driving patterns the assumption of no change in behavior is made for the prosumer. Hence, these weekly driving patterns are repeated each week for the whole year of 2020 not considering public holidays, vacations or any changes that might occur for real prosumers.

3 System Modeling

The MATLAB-based graphical program Simulink[1] was used to create a model that can simulate the house-grid-PV-EV system. The Simulink model consists of four major sections; the inputs to the model, the outputs from the model, the model of the house-grid-PV-EV system and lastly the five controllers, which are described in the next chapter, Chapter 4. In this chapter, the modeling of the house-grid-PV-EV system will be described, the implemented model can be seen in Appendix A.1.

The model of the house-grid-PV-EV system has three inputs; PV production, consumption and EV power, which is used to calculate the outputs; power to grid and power from grid. The overview of the house-grid-PV-EV model is seen in Figure 3.1.

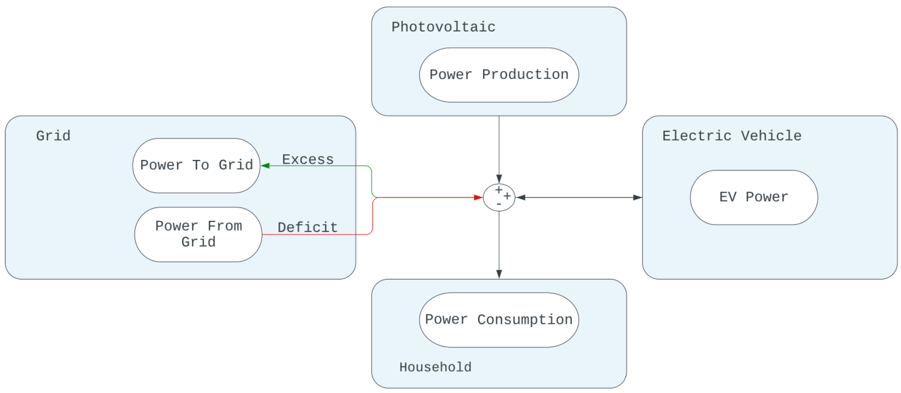

Figure 3.1: Overview of the house-grid-PV-EV model used for simulating in Simulink.

The production and consumption data is provided from January 2020 to December 2020, with a resolution of 5-minute intervals, as collected by the smart meter in the prosumer system. To import the data into the model, it must first be converted into average power values for the 5-minute intervals. For example, a data point measuring a consumption of 20 Wh, would be converted to 240 W for use in the simulation as calculated by Equation 3.1.

$$\text{Average power value} = \frac{20\ \text{Wh}}{5\ \text{min}} = 240\ \text{W} \tag{3.1}$$

These average power values are then imported from Matlab into the Simulink model using a from-workspace block. PV production (P_{PV}) provides power to the system and is therefore given as positive values, whereas consumption (P_C) uses power and is given as negative values. Both the PV production and consumption

[1] The version used throughout this thesis is the 2023a version

values cannot be influenced by the controllers, as they are given inputs from MATLAB. The time series for the given PV production data is seen in Figure 3.2 and the consumption data is seen in Figure 3.3.

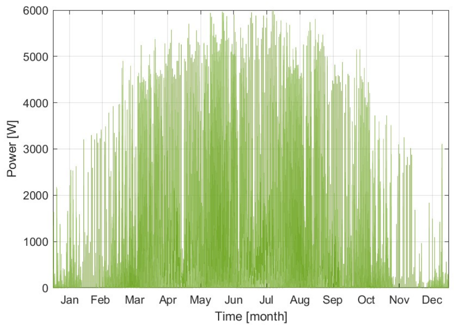

Figure 3.2: PV production data for the modeled system.

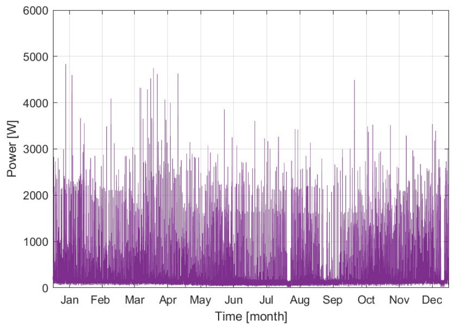

Figure 3.3: Consumption data for the modeled system.

Figure 3.2 shows how the PV production varies throughout the year, following the expected seasonal changes in sun availability, with higher production during the summer months. Conversely, the household consumption is seen to be more steady throughout the year, with random fluctuations arising from the prosumer's energy needs. It is also interesting to analyze the power balance in the system throughout the year, shown in Figure 3.4.

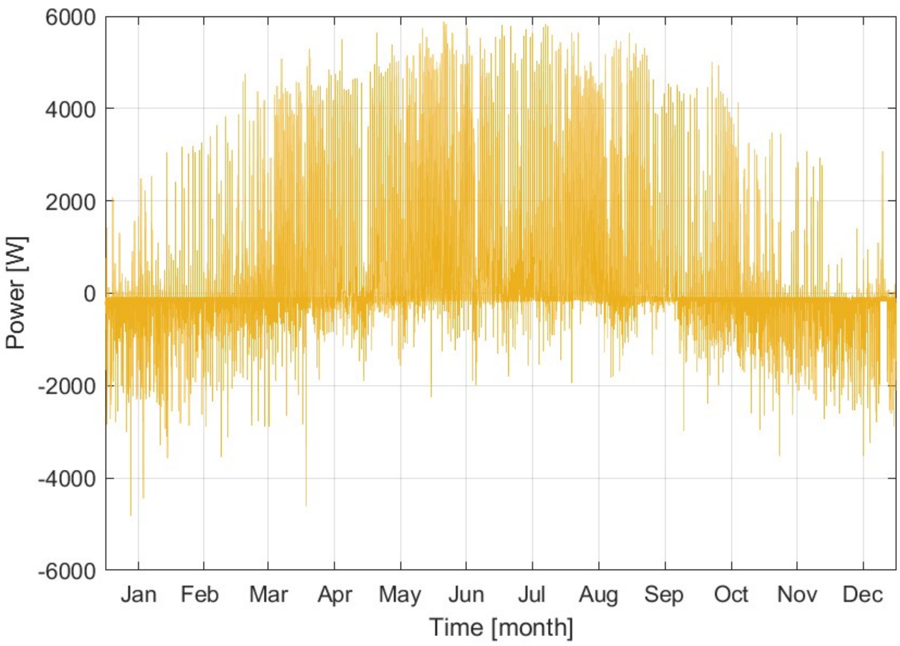

Figure 3.4: The excess power in the system, where positive values indicate an excess and negative values indicate a deficit.

The power difference between household production and consumption shows that there is a large excess of PV production from March to October, as indicated by the mostly positive values in this time frame, whereas PV production is not sufficient in covering consumption during the winter where the values are predominantly negative.

The last input in the model of the house-grid-PV-EV system is the EV, which is connected to a bi-directional charger. When charging the EV consumes energy and the power output will be negative, but when discharging the EV adds energy to the system and the power output will therefore be positive. The power value of the EV (P_{EV}) is decided by one of the five controllers, and depends on the time of day, whether there is excess or deficit power in the system and the state of charge of the EV.

These three inputs are used to determine whether the system needs to import power from the grid or export power to the grid. The grid power (P_{grid}) is calculated using Equation 3.2.

$$P_{grid} = P_{EV} + P_{PV} - P_C \tag{3.2}$$

If the power values are positive, power is exported to the grid as there is a surplus in the system and when the power levels are negative, power is imported from the grid as there is a deficit in the system.

3.1 Modeling the EV

The electric vehicle, with an energy capacity (E_{cap}) of 62 kWh, is controlled by one of the five controllers, and takes the input power, P_{EV}, from the controller. This power value tells the EV how much to either charge or discharge and is the output of the EV model given to the house-grid-PV-EV model as shown in Equation 3.2.

The EV subsystem models how the EV interacts with the smart charger. The three metrics calculated in this subsystem are the power loss, the energy level of the battery and the overall energy throughput of the battery. To calculate these metrics the smart charger efficiency is implemented.

3.1.1 Efficiency

The charger used in the system has a power rating (P_{max}) of 11 kW, which is assumed to have the same efficiency curve as a Fronius Symo 10.0-3-M solar inverter [21]. This is chosen as the inverter technology is well know, and has the same functionalities as a smart charger, including power control and an adaptable DC voltage. It is therefore assumed that the inverter efficiency curves for similar power ratings are sufficient for modeling the smart charger efficiency. Smart chargers also come in many different sizes and it is therefore relevant to understand the range of excess and deficit power in the system throughout the year. In all five controllers, the charging intervals lie between the hours of 17 and 6 the next morning. Therefore, only the power values that lie outside the interval 06-17 are considered in Figure 3.5.

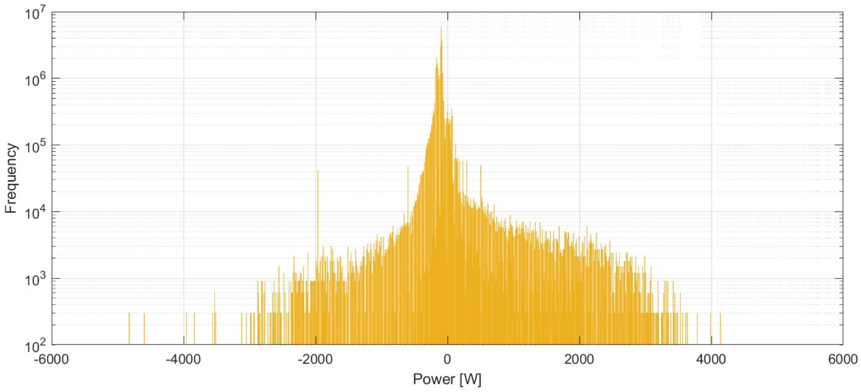

Figure 3.5: Histogram depicting the excess and deficit power values outside the time interval 06-17. Positive values indicate a surplus and negative values indicate a deficit.

The histogram shows that most of the power values lie within the interval [-3000 W:3000 W] and the highest and lowest values are 4140 W and -4824 W respectively. Since the size of a smart charger influences the price of purchasing the charger, where smaller chargers cost less, the prosumer could benefit financially if there are no performance disadvantages of a smaller charger. After modeling the initial system with the 11 kW smart charger, two additional charger sizes will be analyzed to compare the differences in performance. These chargers will be a 3 kW and a 6 kW charger, and the efficiencies are similarly assumed to follow those of corresponding sized solar inverters, Fronius Symo 3.0-3-M [22] and Fronius Symo 6.0-3-M [23]. For all three smart charger sizes the efficiency of the smart charger will vary with the input power P_{EV} used to charge or discharge the EV. The efficiencies for the 3 kW [22] , 6 kW [23] and 10 kW [21] Fronius inverters can be seen in Table 3.1.

Table 3.1: Inverter efficiencies assumed representative for the three different charger sizes [22][23][21].

Percentage of Power	11 kW Efficiency [%]	6 kW Efficiency [%]	3 kW Efficiency [%]
5%	92.5	92.6	85.1
10%	94.9	95.6	91.6
20%	97.1	97.1	95.3
25%	97.3	97.5	96.0
30%	97.5	97.7	96.5
50%	97.9	98.0	97.5
75%	98.0	98.0	97.8
100%	98.0	97.9	98.0

The three efficiency curves are implemented in the Simulink model using the 1-D look-up table block. The first data point given in the look-up table is (0.01, 0.01) in order to create a linear efficiency relation for power values below 5%. The input to the table is P_{EV} and from this the look-up table finds the equivalent efficiency which will be the output. The efficiency curves for all three charger sizes are shown using the absolute power in Figure 3.6 and the normalized power in Figure 3.7.

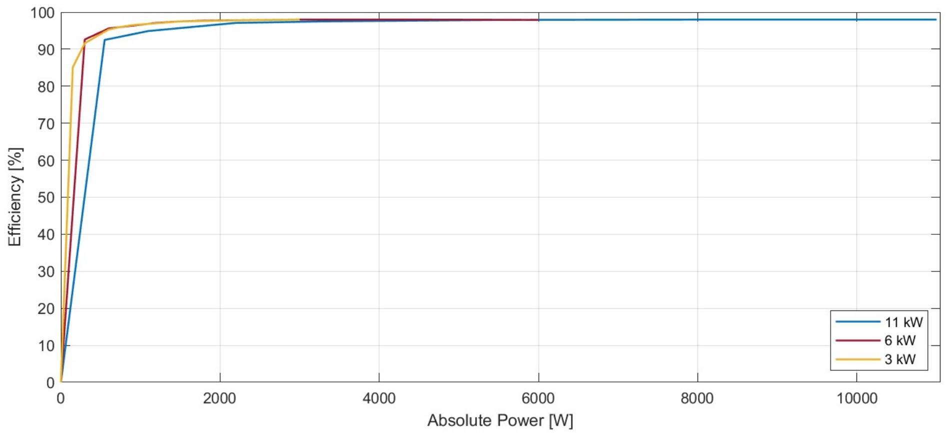

Figure 3.6: Efficiency curve for all three charger sizes for the absolute power.

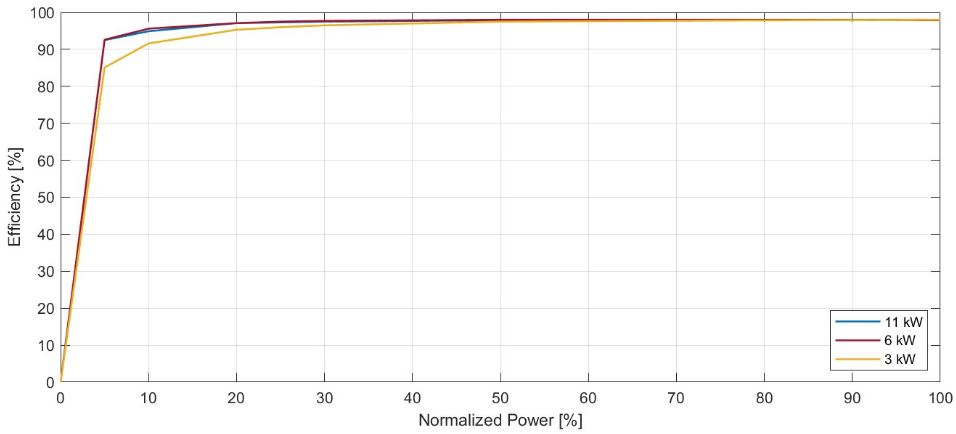

Figure 3.7: Efficiency curve for all three charger sizes for the normalized power.

3.1.2 Power Loss

As stated in Section 3.1.1, the smart charger is not 100% efficient, but uses an efficiency curve to determine the efficiency (η). To find the power losses associated with charging and discharging the EV, the internal power of the EV battery can be calculated using Equation 3.3 and 3.4. The internal power is the power that the EV battery either receives or sends out.

- EV charging with efficiency $0 < \eta < 1$

$$P_{int} = P_{EV} \cdot \eta \tag{3.3}$$

- EV discharging with efficiency $0 < \eta < 1$

$$P_{int} = \frac{P_{EV}}{\eta} \tag{3.4}$$

The power loss is then calculated by subtracting the internal power from the power from the controller:

$$P_{loss} = P_{EV} - P_{int} \tag{3.5}$$

In the simulation it is assumed that heat losses from charging and discharging the EV battery are negligible and they are therefore not accounted for in the power loss.

3.1.3 Energy Level

The energy level is the amount of energy stored in the EV's battery at a given time. It is modeled by integrating the internal power of the battery over time:

$$E_{level} = \int_{t_1}^{t_2} P_{int}(t)\,\mathrm{d}t \tag{3.6}$$

The energy level value can be both positive and negative corresponding to charging and discharging the battery respectively. The energy level is used for calculating the SOC, which is the percentage of energy available in the battery:

$$SOC = \frac{E_{level}}{E_{cap}} \cdot 100 \tag{3.7}$$

3.1.4 Energy Throughput

The energy throughput of the EV is a summation of the total energy that passes through the battery for the whole year. It is modeled in the same way as energy level, but instead of using power it takes the absolute power values integrated over time:

$$E_{throughput} = \int_{t_1}^{t_2} |P_{int}(t)|\,\mathrm{d}t \tag{3.8}$$

Energy throughput can be used to calculate the number of battery cycles the vehicle undergoes in a year, by dividing by two times the capacity of the battery:

$$\text{Number of battery cycles} = \frac{E_{throughput}}{2 \cdot E_{cap}} \tag{3.9}$$

One cycle is considered a full charge and discharge of the battery.

3.1.5 Modeling the Driving Pattern

When the EV is driving the battery discharges, which is modeled as a linear discharge in the period that the vehicle is not home. In reality, the EV will discharge in the morning, then remain at constant SOC until the afternoon, when the vehicle returns home, however it is assumed that the average SOC with linear decrease in the model is equal to that of the actual SOC in the real life discharge pattern.

The model of the driving pattern outputs the power that the EV uses while driving. The power is found by dividing the distance the EV drives a given day by the driving energy efficiency, which is the number of km the vehicle can drive per kWh of electricity chosen at 5.5 $\frac{\text{km}}{\text{kWh}}$ [14].

To determine the power value, the total energy required is divided by the number of hours the car is driving and converted from kW to W to match the units of the rest of the model.

- Power weekdays

$$P_{drive,weekdays} = \frac{\frac{45\ \text{km}}{5.5\ \frac{\text{km}}{\text{kWh}}} \cdot 1000}{9\ \text{h}} = 909\ \text{W} \tag{3.10}$$

- Power Saturday

$$P_{drive,Saturday} = \frac{\frac{90\ \text{km}}{5.5\ \frac{\text{km}}{\text{kWh}}} \cdot 1000}{7\ \text{h}} = 2338\ \text{W} \tag{3.11}$$

This power is then added to P_{EV} in the time periods where the EV is not home as stated in Section 2.3. When the power is integrated, the energy level is seen to decrease linearly over time.

The state of charge of the car on December 31, 2019 is unknown and therefore a start SOC value is chosen for the simulation. This starting power value is chosen to be equivalent to the energy level after driving a distance of 45 km on a weekday. This value is calculated to be 160265454 W. An IC-block was used, which at the simulation time equal to 0 seconds sends the chosen start value into the EV.

4 Control Algorithms

In this chapter the algorithms used to control the charging pattern of the EV will be described. The controllers implemented in Simulink can be seen in Appendix A.2.

4.1 Overview

Five controllers of different complexity levels were designed with the purpose of controlling the charging and discharging of the EV. The motivation was to determine how the controller could be improved upon with respect to different parameters and then to measure how each controller performs compared to the others. An overview of the five controllers can be seen in Table 4.1 and are described in more detail in the following sections.

Table 4.1: Overview of the five controllers.

Controller Name	Description
Dumb	Charge upon arriving home
V1H	Charge during low-tariffs
V1HS	Charge during low-tariffs or excess PV
V1HSD	Charge during low-tariffs or excess PV aiming at reduced degradation
V2H	Bi-directional charging

4.2 Controller Dumb

The first case to be investigated is that of an EV owner who plugs in their vehicle when they return home from work. This case is used to demonstrate the economic implications and consumption pattern that the average EV owner has without a smart charger.

In this case, the car charges using a conventional uni-directional charger. The schematic overview of a system utilizing a uni-directional charger can be seen in Figure 4.1.

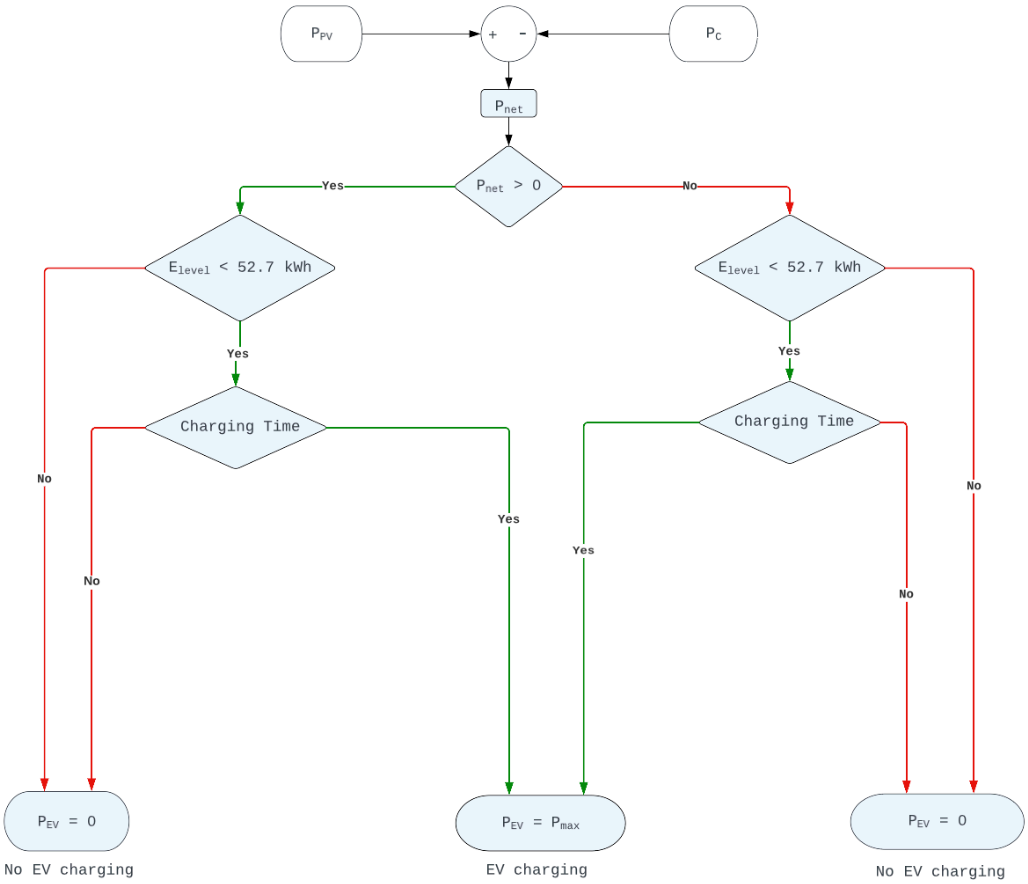

Figure 4.1: Flowchart for the uni-directional controllers used to control the EV in the simulated model for Dumb and V1H.

The controller is the part of the simulation in which a set of heuristic rules are used to determine the time and amount the EV should charge. The output of the controller is the power needed to charge the EV at a given time. Thereby, the controller makes all the charging decisions for the EV. The controller is set to only make charging decisions when the EV is at home.

In the controllers if-blocks are used to determine the day of the week, and the subsequent charging times associated with each day. The repeating-sequence block is used to send out a periodic scalar, which can be used to simulate a week in seconds by ranging from 0 seconds to one week of 7 days equal to 604800 seconds. It is also used to simulate a day which ranges from 0 seconds to 24 hours equal to 86400 seconds. These blocks were used to model the time control in the controller system. The year 2020 started on a Wednesday, so the simulation start time is set to Wednesday at 00.

In this scenario, the vehicle will be plugged in and set to charge at 17 on weekdays, Monday to Friday, and at 16 on Saturday. The time control is therefore defined as:

- **Charging** *(weekdays: 17-24 and Saturday: 16-24)*

In this time period, the EV will charge with excess power production from the PV and power from the grid.

- **EV not home** *(weekdays: 08-17 and Saturday: 09-16)*
  In this time period, the EV is not home. Linear discharge due to driving is modeled in the house-grid-PV-EV model.

This model allows for excess PV production in the late afternoons to be used as a means of charging the EV. To reach the 11 kW charging power, the remaining power will be imported from the grid. By using the maximum charging power, it is expected that the EV will be fully charged in a couple of hours and will therefore be idle until the next morning, when the EV is disconnected from the charger.

To ensure the simulated model corresponds to the given heuristic controls and driving pattern, the SOC is plotted for a week in July:

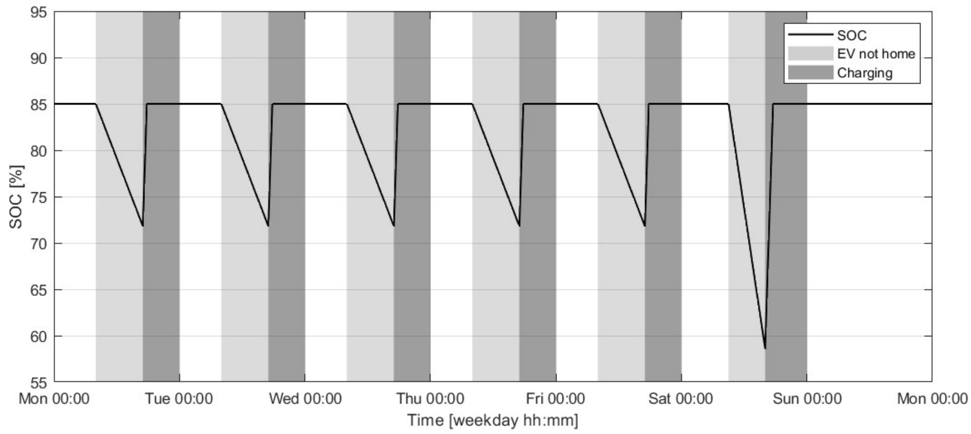

Figure 4.2: The SOC for Dumb in week 29.

The white areas show when the car is home and idle, the light grey areas indicate when the car is not at home and driving, and the dark grey intervals indicate the charging window. As seen on Figure 4.2 the car discharges linearly between the hours of 8 and 17, Monday to Friday and when it returns home it starts charging. On Saturday it drives twice the distance, which is seen by the larger fall in SOC and because it charges when it returns home at 16, no charging is needed on Sunday.

4.3 Controller V1H

As described in Section 2.2 the grid tariffs on electricity were greatly increased in 2023. This encourages people to reduce their electricity consumption during peak demand hours by shifting consumption to other hours. Therefore, it is beneficial for EV owners to implement smart charging strategies to shift charging to low tariff hours.

The uni-directional controller is modeled, using the flowchart in Figure 4.1, to best utilize these variable tariffs, to create the smallest economic impact on the prosumer. Therefore, the charging window is shifted to lie during the hours where the grid tariffs are lowest and the time control is set at follows:

- **Charging** *(all days: 00-06)*
  In this time period, the EV will charge with excess power production from the PV and power from the grid.
- **EV not home** *(weekdays: 08-17 and Saturday: 09-16)*
  In this time period, the EV is not home. Linear discharge due to driving is modeled in the house-grid-PV-EV model.

This change in charging time can be visualized by plotting the SOC of the EV for a week in July:

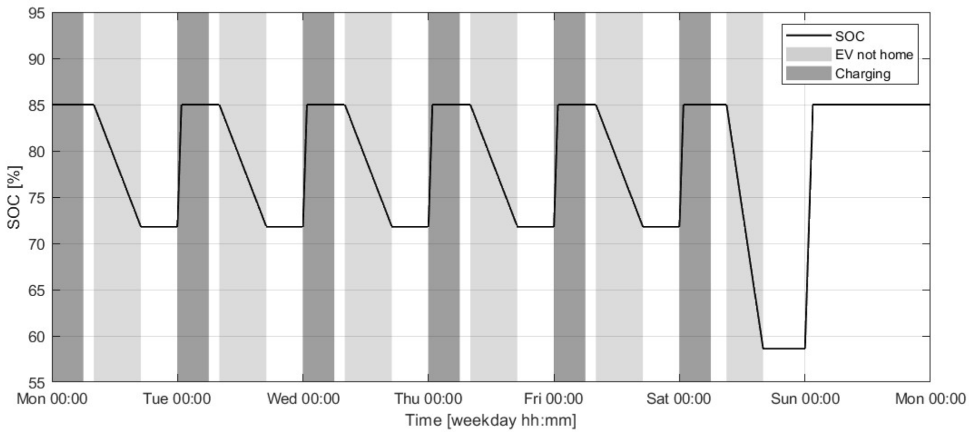

Figure 4.3: The SOC for V1H in week 29.

The urgent charging time has shifted so that the vehicle first charges at midnight as seen by the idle SOC when the vehicle returns home from work.

4.4 Controller V1HS

For a prosumer to increase their self-consumption, it is necessary to utilize the available excess PV power to charge the EV. As explained in Section 2.2, PV produced power can be sold to the grid at spot price, but when purchasing electricity one must also pay for the grid tariffs and VAT. It could therefore benefit the prosumer to use as much of the excess power from the PV as possible to charge the EV, thus saving the extra costs of tariffs and VAT when buying from the grid.

In this scenario, the controller is modified to include charging from PV production throughout the week when the car arrives home, with the remaining power being charged to the vehicle during urgent charging time between 00 and 06. The uni-directional diagram is therefore modified to include PV charging and the new flowchart is seen in Figure 4.4.

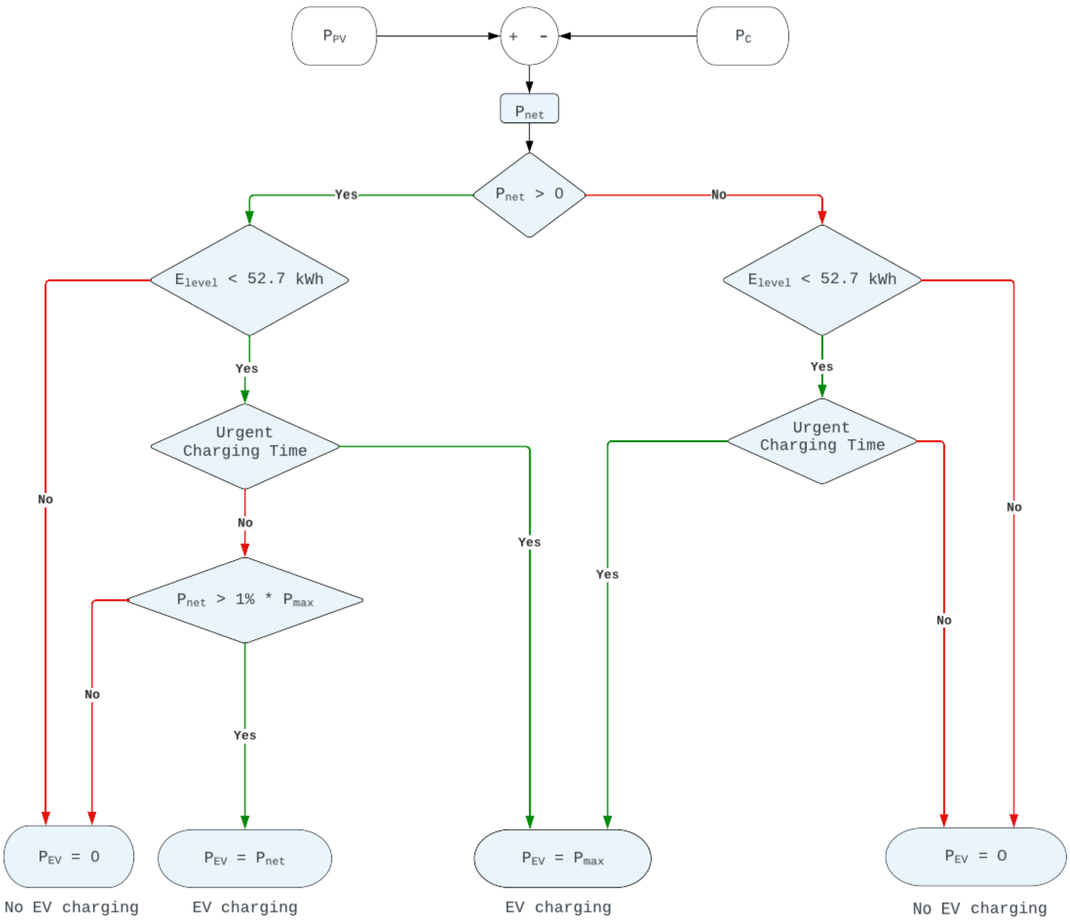

Figure 4.4: Flowchart for the uni-directional controllers used to control the EV in the simulated model for V1HS and V1HSD.

To allow for the car to charge using PV on Sundays, the urgent charging time during the night between Saturday and Sunday is removed, and an urgent charging time is added the night between Sunday and Monday to ensure the battery is charged Monday morning. The time control is defined as follows:

- **Urgent charging** *(weekdays: 00-06 and Saturday: 00-06)*
  In this time period, the EV will charge with excess power production from the PV and power from the grid.
- **PV charging** *(When EV is home)*
  In this time period, the EV will charge using excess power from PV production.
- **EV not home** *(weekdays: 08-17 and Saturday: 09-16)*
  In this time period, the EV is not home. Linear discharge due to driving is modeled in the house-grid-PV-EV model.

This controller is designed to increase self-consumption of solar power in the system. The time control of the model can be seen using the state of charge, as seen in Figure 4.5.

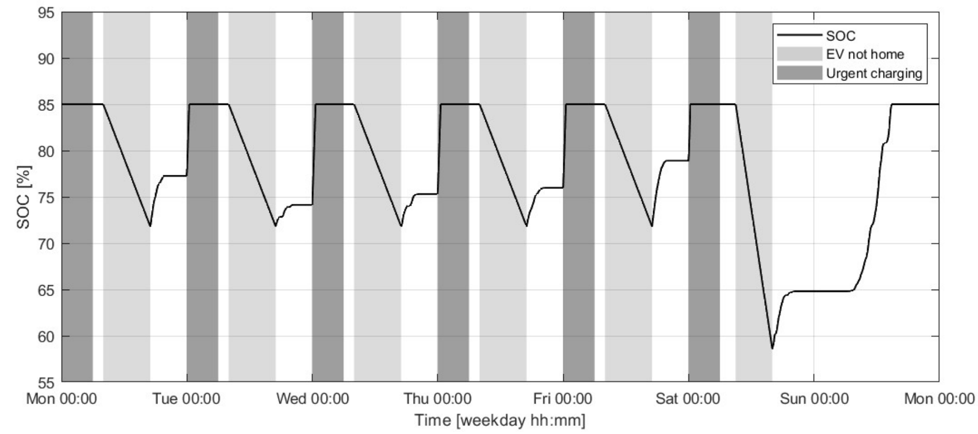

Figure 4.5: The SOC for V1HS in week 29.

The use of PV charging can be seen by the immediate charging when the EV returns home from work, whereas urgent charging is first used at midnight to ensure the battery is charged before work the next morning. The addition of PV charging Sunday is also seen, as the vehicle is able to fully charge using excess PV production between Saturday afternoon and Sunday evening.

4.5 Controller V1HSD

EV batteries are expensive to both buy and change, and it is therefore important for EV owners to keep their battery healthy in order to prolong the battery's lifetime. There are two parameters that are important for battery health, battery cycles [24] and average SOC [14]. The number of battery cycles is determined using the energy throughput as described in Section 3.1.4. As the total energy throughput is largely dependent on how far the EV drives, the number of battery cycles cannot be influenced by a change in charging time.

However, the average SOC can be decreased by moving the charging time closer to the driving time. High SOC values have been linked to a faster calendar aging, and therefore lower average SOC values are desirable [14].

The controller for V1HSD, is constructed simply by changing the urgent charging time to 04-06 from the V1HS controller, as it was seen that the vehicle does not require more than two hours to charge. The controller can be modeled using the schematic in Figure 4.4 with the following time control:

- **Urgent charging** *(weekdays: 04-06 and Saturday: 04-06)*
  In this time period, the EV will charge with excess power production from the PV and power from the grid.
- **PV charging** *(When EV is home)*
  In this time period, the EV will charge using excess power from PV production.
- **EV not home** *(weekdays: 08-17 and Saturday: 09-16)*

In this time period, the EV is not home. Linear discharge due to driving is modeled in the house-grid-PV-EV model.

This change in urgent charging time can be seen by the shortened urgent charging window in Figure 4.6.

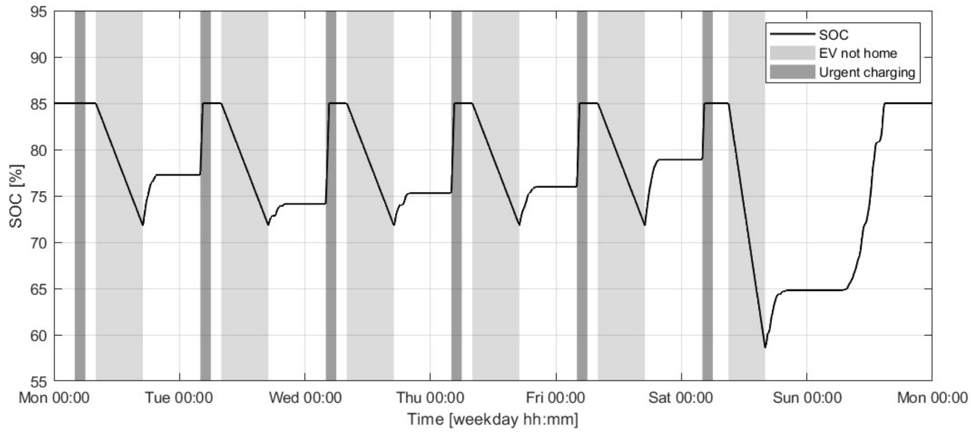

Figure 4.6: The SOC for V1HSD in week 29.

Figure 4.6 shows the car is charged at 85% SOC for a much shorter amount of time than in the previous controllers, thus hopefully lowering the average SOC and extending the calendar life of the EV's battery.

4.6 Controller V2H

In this scenario, the uni-directional charger is replaced with a bi-directional charger, thus allowing the EV to discharge into the household. This allows the EV an additional function as a battery, that allows for both charging and discharging when the vehicle is home and connected to the household. The EV will be used as a vehicle-to-home rather than a vehicle-to-grid, as it will only discharge to the household, covering consumption. By utilizing vehicle-to-home connections, it is possible to cover private consumption during peak hours, when the strain on the electricity grid is largest and prices often are highest. This has the potential to be economically beneficial for the prosumer, as the peak hour tariffs can be avoided.

For this scenario the schematic overview has changed to include the possibility of discharge. This can be seen in Figure 4.7.

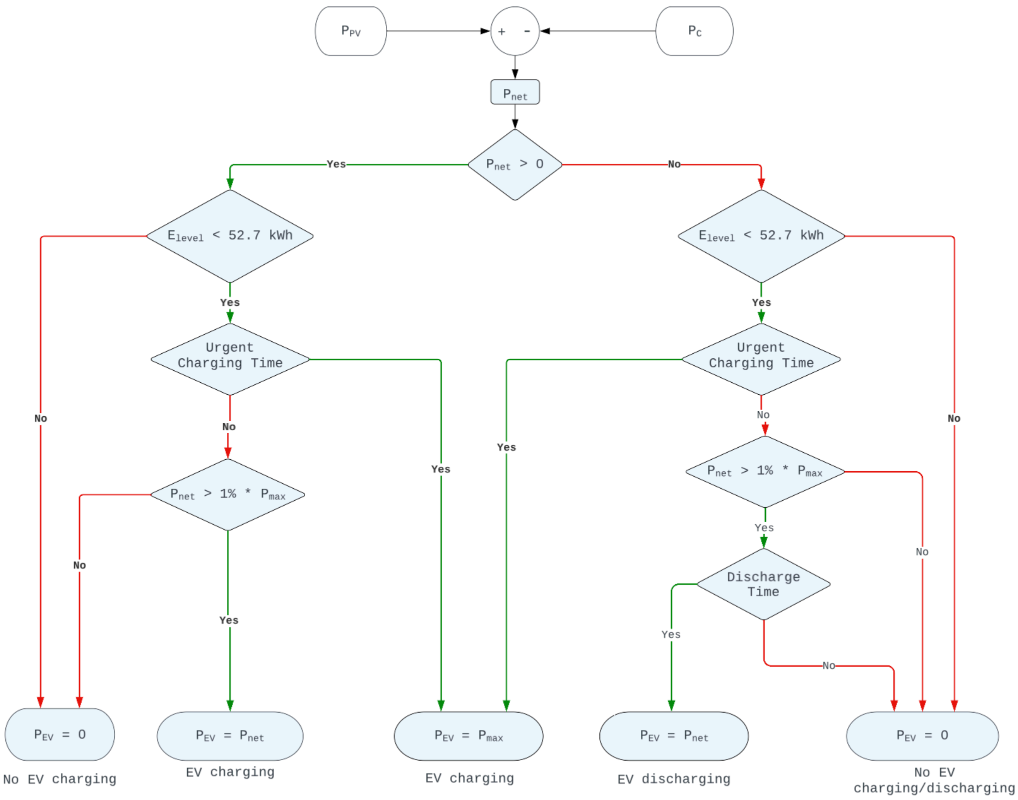

Figure 4.7: Flowchart for bi-directional controllers used to control the EV in the simulated model.

Discharge occurs when PV production cannot cover household consumption during the evening hours with high and peak tariffs. The time control for this controller is as follows:

- **Urgent charging** *(weekdays: 00-06 and Saturday: 00-06)*
  In this time period, the EV will charge with excess power production from the PV and power from the grid.
- **PV charging** *(When EV is home)*
  In this time period, the EV will charge using excess power from PV production.
- **Discharge time** *(all days: 17-24)*
  In this time period, the EV will discharge to the household covering consumption.
- **EV not home** *(weekdays: 08-17 and Saturday: 09-16)*
  In this time period, the EV is not home. Linear discharge due to driving is modeled in the house-grid-PV-EV model.

To visualize the time control, with the added discharge statement, the state of charge for a week in July was plotted in Figure 4.8.

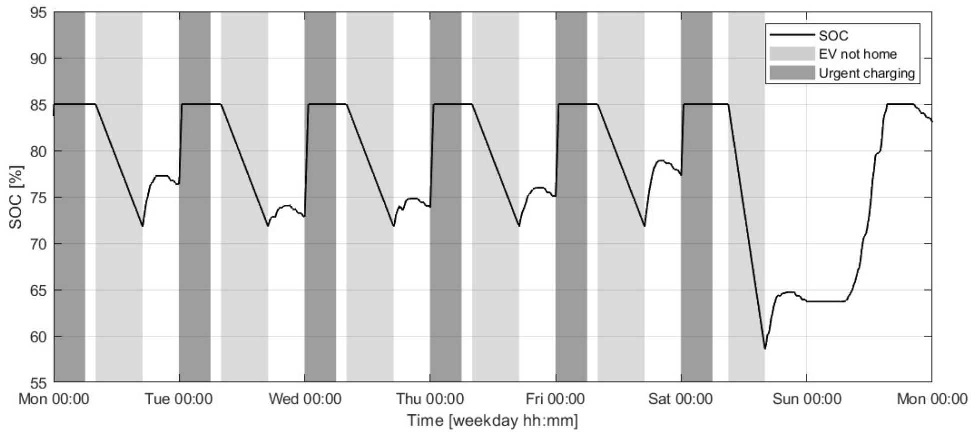

Figure 4.8: The SOC for V2H in week 29.

The plot illustrates how the EV discharges in the evenings to cover household consumption when the PV production is no longer sufficient. As the SOC is plotted for July, the EV first charges with PV power and then discharges power back into the system, decreasing the SOC of the car. It is seen that discharge is required all days of the week, and only acts until 24, after which the car enters urgent charging time and the remaining power is taken from the grid.

5 Results and Discussion

In this chapter, the important results acquired from running various simulations on the five controllers will be presented. These results will be compared and discussed to understand the influence an electric vehicle can have on a prosumers interaction with the electricity grid.

5.1 Comparison of Algorithms

The results obtained from simulating the five controllers in driving pattern 1 with an 11 kW charger will be analyzed and compared in this section to evaluate the potential of each controller.

5.1.1 Technical Performance

The overall technical performance of the controllers can be assessed with respect to different metrics measured in the simulation. To best assess the behavior of the EV and ensure that the battery charges and discharges as expected the yearly SOC for case V2H is plotted in Figure 5.1.

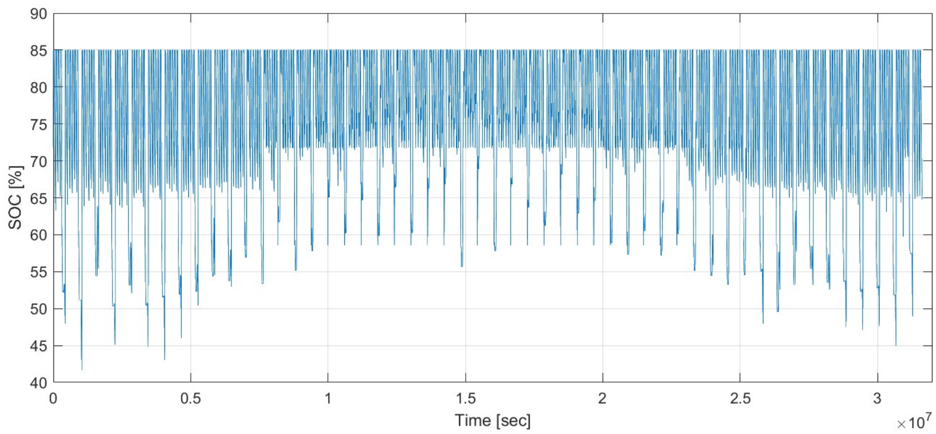

Figure 5.1: The SOC for V2H in 2020.

The plot shows that there are no values that exceed a SOC of 85% or fall below a SOC of 35% as expected by the parameters chosen in Section 2.1. The plot illustrates that the SOC does not fall below 40%, which gives leeway to the prosumer if consumption were to increase, as the EV has additional energy available to discharge further if necessary. It is also seen that far less discharge is required during the summer months, with smaller fluctuations, likely due to a larger amount of PV production being able to cover more of the household consumption. The weekly driving pattern is also illustrated as the weekly minimum SOC values are approximately 72% and Saturday's longer driving distance is represented by the spikes in SOC which are around 58% in the summer months.

To visualize how much discharge varies in V2H, the energy from the battery to the household is plotted in Figure 5.2.

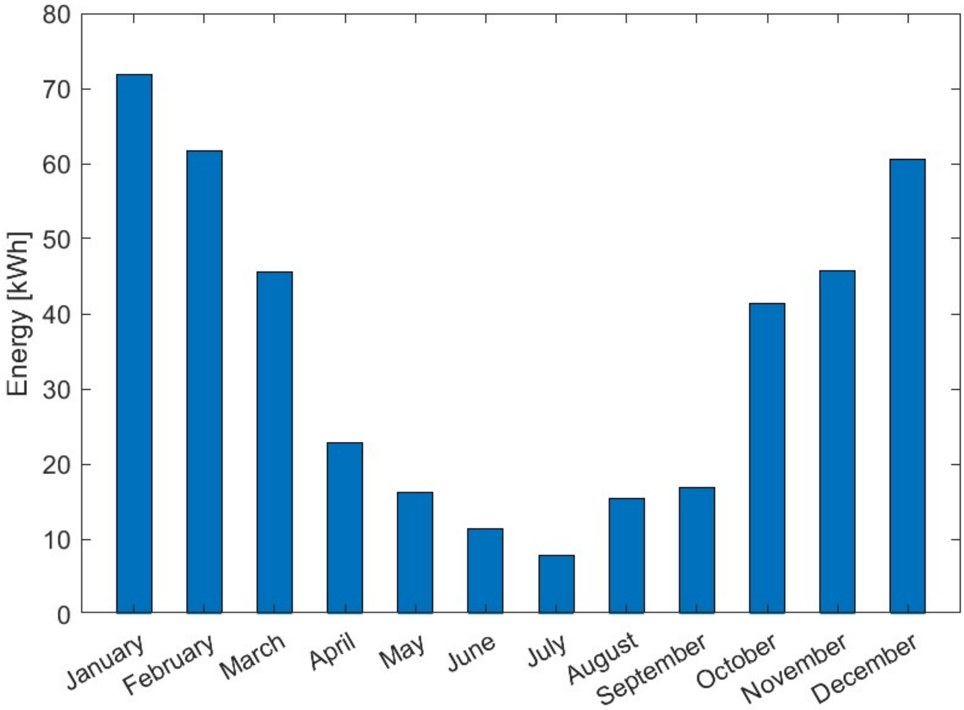

Figure 5.2: Monthly energy discharged from the EV to the household for V2H.

The figure shows that more discharge is required from the EV to the household during the winter, with a maximum usage of 72 kWh in January. The discharge required for the summer months is significantly lower, with the household needing between 8 kWh and 15 kWh of electricity from the EV. These results are concurrent with the tendencies seen in the yearly SOC in Figure 5.1 and as previously mentioned are likely a result of increased PV production in the summer months.

After delving into the parameters specific to controller V2H and ensuring that the simulation was run correctly for all five controllers (See Appendix A.3), it is of interest to compare the results of all five controllers. One of the important results from the model is the amount of energy that flows to and from the grid. This is seen in Figure 5.3.

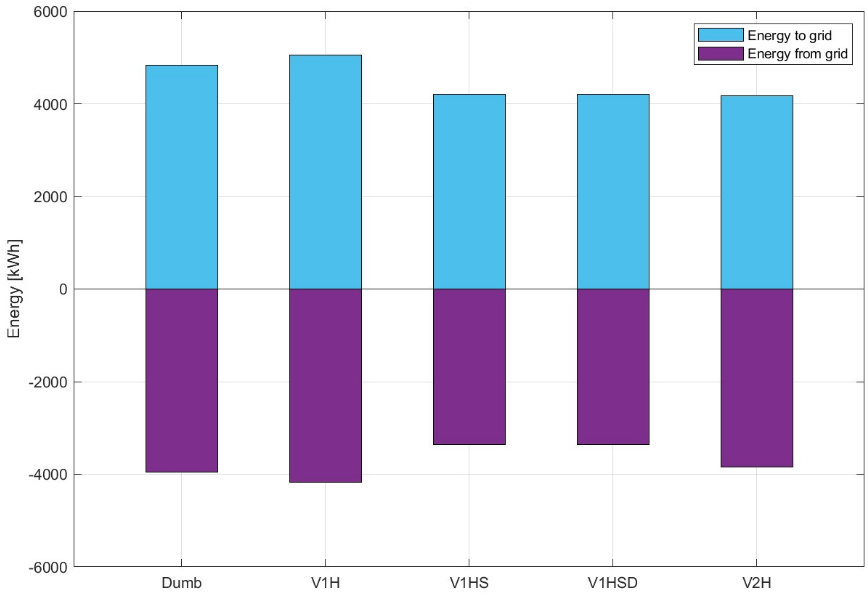

Figure 5.3: Yearly energy flows to and from the grid for the five controllers.

It is seen that the export of PV power is slightly higher than the necessary import of energy from the grid to the EV and household in all cases. Hence, on a yearly basis the total PV production has the potential to cover both EV and household consumption. The interaction with the grid in both directions decreases for the last three cases compared to the first two, which results in an expected increase in self-consumption. As more PV production is used to charge the EV, the percentage of PV production used locally increases, which increases self-consumption as illustrated in Figure 5.4.

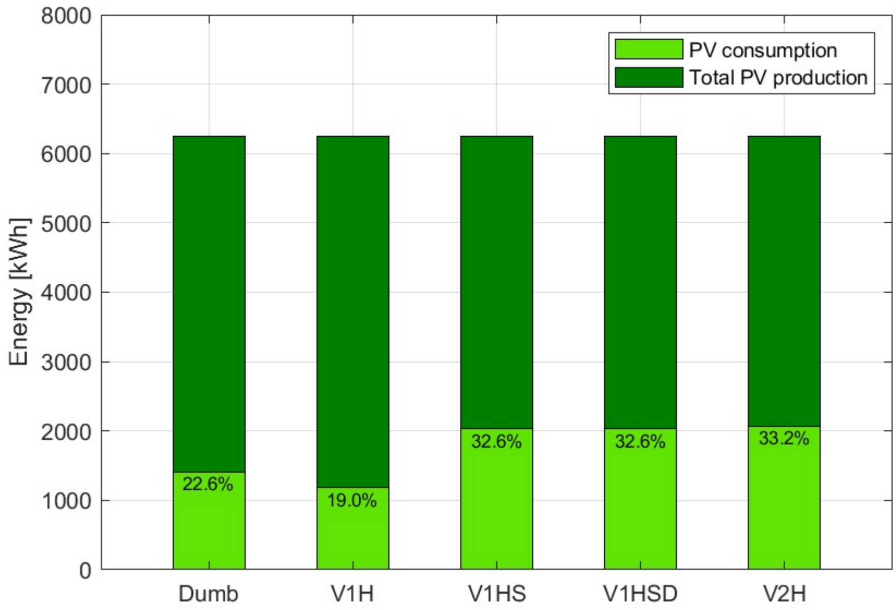

Figure 5.4: Yearly self-consumption ratios for the five different controllers. The numbers in the light green bar indicate the self-consumption.

It is seen that the self-consumption of the household increases from 19.0% to 33.2% as seen between V1H and V2H. V1H has the lowest self-consumption as solar power is only used to cover household consumption, and not to charge the EV. V2H is seen to have the highest level of self-consumption, which is slightly higher than V1HS and V1HSD. V2H's additional discharge allows for more sun to be used to charge the EV from a lower SOC, slightly increasing the overall self-consumption.

A similar metric used to measure the amount of consumption covered by PV production is the overall self-sufficiency of the system [25], which is shown for the five cases in Figure 5.5.

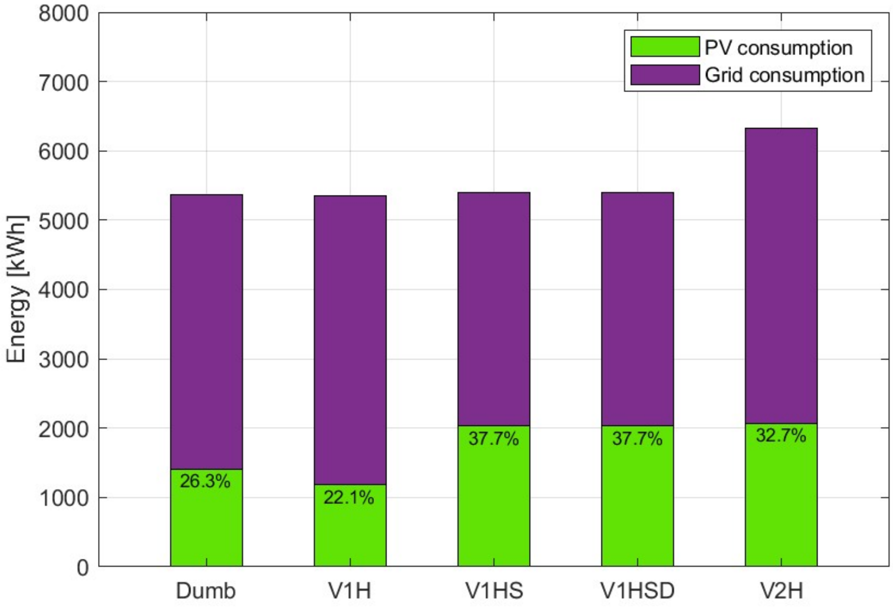

Figure 5.5: Yearly self-sufficiency ratios for the five different controllers. The numbers in the green bar indicate the self-sufficiency.

By allowing the EV to charge with PV production, the yearly self-sufficiency increased by 15.6 percentage points from V1H to V1HS. This increase is attributed to the EV charging in the afternoons, when it returns home from work and on Sundays and has a big positive impact on the overall system. However, the self-sufficiency is seen to decrease when discharge is introduced in V2H, despite the overall increase in PV usage. This is a result of the subsequent increase in overall grid consumption from 3360 kWh in V1HSD to 3842 kWh in V2H. Higher grid consumption is a negative consequence of discharging into the system. The key results from the simulated system with each controller are summarized in Table 5.1.

Table 5.1: Yearly technical performance data for the five controllers.

	Dumb	V1H	V1HS	V1HSD	V2H
Household consumption [kWh]	2296	2296	2296	2296	2296
of which from PV [kWh]	1185	1185	1185	1185	1185
of which from grid [kWh]	1111	1111	1111	1111	693
of which from EV [kWh]	0	0	0	0	417
EV consumption [kWh]	3064	3056	3099	3099	4034
of which from PV [kWh]	227	0	850	850	885
of which from grid [kWh]	2837	3056	2249	2249	3149
Total consumption [kWh]	5360	5351	5394	5394	6329
Self-consumption [%]	22.6	19.0	32.6	32.6	33.2
Self-sufficiency [%]	26.3	22.1	37.7	37.7	32.7
Total energy loss [kWh]	61	61	104	104	626
Total energy to grid [kWh]	4829	5056	4207	4207	4171
Total energy from grid [kWh]	3948	4166	3360	3360	3842
Total energy throughput [kWh]	5997	5989	5989	5989	7825
Number of battery cycles	48	48	48	48	63
Average SOC [%]	82.4	78.4	76.5	74.9	75.2

The controllers can be analyzed based on the total energy loss in the system, as this is an indicator of the overall efficiency of the system. The total energy loss is seen to be lowest in the first two cases, where the EV always charges at a maximum power of 11 kW and thus at higher efficiencies. When excess PV production is used to charge the EV in V1HS, the energy loss increases, due to the lower charging power from the PV, which have an associated lower efficiency as seen in Section 3.1.1. The total energy loss increased by 500% between V1HSD and V2H. This is likely due to the low energy consumption of the household that require discharge at low power values, as well as, the subsequent losses associated with having energy flow to and from the battery.

The performance of the different controllers can also be evaluated based on the potential impact they have on the electric vehicles battery health. As mentioned, this can be assessed by looking at the number of cycles and the average state of charge. The first four cases are seen to have the same number of cycles, however the SOC decreases between each of the cases. Therefore, the battery health is improved when the charging time is shifted from 17 to 24 and again when PV is introduced into the system, as the urgent charging time between Saturday and Sunday is removed, thus reducing the time the cars battery is idle at full charge. The average SOC decreased further by approximately 1.6 percentage points as a result of shifting the urgent charging time from 24 in V1HS to 04 in V1HSD. This shows that charging the EV as close to the driving time as possible, had the desired positive effect on battery health.

Table 5.1 also shows that the number of cycles increased from 48 cycles in the first four cases to 63 cycles in V2H. This increase of 15 cycles is relatively insignificant, as the EV acted as a battery in V2H. The increase in overall number of cycles is quite small compared to most conventional home battery systems, that cycles once a day, equivalent to approximately 350 cycles per year [26]. The average SOC in V2H has decreased in comparison to the first three cases and increased by 0.3 percentage points from V1HSD. A lower average SOC is desirable, so V1HSD performs slightly better with regard to this metric.

5.1.2 Economics

In this section, the controllers will be measured based on their economic performance for the prosumer. The yearly earnings and payments were calculated for each of the five controllers, where the payments were divided between the house and the EV and the earnings were determined based on the sale of PV, as seen in Figure 5.6.

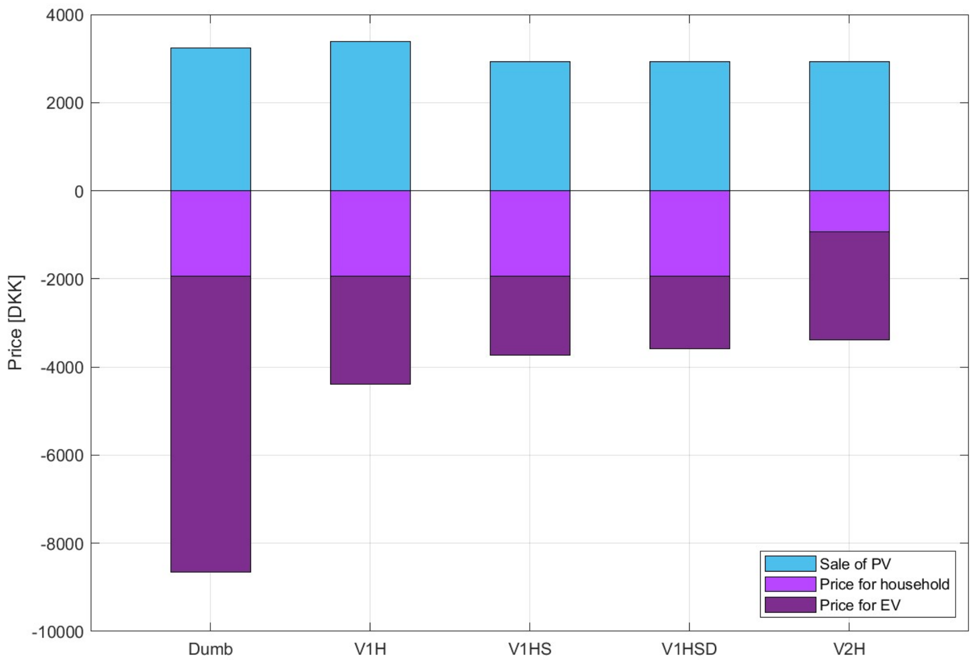

Figure 5.6: Yearly earnings from PV production and yearly payments for household and EV consumption.

It is seen that Dumb is the most expensive controller to have implemented, due to its charging of the EV during peak tariff hours. The remaining four cases charge during low tariff hours and are seen to have much lower overall costs for charging the EV. When PV is introduced the charging cost is reduced even further as the EV requires less energy from the grid. The lowest EV charging cost is seen in V1HSD, which is due to the variable spot price being lower between 4 and 6. In V2H the price of electricity to the household is seen to be reduced as discharge has been implemented. Energy flows through the EV in peak hours, reducing the cost associated with the household. The EV charging costs increased to cover the household consumption, however since charging occurs at low tariff prices, the total cost to the prosumer decreases.

The reduction in cost for household consumption is associated with an avoided cost for the prosumer. The avoided cost of electricity is how much the prosumer would have spent on importing energy from the grid to cover consumption between the hours of 17 and 24, if the EV did not discharge. It was seen that the prosumer would be required to pay 1015 DKK. The avoided cost does not consider the additional charging cost to the EV for the energy discharged in the system and is therefore not the total savings acquired due to discharge.

The yearly economic values for each case can be seen in Table 5.2.

Table 5.2: Yearly economic data for the five controllers.

	Dumb	V1H	V1HS	V1HSD	V2H
Total payment [DKK]	8661	4400	3723	3580	3382
Of which to house [DKK]	1946	1946	1946	1946	931
Of which to EV [DKK]	6715	2454	1777	1634	2451
Sale of PV [DKK]	3236	3387	2933	2933	2923
Total electricity bill [DKK]	5425	1012	790	647	458

The table shows that each controller performs better than the previous one, with the highest total electricity bill in Dumb and lowest in V2H. However, the largest savings on the total electricity bill occur between Dumb and V1H, where shifting the charging time from peak tariff hours to low tariff hours results in an estimated savings of 4413 DKK per year. Therefore, there is potential for all EV owners to save money by simply changing the charging time from when the EV arrives home to 00 when tariff prices are lowest.

It is also interesting to see that switching from a uni-directional charger to a bi-directional charger has minimal impact on the overall electricity bill, with the prosumer saving 189 DKK per year. Therefore, for a bi-directional charger to be more economically viable than an uni-directional charger over a 10 year expected lifetime [27], the bi-directional charger must only cost 1890 DKK more than a uni-directional charger.

5.2 Impact of Alternative Driving Pattern

As mentioned in Section 2.3 an alternative driving pattern is investigated. This driving pattern is chosen to better represent prosumers who occasionally work from home or decide to walk or bike to work in nice weather. Prosumers using driving pattern 2 therefore drive 90 km less per week than those using driving pattern 1.

5.2.1 Technical Performance

The overall technical performance of the controllers in driving pattern 2 will be measured in comparison to the performance in driving pattern 1. The biggest difference between the two driving patterns is the reduced driving distance of 90 km per week and the vehicle being home an additional two days with potential for increased use of excess PV power. Since the two days during the week were chosen so that almost every other day is driving, the EV is able to use excess PV the following day instead of power from the grid. The weekly SOC for all cases using this driving pattern can be seen in Appendix A.4. The energy supplied to the EV from PV production, as well as from the grid, is shown in Figure 5.7.

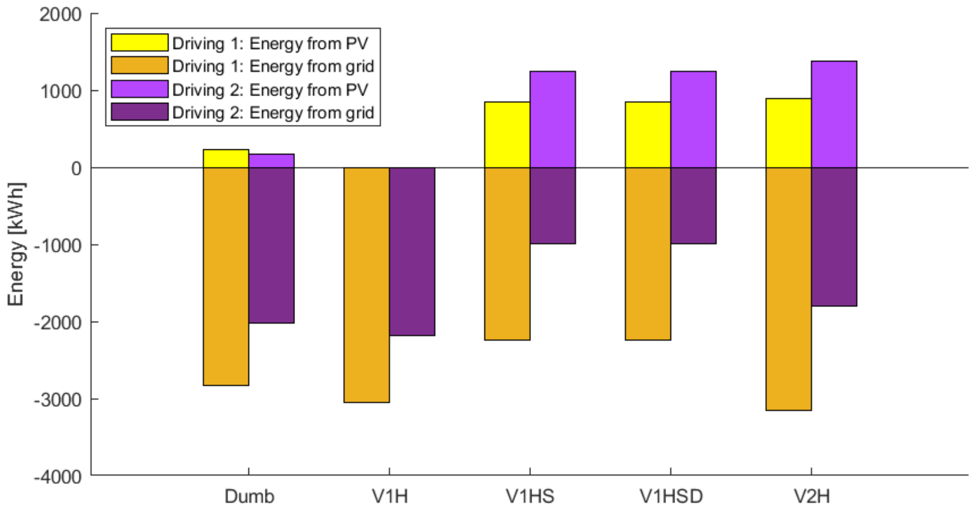

Figure 5.7: Yearly energy supply to the EV from the grid and PV production for the five controllers in driving pattern 1 and 2.

All five cases show a decrease in energy from the grid due to fewer kilometers driven in driving pattern 2. In Dumb the PV usage is seen to decrease slightly, due to less driving days with potential for using PV when the vehicle returns home. However, the last three cases are seen to increase their total PV consumption in driving pattern 2, due to the increased number of days the EV is home and can utilize PV.

This change in PV usage is likely to have a positive effect on both self-consumption as seen in Figure 5.8 and self-sufficiency as seen in Figure 5.9.

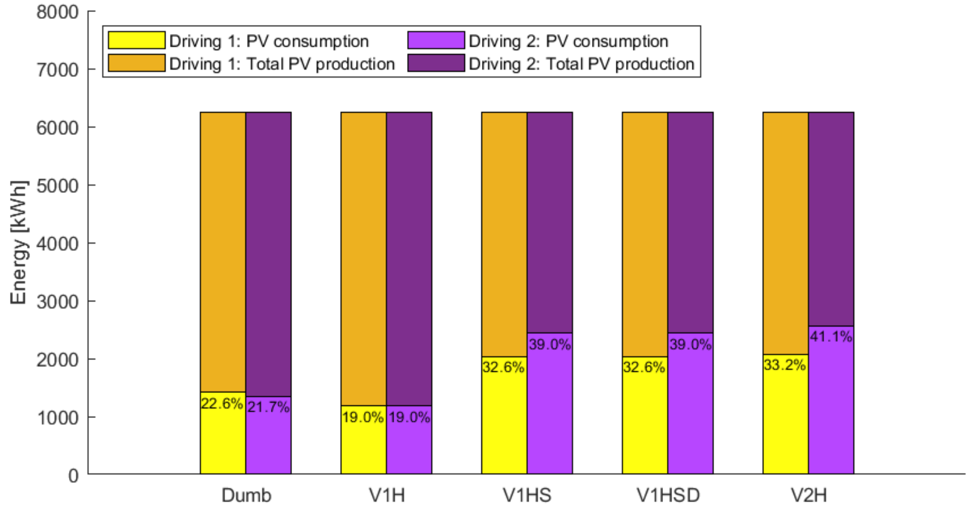

Figure 5.8: Yearly self-consumption ratios for the five controllers in driving pattern 1 and 2.

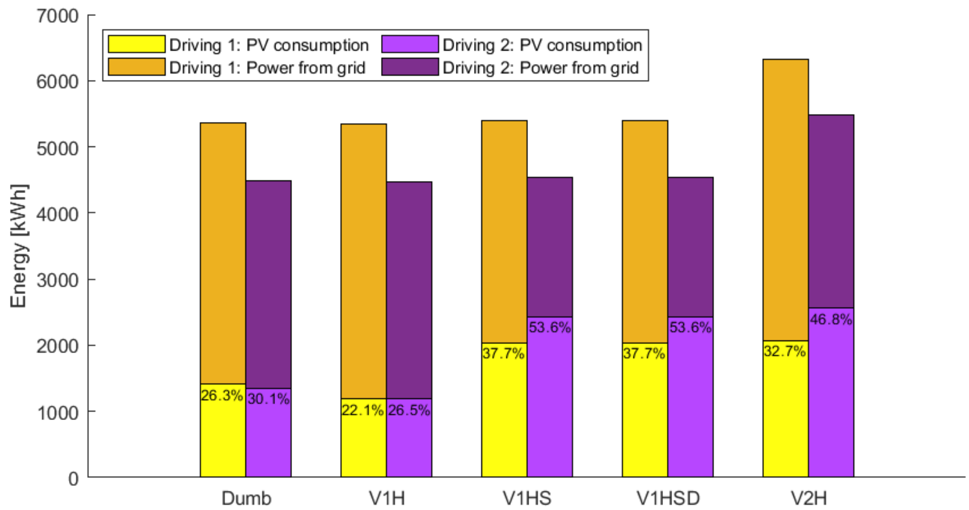

Figure 5.9: Yearly self-sufficiency ratios for the five controllers in driving pattern 1 and 2.

Dumb is seen to have a slightly lower self-consumption, while in V1H the self-consumption remains the same as expected since no PV is utilized for EV charging in either driving pattern. However, the self-sufficiency is seen to increase slightly in both these cases, due to the reduced EV consumption.

In the three remaining cases both self-consumption and self-sufficiency are seen to increase drastically from driving pattern 1 to driving pattern 2, as expected. The self-consumption is increased by 6.4 percentage points in V1HS and V1HSD, while the self-sufficiency increased by 15.9 percentage points, allowing the prosumer to be over 50% self-sufficient in driving pattern 2. V2H has a higher increase in self-consumption at 7.9 percentage points, due to discharge, which allows the EV to use more of the total PV production. The increase in self-sufficiency is lower than in V1HS and V1SHD, at 14.1 percentage points, as the EV has a higher energy loss in V2H and requires more energy import from the grid.

The increased use of PV in driving pattern 2 has had a negative impact on the energy loss. This is due to the smart charger being less efficient at lower power values and PV production often being provided at power values below 3 kW, and thus an efficiency of below 97.3%, compared to 98.0% at 11 kW as seen in Section 3.1.1. Thus, the more energy provided by PV production, the higher the energy loss. However, the absolute energy loss is not seen to increase in driving pattern 2 due to the decrease in total EV consumption (See Appendix A.4). Therefore, the energy loss relative to the total EV consumption is calculated for the two driving patterns and shown in Table 5.3

Table 5.3: Percentage energy loss relative to total EV consumption for the five controllers in driving pattern 1 and 2.

	Dumb	V1H	V1HS	V1HSD	V2H
Driving Pattern 1 Percentage Energy Loss of EV Consumption [%]	2	2	3	3	16
Driving Pattern 2 Percentage Energy Loss of EV Consumption [%]	2	2	5	5	20

The table shows that in Dumb and V1H, the relative energy loss is not changed, due to these controllers continued use of 11 kW to charge the EV. However, the last three cases utilize more sunlight for charging in driving pattern 2 and therefore have a slightly increased relative energy loss associated with them. V2H has the highest consumption of PV production, as seen in Figure 5.7, which is also reflected in the increased energy loss of 4 percentage points between the two driving patterns. The higher energy loss has a negative effect on the efficiency of the system compared to driving pattern 1.

The performance of driving pattern 2 can also be evaluated based on its effect on the EV's battery health. Here, the number of cycles can be consider. The number of days the vehicle drives is reduced from six days in driving pattern 1 to four days in driving pattern 2, and so it is expected that the energy throughput of the battery will be reduced, and hence the number of cycles as well. These results are seen in Table 5.4.

Table 5.4: Yearly battery performance data for the five controllers in driving pattern 2.

	Dumb	V1H	V1HS	V1HSD	V2H
Total energy throughput [kWh]	4279	4271	4271	4271	6107
Number of battery cycles	35	34	34	34	49
Average SOC [%]	83.1	80.3	76.1	75.4	74

It is seen that the yearly number of battery cycles decreases by 14 cycles for all five cases from driving pattern 1 to driving pattern 2.

Table 5.4 also shows the average SOC, which is the other factor affecting battery health. Similar to number of cycles, it is desirable to have lower values. In Dumb, V1H and V1HSD the average SOC is seen to increase with 0.7, 1.8 and 0.5 percentage points, respectively. In Dumb and V1H this increase is attributed to the vehicle charging either when it returns home or the night after driving, so the EV will be home for an additional day with a fully charged battery. In driving pattern 1, for V1HSD, the vehicle charges using PV production when it returns home and then right before driving, but in driving pattern 2 it also charges using PV production during the following day, resulting in the vehicle having a higher SOC before urgent charging commences before the next driving day. V1HS experiences a decrease in average SOC by 0.4 percentage points, whereas V2H sees a 1.3 percentage point decrease, which is beneficial for the prosumer. These decreases are a result of not charging the night between driving days and non driving days, resulting in a lower SOC until PV charging the following day and grid charging at night, which is beneficial for the battery health.

5.2.2 Economics

For prosumers it is often more profitable to use the energy they produce themselves instead of selling it. This is due to the price difference between selling PV energy at only the spot price and purchasing energy at the combined spot, tariff and VAT price, as described in Section 2.2. This is also reflected in the economics of driving pattern 2, shown in Figure 5.10.

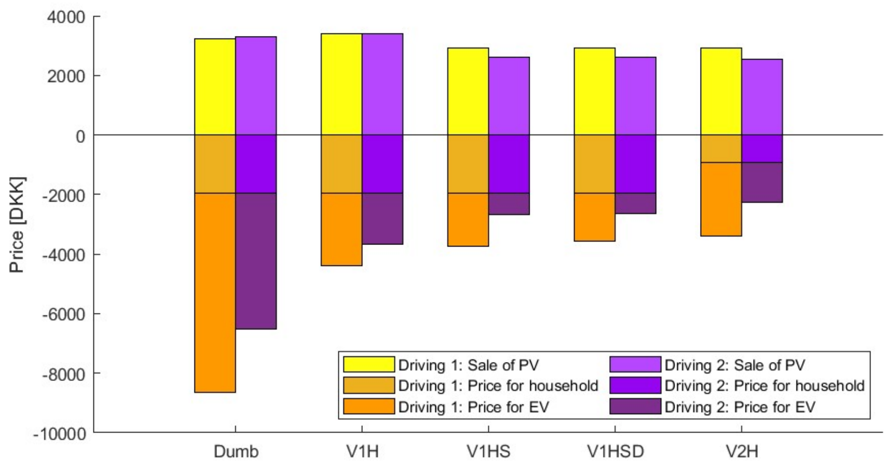

Figure 5.10: Yearly earnings from PV production and payments for household and EV consumption for driving pattern 1 and 2.

The figure illustrates that the overall payment for household consumption is unaffected by the change in driving pattern, whereas the payment for EV consumption is seen to decrease in driving pattern 2 for all five cases, due to the decreased weekly driving distance. The sale of PV is also seen to decrease in the last three cases, however marginally less than the reduction in payment for EV consumption. The yearly economic values for driving pattern 2 can be seen in Table 5.5, to further understand the economic implications of changing the driving pattern.

Table 5.5: Yearly economic data for the five controllers in driving pattern 2.

	Dumb	V1H	V1HS	V1HSD	V2H
Total Payment [DKK]	6501	3676	2670	2644	2247
of which to household [DKK]	1946	1946	1946	1946	931
of which to EV [DKK]	4555	1730	724	698	1316
Sale of PV [DKK]	3283	3387	2605	2604	2528
Total electricity bill [DKK]	3219	289	66	41	-282

The difference between the decrease in sale of PV and payment for EV consumption is seen clearly when compared in case V2H. In V2H the earnings made from the sale of PV decreased with 396 DKK from driving pattern 1 to driving pattern 2, due to the increase in PV used to charge the EV. However, the payments to the grid to charge the EV where reduced by 1135 DKK, significantly higher than the loss in earnings. This illustrates the effect grid tariffs and VAT have on the purchase price of electricity and the economic benefits to the prosumer that works from home twice a week.

The economic implications of changing the driving pattern are best illustrated by the percentage change in the total electricity bill as seen in Table 5.6.

Table 5.6: Percentage change in total electricity bill between driving pattern 1 and 2.

	Dumb	V1H	V1HS	V1HSD	V2H
Total electricity bill change [%]	-40.7	-71.4	-91.6	-93.7	-161.6

Dumb has the smallest improvement in total electricity bill with a 40% reduction, while V1H has a 71% reduction, both due to the decreased overall charging needs. V1HS and V1HSD have a 92% and 94% decrease in the total electricity bill respectively, due to the increased use in PV production to charge the EV. The biggest economic improvement between driving pattern 1 and 2 is seen in V2H, where the total electricity bill is reduced by 162%. This has resulted in the total price for energy consumption of the household and EV being covered by the sale of PV production from the household and yields a profit of 282 DKK.

5.3 Sensitivity Analysis on Charger Size

In this section a sensitivity analysis on the size of the smart charger will be performed. The motivation behind this analysis is based on the findings in Section 3.1.1, where the power differences were seen to lie far below 11 kW and therefore a smaller charger may perform equally well in the different cases. As smaller chargers are often cheaper to purchase, it is of interest to determine whether an 11 kW charger is necessary or a 3 kW or 6 kW charger is just as proficient.

5.3.1 Technical Performance

The technical performance of the controllers will first be evaluated by comparing the self-consumption of the system for driving pattern 1 with different charger sizes for each of the five controllers as seen in Figure 5.11.

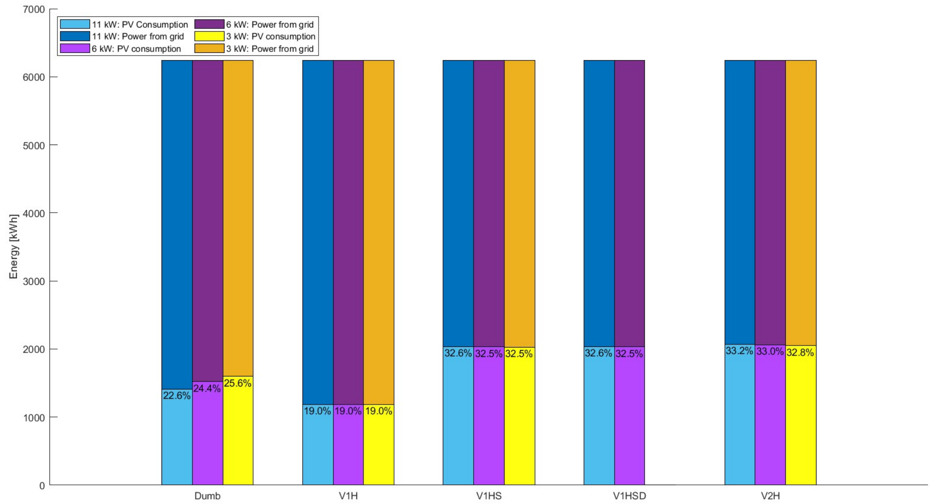

Figure 5.11: Yearly self-consumption rations for the three charger sizes in all five controllers.

The 3 kW smart charger is insufficient for fully charging the battery in V1HSD, due to the small charging window of only 2 hours, see the yearly SOC in Appendix A.5. Therefore no values for self-consumption are present in the figure for this case and charger size. The results show that a smaller charger size has very little effect on the self-consumption of the system, but is seen to improve it in Dumb. A smaller charger is seen to perform equally well regarding the self-consumption metric.

Another aspect of interest is the overall self-sufficiency of the household for different charger sizes, shown in Figure 5.12.

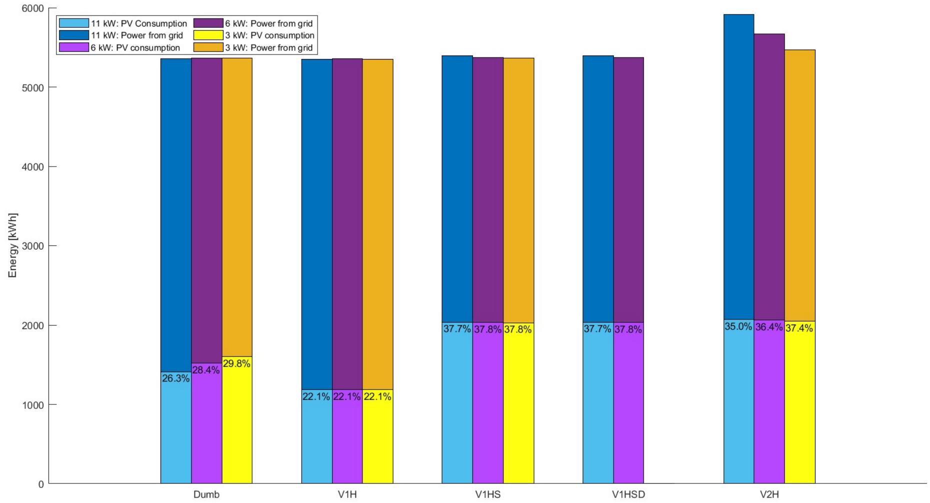

Figure 5.12: Yearly self-sufficiency rations for the three charger sizes in all five controllers.

The self-sufficiency is also seen to only vary slightly for the three charger sizes in the first four cases. However, in V2H the overall necessary power from the grid is seen to decrease as the charger size decreases, thus increasing the overall self-sufficiency of the household. It is therefore chosen to further analyze the effect charger sizes has on the discharge scenario V2H.

The results for V2H for the three charger sizes are summarized in Table 5.7.

Table 5.7: Yearly technical performance data for the 11 kW, 6 kW and 3 kW chargers for V2H in driving pattern 1.

	11 kW Charger	6 kW Charger	3 kW Charger
Household Consumption [kWh]	2295	2295	2295
of which from PV [kW]	1185	1185	1185
of which from Grid [kWh]	693	643	642
of which from EV [kWh]	417	468	469
EV Consumption [kWh]	4034	3844	3642
of which from PV [kWh]	885	878	862
of which from Grid [kWh]	3149	2966	2780
Total Consumption [kWh]	6329	6139	5938
Self-consumption [%]	33.2	33.1	32.8
Self-sufficiency [%]	32.7	33.6	34.5
Total Energy Loss [kWh]	626	385	181
Total Energy to Grid [kWh]	4171	4178	4194
Total Energy from Grid [kWh]	3842	3609	3422
Total Energy Throughput [kWh]	7825	7495	7115
Number of Battery Cycles	63	60	57
Average SOC [%]	75.2	75.3	74.9

One of the metrics that is seen to differ for the three charger sizes is the total energy loss in the system. It is seen to be largest for a charger size of 11 kW and be reduced by 38% to the 6 kW charger and by 71% to the 3 kW charger. This is due to the efficiencies being higher at lower absolute power levels for the smaller chargers as seen in Figure 3.6. As the majority of the discharge capabilities occur at very low power levels the smaller chargers become more advantageous for the overall loss in the system. This is also reflected by the energy converted from the EV to the household increasing for the smaller chargers.

Another metric of interest is the number of battery cycles and average SOC measured in the three scenarios. The number of battery cycles are seen to be reduced from 63 for the 11 kW charger to 57 in the 3 kW charger. There is only seen a change in battery cycles in V2H, as this is due to the EV discharging more efficiently with the 3 kW charger. In the other four cases the number of cycles remains constant at 48 (see Appendix A.6). Thus, reducing the number of cycles for the 3 kW charger makes V2H more competitive with the remaining four cases with regard to this metric, as a lower number of battery cycles is preferred. The average SOC varies slightly for the three charger sizes with the highest being for the 6 kW charger, 0.1 percentage points higher than the 11 kW charger and the lowest being for the 3 kW charger, 0.3 percentage points lower than the 11 kW charger.

A similar analysis is done for driving pattern 2 where it is concluded that the tendencies between charger sizes are similar to those found for driving pattern 1. For a detailed results summary see Appendix A.6.

5.3.2 Economics

In this section the economic differences resulting from the different charger sizes will be analyzed. The results can be seen in Table 5.8.

Table 5.8: Total electricity bill for the three charger sizes for the five controllers.

	11 kW Charger	6 kW Charger	3 kW Charger
Dumb [DKK]	5425	5627	5637
V1H [DKK]	1012	947	843
V1HS [DKK]	790	755	699
V1HSD [DKK]	647	678	-
V2H [DKK]	458	207	-2

The total electricity bill is seen to vary slightly between cases, with the tendency for the total price to decrease with charger size in V1H, V1HS and V2H. The best economic output is for the 3 kW charger in V2H, with a change of 460 DKK per year from the 11 kW charger, creating a surplus of 2 DKK each year. Because of the 460 DKK increase the prosumer will be able to cover both household consumption and the charging of the EV and still have a surplus of 2 DKK. It is also noted that smaller chargers are less expensive, so by choosing a 3 kW charger the prosumer is expected to gain an additional saving in comparison to, if the 11 kW charger was purchased.

The avoided cost, shown in Appendix A.13, was also seen to increase for each of the charger sizes, as the smaller chargers allowed for smaller consumption power values to be covered. Using the 11 kW smart charger the avoided cost was 1015 DKK which increased to 1095 DKK when using a 3 kW smart charger.

Driving pattern 2 yields similar economic results, where the total electricity bill is seen to increase from a profit of 282 DKK for the 11 kW charger to a profit of 674 DKK for the 3 kW charger in V2H. For a detailed results summary see Appendix A.7.

6 Conclusion

6.1 Summary

This bachelor thesis investigated how a prosumer's system can benefit from different smart charging strategies. Each strategy was developed using heuristic controls, determined by different motivations from either a technical or economic perspective. The five cases also built on the previous scenarios to some degree and are as follows:

- Dumb: Charging from 17-24.
- V1H: Charging from 24-06 when tariffs are low.
- V1HS: Charging from 24-06 or when there is excess PV.
- V1HSD: Charging from 04-06 or when there is excess PV aiming at reduced battery degradation.
- V2H: Charging from 24-06 or when there is excess PV and discharging from 17-24 to cover household consumption.

All five cases were assessed on both technical performance and economics, using a techno-economic approach.

The controllers were first evaluated in comparison to one another, with the simulations performed for driving pattern 1 and an 11 kW smart charger. V1HSD was found to perform technically well with a high self-consumption and self-sufficiency, at 32.6% and 32.7% respectively. V1HSD also has the lowest average SOC of the five controllers at 74.9%. From the uni-directional case V1HSD to the bi-directional case V2H, the self-consumption was seen to increase by 0.6 percentage points, while the self-sufficiency decreased by 5 percentage points, due to the increased import of energy from the grid.

The economic perspective yields different results for the controllers. The biggest change in the total electricity bill is seen in the shift from Dumb to V1H, where smart charging is implemented with a subsequent price reduction of 4400 DKK. This shows the significant benefits of utilizing a smart charger to regulate charging at lower tariff prices. The most profitable case is seen to be V2H, where the yearly cost is 458 DKK. This is an additional savings of 189 DKK from the cheapest uni-directional case V1HSD. Therefore, for the bi-directional charger to be profitable for a prosumer over a 10 year period it can only cost 1890 DKK more than a uni-directional charger.

To understand the impact of prosumer behavior a second driving pattern was created, in which the prosumer drives two days less, with a saved distance of 90 km per week. This allowed the EV to utilize more PV power for charging. Dumb and V1H do not consider PV and always charge at maximum charging power so their overall performance was relatively unaffected by the change in driving pattern. However, in the last three cases the self-consumption and self-sufficiency increased significantly. In V2H the self-consumption increased by 7.9 percentage points and self-sufficiency increased by 14.1 percentage points from driving pattern 1. The average SOC also decreased slightly improving battery health in this scenario. This increase in performance is also seen in the economic outcomes for driving pattern 2. The total electricity bill was seen to decrease significantly for all five cases and earned the prosumer a profit of 282 DKK in case V2H. This is significant, as it implies that the prosumer is able to cover the cost of all household and EV consumption with the money earned from selling excess PV power.

Lastly, a sensitivity analysis on the size of the smart charger was performed. This analysis was motivated by the majority of energy differences in PV production and household consumption lying between -3 kW and 3 kW, and the lower cost of smaller chargers. A 6 kW and 3 kW charger were chosen for the investigation. The charger size had the biggest impact in V2H, due to much of the discharge into the household occurring at low power values. The controller performance was improved as the smart charger decreased in size. The energy loss from the 11 kW charger was seen to decrease by 38% to the 6 kW charger and by 71% to the 3 kW charger. This decrease in energy loss is also reflected in the economic values for the V2H case. The total electricity bill was seen to decrease as the charger size decreased, with a total savings of 460 DKK per year when choosing a 3 kW charger over an 11 kW charger. The 3 kW charger also yielded a profit of 2 DKK, allowing for prosumers who drive six days a week to cover all consumption costs with the sale of PV.

6.2 Perspectives for Future Research

Based on the results obtained in this thesis, further investigations into several topics could be of interest to better understand how electric vehicles can be used in the future.

Alternative charging strategies could be explored. The charging strategies in this thesis were based on a set of heuristic rules. However, as 24-hour ahead electricity prices are published daily, it could be interesting to develop an optimization algorithm that could be used to determine when it is best to charge and discharge the EV. This would likely increase the economic performance as decisions would be based on the total electricity price and not just grid tariffs.

Another study could be done into the effects of average SOC and number of battery cycles has on battery health and the implications it has for the results found in this thesis and the future of bi-directional charging.

Furthermore, the results found in this investigation can be expanded to a larger scale by looking at the use of vehicle to grid applications in communities. When used in vehicle-to-grid applications, electric vehicles have the potential to be used as energy storage to regulate fluctuations in the energy grid as more renewable energy sources are coupled to the energy mix.

Bibliography

[1] United Nations Climate Change. *The Paris Agreement*. Last accessed 04 June 2023. URL: https://unfccc.int/process-and-meetings/the-paris-agreement.

[2] Tatiana Gabderakhmanova et al. *Demonstrations of DC Microgrid and Virtual Power Plant Technologies on the Danish Island of Bornholm*. 2020. DOI: 10.1109/upec49904.2020.9209853.

[3] Energinet. *2022 sætter dansk rekord i vind og sol*. Last accessed 10 June 2023. 2022. URL: https://via.ritzau.dk/pressemeddelelse/2022-saetter-dansk-rekord-i-vind-og-sol?publisherId=10304728&releaseId=13667585.

[4] Energistyrelsen. *Dansk klimapolitik*. Last accessed 04 June 2023. URL: https://ens.dk/ansvarsomraader/energi-klimapolitik/fakta-om-dansk-energi-klimapolitik/dansk-klimapolitik.

[5] Thomas Jensen. *Socialdemokratiets transportordfører: Regeringen sætter barren højt for grøn omstilling af transporten*. Last accessed 04 June 2023. 2023. URL: https://www.altinget.dk/transport/artikel/socialdemokratiets-transportordfoerer-dansk-indenrigsflyvning-skal-vaere-helt-groen-i-2030.

[6] Jan Engelhardt et al. "Double-String Battery System with Reconfigurable Cell Topology Operated as a Fast Charging Station for Electric Vehicles". In: *Energies* 14.9 (2021), p. 2414. ISSN: 1996-1073. DOI: 10.3390/en14092414.

[7] Jan Engelhardt et al. "Energy management of a multi-battery system for renewable-based high power EV charging". In: *eTransportation* 14 (2022), p. 100198. DOI: https://doi.org/10.1016/j.etran.2022.100198.

[8] Jan Engelhardt. "Reconfigurable Batteries in Electric Vehicle Fast Chargers: Towards Renewable-Powered Mobility". PhD thesis. Technical University of Denmark, 2022. DOI: 10.11581/DTU.00000254.

[9] Lisa Calearo et al. "Comparison of Reconfigurable BESS and Direct Grid Installation for EV Fast-Chargers: a Danish Case Study". In: *2022 International Conference on Renewable Energies and Smart Technologies (REST)*. Vol. I. 2022, pp. 1–5. DOI: 10.1109/REST54687.2022.10022505.

[10] Mads Bregenov-Pedersen. *Snart stiger strømprisen endnu mere – se hvorfor*. Last accessed 09 June 2023. 2022. URL: https://fdm.dk/nyheder/bilist/2022-09-snart-stiger-stroemprisen-endnu-mere-se-hvorfor.

[11] Mari Halldis Tveit et al. "Behind-the-Meter Residential Electric Vehicle Smart Charging Strategies: Danish Cases". In: *2022 International Conference on Renewable Energies and Smart Technologies (REST)*. Vol. I. 2022, pp. 1–5. DOI: 10.1109/REST54687.2022.10022910.

[12] Charalampos Ziras, Lisa Calearo, and Mattia Marinelli. *The effect of net metering methods on prosumer energy settlements*. en. 2021. DOI: 10.1016/j.segan.2021.100519.

[13] Stine Bülow and Thea Hein Petersen. "A techno-economic assessment of implementing an electric vehicle and stationary storage to increase the domestic self-consumption of a prosumer with photovoltaic installation". MA thesis. Technical University of Denmark (DTU), 2020.

[14] Mattia Marinelli, Lisa Calearo, and Jan Engelhardt. “A Simplified Electric Vehicle Battery Degradation Model Validated with the Nissan LEAF e-plus 62-kWh”. English. In: *Proceedings of 6th International Electric Vehicle Technology Conference*. 2023.

[15] Mattia Marinelli et al. “Electrical Thermal and Degradation Measurements of the LEAF e-plus 62-kWh Battery Pack”. English. In: *Proceedings of 2022 International Conference on Renewable Energies and Smart Technologies*. United States: IEEE, 2023. DOI: 10.1109/REST54687.2022.10023130.

[16] Nord Pool. *Day Ahead Prices*. Last accessed 03 May 2023. 2023. URL: https://www.nordpoolgroup.com/en/Market-data1/Dayahead/Area-Prices/DK/Yearly/?view=table.

[17] Cerius. *Tariffer og netabonnement*. Last accessed 29 May 2023. 2023. URL: https://cerius.dk/priser-og-tariffer/tariffer-og-netabonnement/.

[18] Aidan Bowen et al. “Battery Buffered EV Fast Chargers on Bornholm: Charging Patterns and Grid Integration”. In: *2022 57th International Universities Power Engineering Conference (UPEC)*. 2022, pp. 1–6. DOI: 10.1109/UPEC55022.2022.9917690.

[19] Andreas Thingvad et al. “Electrification of personal vehicle travels in cities - Quantifying the public charging demand”. In: *eTransportation* 9 (2021), p. 100125. ISSN: 2590-1168. DOI: https://doi.org/10.1016/j.etran.2021.100125. URL: https://www.sciencedirect.com/science/article/pii/S2590116821000230.

[20] Odysse Mure. *CHANGE IN DISTANCE TRAVELLED BY CAR*. Last accessed 11 June 2023. 2021. URL: https://www.odyssee-mure.eu/publications/efficiency-by-sector/transport/distance-travelled-by-car.html.

[21] Fronius. *Fronius Symo 10.0-3-M*. Last accessed 29 May 2023. 2023. URL: https://www.fronius.com/en/solar-energy/installers-partners/technical-data/all-products/inverters/fronius-symo/fronius-symo-10-0-3-m.

[22] Fronius. *Fronius Symo 3.0-3-M*. Last accessed 29 May 2023. 2023. URL: https://www.fronius.com/en/solar-energy/installers-partners/technical-data/all-products/inverters/fronius-symo/fronius-symo-3-0-3-m.

[23] Fronius. *Fronius Symo 6.0-3-M*. Last accessed 29 May 2023. 2023. URL: https://www.fronius.com/en/solar-energy/installers-partners/technical-data/all-products/inverters/fronius-symo/fronius-symo-6-0-3-m.

[24] Jan Engelhardt et al. “Energy recovery strategies for batteries providing frequency containment reserve in the Nordic power system”. English. In: *Sustainable Energy, Grids and Networks* 32 (2022). ISSN: 2352-4677. DOI: 10.1016/j.segan.2022.100947.

[25] Jan Martin Zepter et al. “Re-Thinking the Definition of Self-Sufficiency in Systems with Energy Storage”. In: *Proceedings of 2022 International Conference on Smart Energy Systems and Technologies (SEST)*. United States: IEEE, 2022. DOI: 10.1109/SEST53650.2022.9898436.

[26] NeoVolta. *NeoVolta Increases Battery Life from 10.95 Years to 16.5 Years*. Last accessed 11 June 2023. 2021. URL: https://www.neovolta.com/neovolta-increases-battery-life-from-10-95-years-to-16-5-years/.

[27] Energy5. *Electric Vehicle Charger Maintenance Basics*. Last accessed 11 June 2023. 2023. URL: https://energy5.com/electric-vehicle-charger-maintenance-basics.

A Appendix

A.1 Simulink model of the physical system

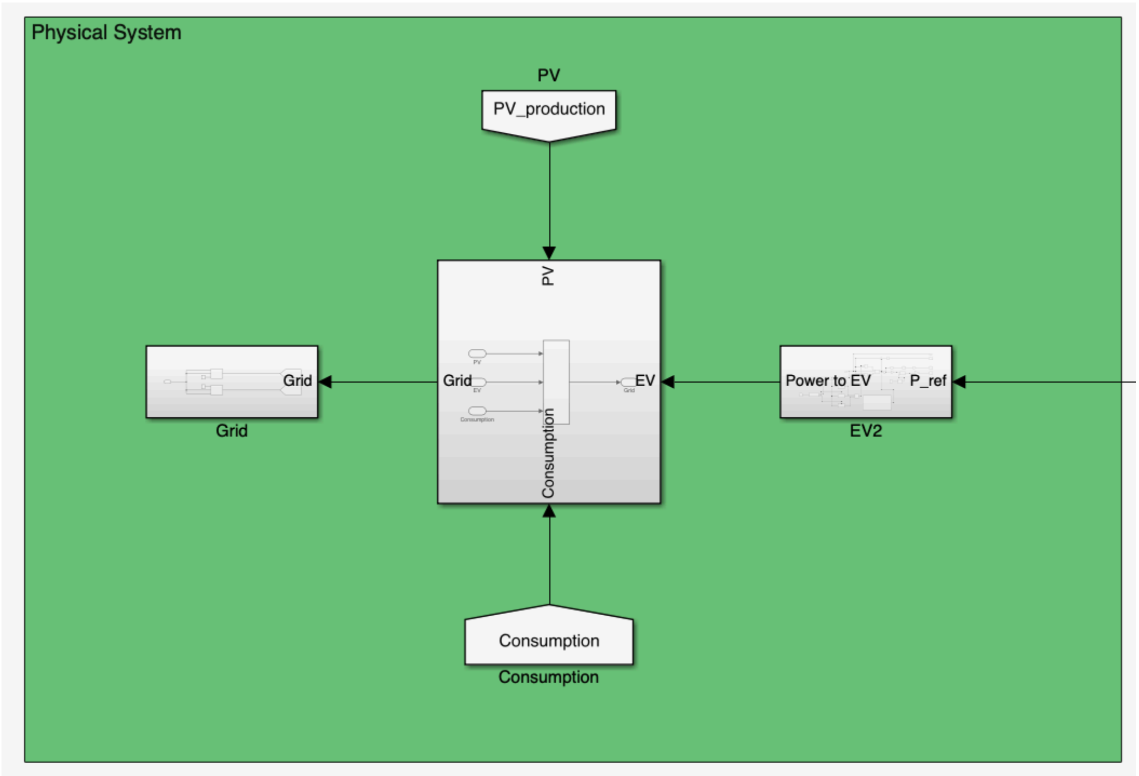

Figure A.1: The modeled physical system in Simulink.

A.2 Simulink models for the five cases

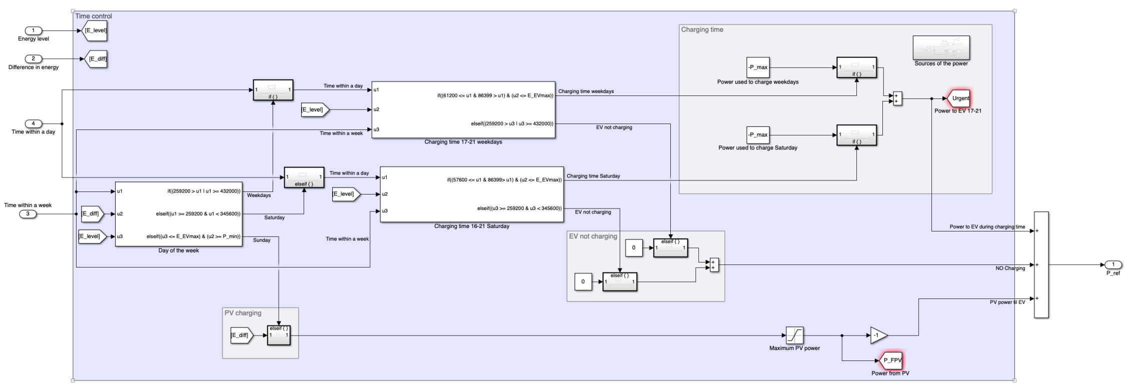

Figure A.2: The model of the controller for case Dumb

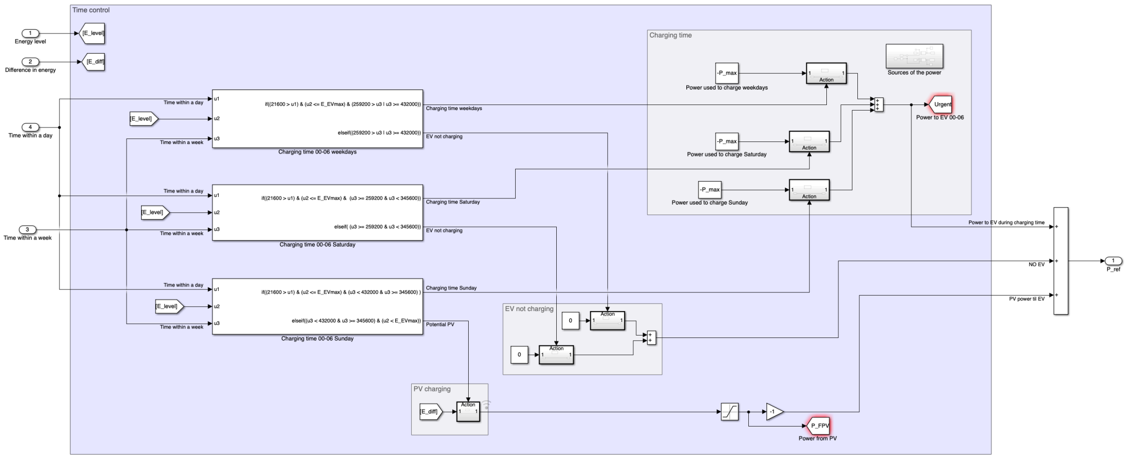

Figure A.3: The model of the controller for case V1H

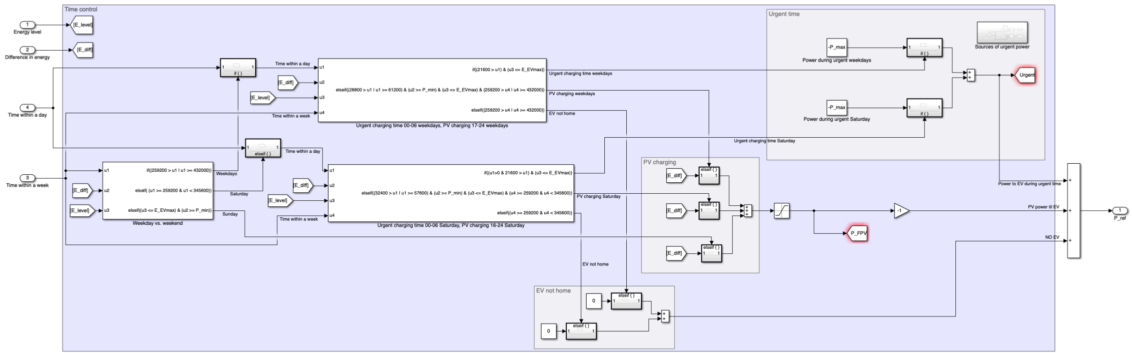

Figure A.4: The model of the controller for case V1HS

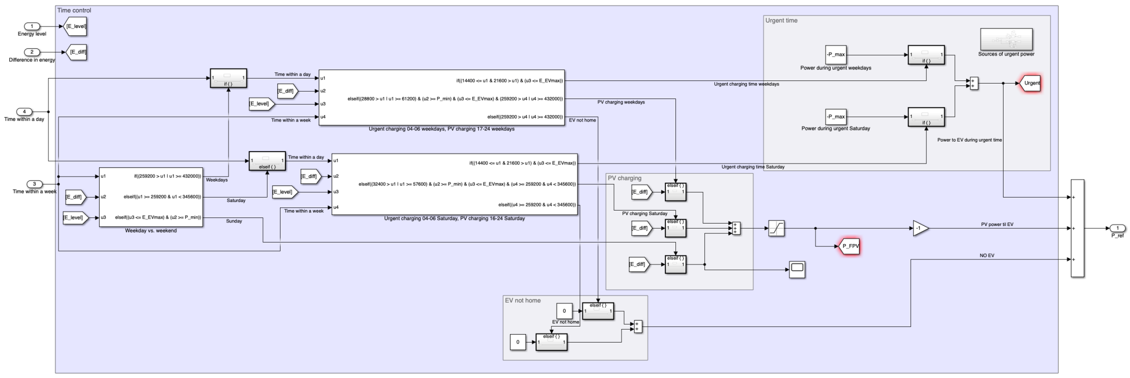

Figure A.5: The model of the controller for case V1HSD

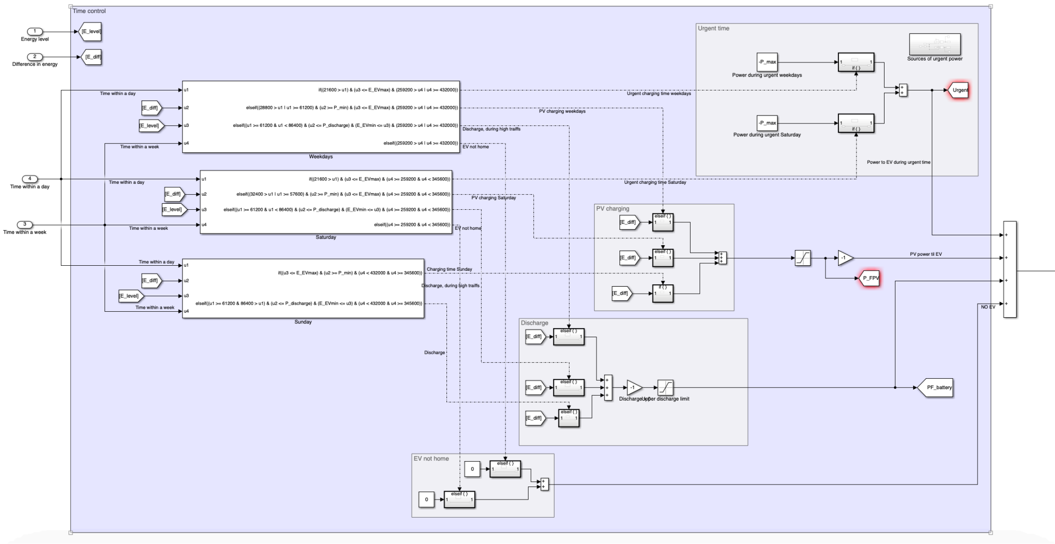

Figure A.6: The model of the controller for case V2H

A.3 Yearly SOC for control algorithms

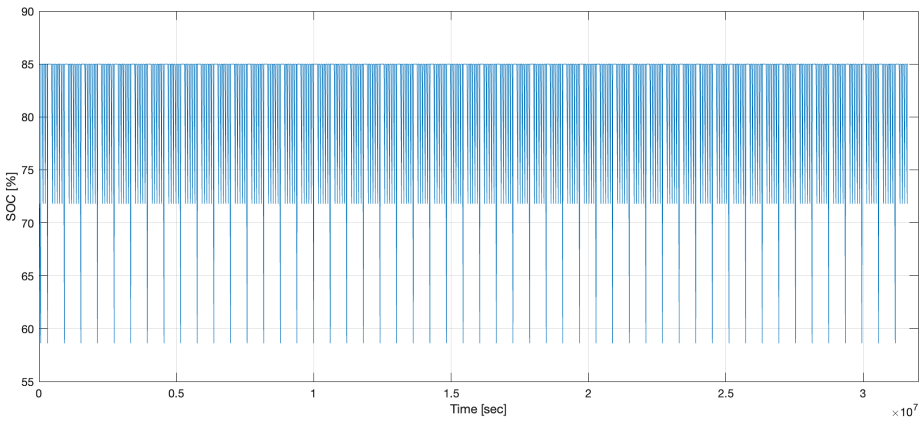

Figure A.7: Yearly SOC for case Dumb using driving pattern 1.

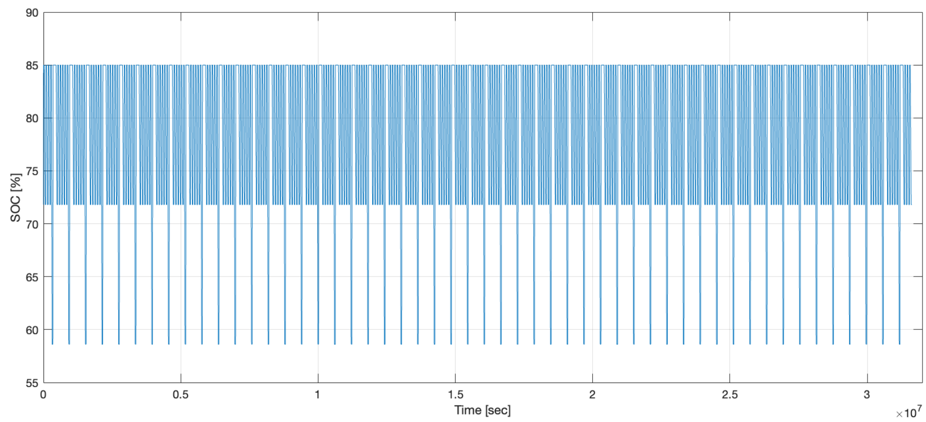

Figure A.8: Yearly SOC for case V1H using driving pattern 1.

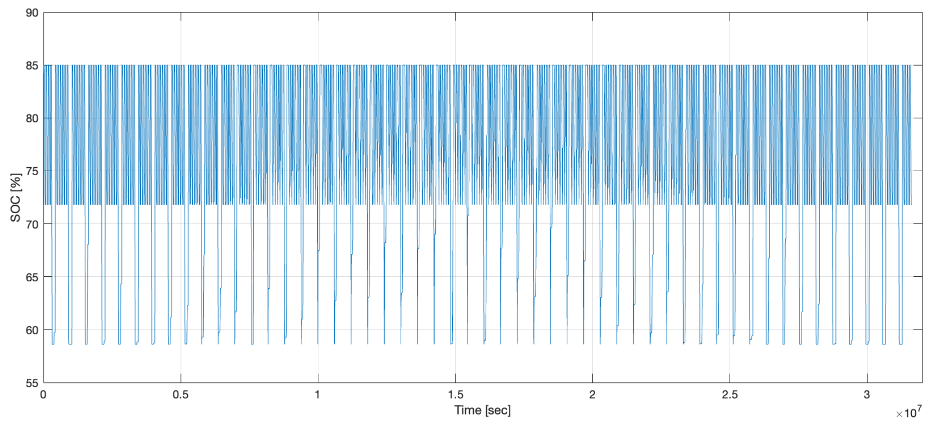

Figure A.9: Yearly SOC for case V1HS using driving pattern 1.

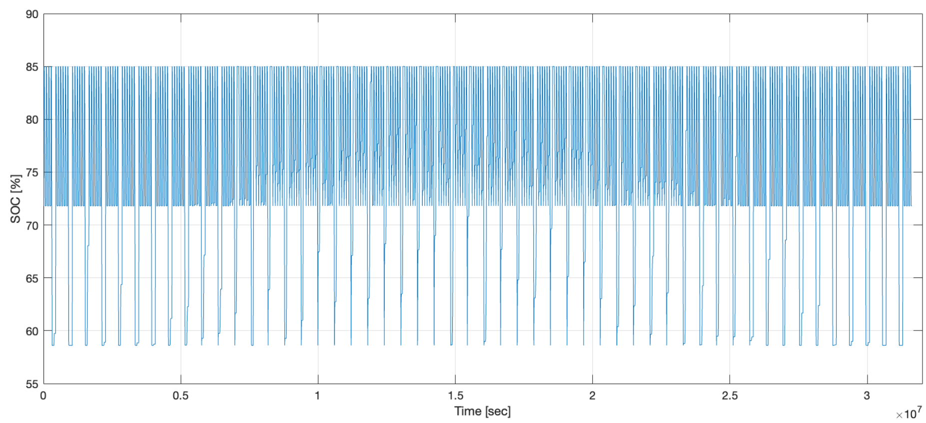

Figure A.10: Yearly SOC for case V1HSD using driving pattern 1.

A.4 SOC for Week 29 for control algorithm using driving pattern 2

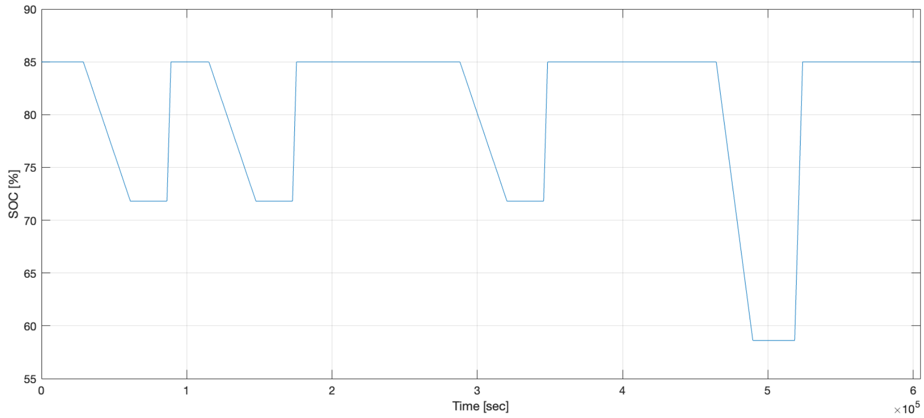

Figure A.11: SOC for case Dumb using a charger size of 3 kWh for driving pattern 1 in week 29.

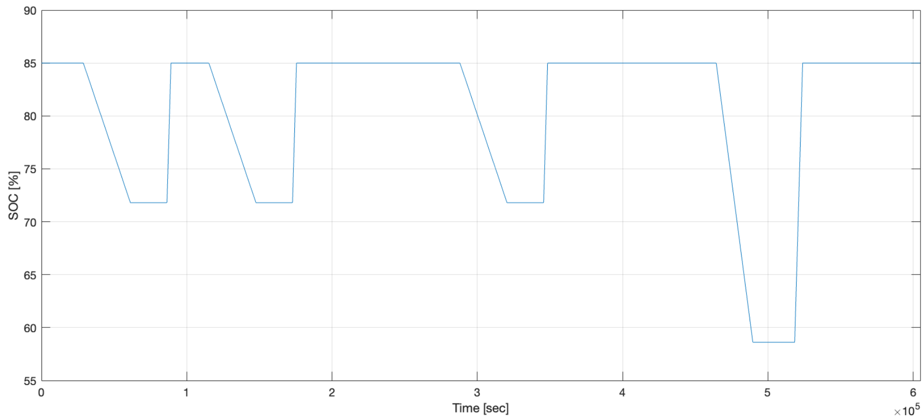

Figure A.12: SOC for case V1H using a charger size of 3 kWh for driving pattern 1 in week 29.

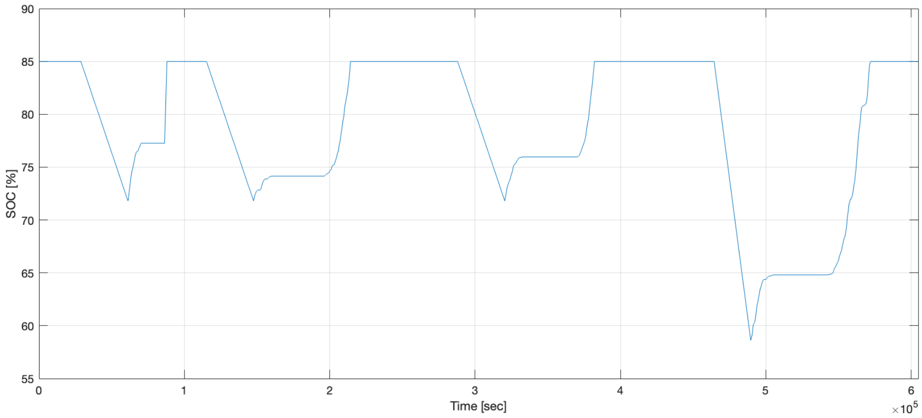

Figure A.13: SOC for case V1HS using a charger size of 3 kWh for driving pattern 1 in week 29.

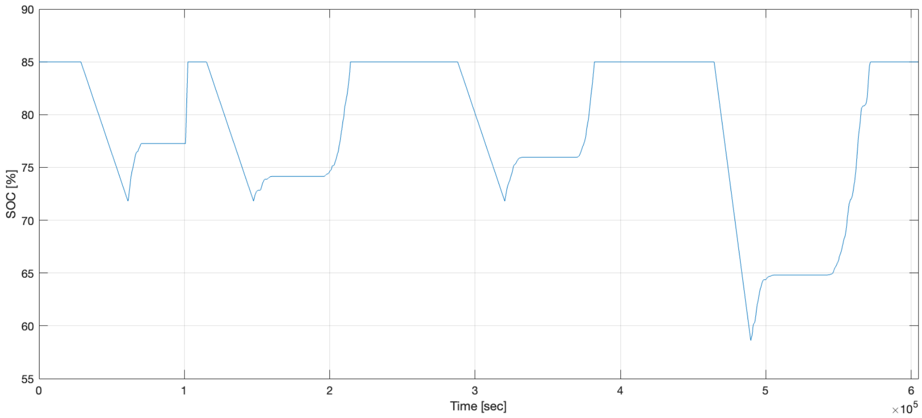

Figure A.14: SOC for case V1HSD using a charger size of 3 kWh for driving pattern 1 in week 29.

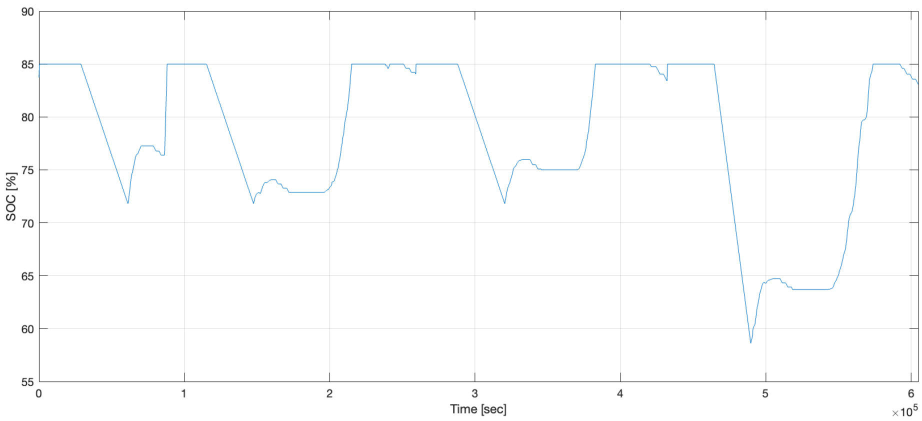

Figure A.15: SOC for case V2H using a charger size of 3 kWh for driving pattern 1 in week 29.

A.5 Yearly SOC for case V1HSD using charger size 3 kWh

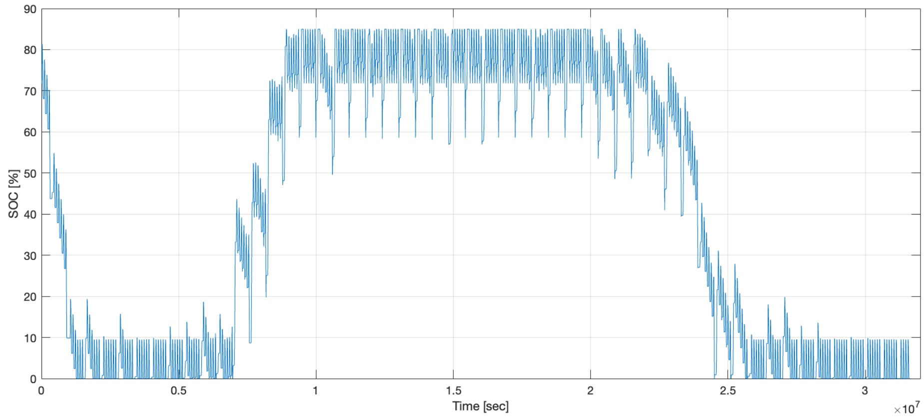

Figure A.16: Yearly SOC for case V1HSD using a charger size of 3 kWh for driving pattern 1.

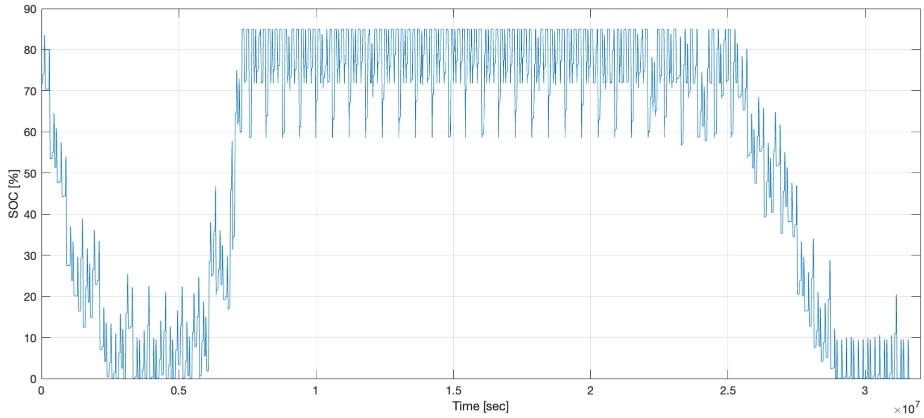

Figure A.17: Yearly SOC for case V1HSD using a charger size of 3 kWh for driving pattern 2.

A.6 Yearly performance values for all cases

Table A.1: Yearly performance data for the five controllers in driving pattern 1 with an 11 kW charger.

Case	Dumb	V1H	V1HS	V1HSD	V2H
Household Consumption [kWh]	2296	2296	2296	2296	2296
of which from PV [kWh]	1185	1185	1185	1185	1185
of which from Grid [kWh]	1111	1111	1111	1111	693
of which from EV [kWh]	0	0	0	0	417
EV Consumption [kWh]	3064	3056	3099	3099	4034
of which from PV [kWh]	227	0	850	850	885
of which from grid [kWh]	2837	3056	2249	2249	3149
Total Consumption [kWh]	5360	5351	5394	5394	6329
Self-consumption [%]	22.6	19	32.6	32.6	33.2
Self-sufficiency [%]	26.3	22.1	37.7	37.7	32.7
Total Energy loss [kwh]	61	61	104	104	626
Total energy to grid [kWh]	4829	5056	4207	4207	4171
Total energy from grid [kWh]	3948	4166	3360	3360	3842
Total Energy Throughput [kWh]	5997	5989	5989	5989	7825
Number of battery cycles	48	48	48	48	63
Average SOC [%]	82.4	78.4	76.5	74.9	75.2

Table A.2: Yearly performance data for the five controllers in driving pattern 1 with a 6 kW charger.

Case	Dumb	V1H	V1HS	V1HSD	V2H
Household Consumption [kWh]	2296	2296	2296	2296	2296
of which from PV [kWh]	1185	1185	1185	1185	1185
of which from Grid [kWh]	1111	1111	1111	1111	643
of which from EV [kWh]	0	0	0	0	468
EV Consumption [kWh]	3067	3059	3076	3076	3844
of which from PV [kWh]	336	0	846	846	878
of which from grid [kWh]	2732	3059	2230	2230	2966
Total Consumption [kWh]	5363	5354	5372	5372	6139
Self-consumption [%]	24.4	19	32.5	32.5	33
Self-sufficiency [%]	28.4	22.1	37.8	37.8	33.6
Total Energy loss [kwh]	64	64	82	82	385
Total energy to grid [kWh]	4720	5056	4210	4210	4178
Total energy from grid [kWh]	3842	4169	3340	3340	3609
Total Energy Throughput [kWh]	5997	5989	5989	5989	7495
Number of battery cycles	48	48	48	48	60
Average SOC [%]	82.2	78.2	76.4	74.5	75.3

Table A.3: Yearly performance data for the five controllers in driving pattern 1 with a 3 kW charger.

Case	Dumb	V1H	V1HS	V1HSD	V2H
Household Consumption [kWh]	2296	2296	2296	-	2296
Of which from PV [kWh]	1185	1185	1185	-	1185
of which from Grid [kWh]	1111	1111	1111	-	642
of which from EV [kWh]	0	0	0	-	469
EV Consumption [kWh]	3064	3056	3069	-	3642
of which from PV [kWh]	414	0	842	-	862
of which from grid [kWh]	2650	3056	2227	-	2780
Total Consumption [kWh]	5360	5351	5364	-	5938
Self-consumption [%]	25.6	19	32.5	-	32.8
Self-sufficiency [%]	29.8	22.1	37.8	-	34.5
Total Energy loss [kwh]	61	61	74	-	181
Total energy to grid [kWh]	4646	5056	4214	-	4194
Total energy from grid [kWh]	3765	4166	3338	-	3422
Total Energy Throughput [kWh]	5997	5989	5989	-	7115
Number of battery cycles	48	48	48	-	57
Average SOC [%]	81.7	77.7	76.1	-	74.9

Table A.4: Yearly performance data for the five controllers in driving pattern 2 with an 11 kW charger.

Case	Dumb	V1H	V1HS	V1HSD	V2H
Household Consumption [kWh]	2296	2296	2296	2296	2296
of which from PV [kWh]	1185	1185	1185	1185	1185
of which from Grid [kWh]	1111	1111	1111	1111	693
of which from EV [kWh]	0	0	0	0	417
EV Consumption [kWh]	2188	2179	2242	2242	3180
of which from PV [kWh]	166	0	1247	1248	1380
of which from grid [kWh]	2021	2179	995	994	1800
Total Consumption [kWh]	4483	4475	4537	4538	5475
Self-consumption [%]	21.7	19	39	39	41.1
Self-sufficiency [%]	30.1	26.5	53.6	53.6	46.8
Total Energy loss [kwh]	44	44	106	107	631
Total energy to grid [kWh]	4890	5056	3809	3808	3676
Total energy from grid [kWh]	3132	3290	2106	2105	2493
Total Energy Throughput [kWh]	4279	4271	4271	4271	6107
Number of battery cycles	35	34	34	34	49
Average SOC [%]	83.1	80.3	76.1	75.4	74

Table A.5: Yearly performance data for the five controllers in driving pattern 2 with a 6 kW charger.

Case	Dumb	V1H	V1HS	V1HSD	V2H
Household Consumption [kWh]	2296	2296	2296	2296	2296
of which from PV [kWh]	1185	1185	1185	1185	1185
of which from Grid [kWh]	1111	1111	1111	1111	643
of which from EV [kWh]	0	0	0	0	468
EV Consumption [kWh]	2190	2181	2207	2207	2976
of which from PV [kWh]	241	0	1231	1233	1351
of which from grid [kWh]	1949	2181	976	974	1625
Total Consumption [kWh]	4485	4477	4502	4503	5271
Self-consumption [%]	22.8	19	38.7	38.7	40.6
Self-sufficiency [%]	31.8	26.5	53.7	53.7	48.1
Total Energy loss [kwh]	46	46	71	72	375
Total energy to grid [kWh]	4815	5056	3825	3823	3706
Total energy from grid [kWh]	3059	3292	2086	2085	2268
Total Energy Throughput [kWh]	4279	4271	4271	4271	5777
Number of battery cycles	35	34	34	34	47
Average SOC [%]	83	80.1	76.2	75.1	74.3

Table A.6: Yearly performance data for the five controllers in driving pattern 2 with a 3 kW charger.

Case	Dumb	V1H	V1HS	V1HSD	V2H
Household Consumption [kWh]	2296	2296	2296	-	2296
of which from PV [kWh]	1185	1185	1185	-	1185
of which from Grid [kWh]	1111	1111	1111	-	642
of which from EV [kWh]	0	0	0	-	469
EV Consumption [kWh]	2187	2179	2198	-	2772
of which from PV [kWh]	291	0	1224	-	1307
of which from grid [kWh]	1896	2179	973	-	1466
Total Consumption [kWh]	4483	4475	4493	-	5068
Self-consumption [%]	23.6	19	38.6	-	39.9
Self-sufficiency [%]	32.9	26.5	53.6	-	49.2
Total Energy loss [kwh]	44	44	63	-	170
Total energy to grid [kWh]	4769	5056	3832	-	3749
Total energy from grid [kWh]	3011	3290	2084	-	2107
Total Energy Throughput [kWh]	4279	4271	4271	-	5397
Number of battery cycles	35	34	34	-	44
Average SOC [%]	82.6	79.7	76	-	74.3

A.7 Yearly economic values for all cases

Table A.7: Yearly economic data for the five controllers in driving pattern 1 with an 11 kW charger.

Case	Dumb	V1H	V1HS	V1HSD	V2H
Total Payment [DKK]	8661	4400	3723	3580	3382
of which to house [DKK]	1946	1946	1946	1946	931
of which to EV [DKK]	6715	2454	1777	1634	2451
Sale of PV [DKK]	3236	3387	2933	2933	2923
Total electricity bill [DKK]	5425	1012	790	647	458

Table A.8: Yearly economic data for the five controllers in driving pattern 1 with a 6 kW charger.

Case	Dumb	V1H	V1HS	V1HSD	V2H
Total Payment [DKK]	8781	4334	3687	3610	3130
of which to house [DKK]	1946	1946	1946	1946	853
of which to EV [DKK]	6835	2388	1741	1664	2277
Sale of PV [DKK]	3154	3387	2932	2932	2923
Total electricity bill [DKK]	5627	947	755	678	207

Table A.9: Yearly economic data for the five controllers in driving pattern 1 with a 3 kW charger.

Case	Dumb	V1H	V1HS	V1HSD	V2H
Total Payment [DKK]	8725	4230	3633	-	2926
of which to house [DKK]	1951	1946	1946	-	851
of which to EV [DKK]	6774	2284	1687	-	2076
Sale of PV [DKK]	3088	3387	2934	-	2928
Total electricity bill [DKK]	5637	843	699	-	-2

Table A.10: Yearly economic data for the five controllers in driving pattern 2 with an 11 kW charger.

Case	Dumb	V1H	V1HS	V1HSD	V2H
Total Payment [DKK]	6501	3676	2670	2644	2247
of which to house [DKK]	1946	1946	1946	1946	931
of which to EV [DKK]	4555	1730	724	698	1316
Sale of PV [DKK]	3283	3387	2605	2604	2528
Total electricity bill [DKK]	3219	289	66	41	-282

Table A.11: Yearly economic data for the five controllers in driving pattern 2 with a 6 kW charger.

Case	Dumb	V1H	V1HS	V1HSD	V2H
Total Payment [DKK]	6675	3627	2650	2655	2029
of which to house [DKK]	1946	1946	1946	1946	853
of which to EV [DKK]	4729	1681	704	709	1176
Sale of PV [DKK]	3228	3387	2613	2612	2541
Total electricity bill [DKK]	3447	240	37	43	-512

Table A.12: Yearly economic data for the five controllers in driving pattern 2 with a 3 kW charger.

Case	Dumb	V1H	V1HS	V1HSD	V2H
Total Payment [DKK]	6679	3552	2637	-	1895
of which to house [DKK]	1950	1946	1946	-	851
of which to EV [DKK]	4729	1606	691	-	1044
Sale of PV [DKK]	3188	3387	2618	-	2569
Total electricity bill [DKK]	3491	165	19	-	-674

Table A.13: Yearly avoided cost for V2H for all smart charger sizes in both driving patterns.

Case V2H	Driving pattern 1 11 kW	Driving pattern 1 6 kW	Driving pattern 1 3 kW	Driving pattern 2 11 kW	Driving pattern 2 6 kW	Driving pattern 2 3kW
Avoided Cost [DKK]	1015	1093	1095	1015	1093	1095

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