

Runar Hillestad

A co-simulation framework to coordinate battery optimization and load flow

Improving voltage quality in the distribution grid

Master's thesis in Energy and Environmental Engineering

Supervisor: Hossein Farahmand

Co-supervisor: Kjersti Berg

May 2022

Runar Hillestad

A co-simulation framework to coordinate battery optimization and load flow

Improving voltage quality in the distribution grid

Master's thesis in Energy and Environmental Engineering
Supervisor: Hossein Farahmand
Co-supervisor: Kjersti Berg
May 2022

Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

Abstract

The increase in distributed energy resources such as photovoltaic (PV) panels and high energy consuming appliances have created challenges regarding the quality of voltage for the distribution grid, and batteries might be used to solve it. In Norway, there are regulation deciding what the voltage has to be at the end user, called the Norwegian regulation on quality of electricity supply. Traditionally, the distribution system operator (DSO) upgrade the infrastructure to improve the voltage quality. The aim of this thesis is to answer the question: How can a co-simulation framework coordinate a battery optimization model and a load flow simulation to improve voltage quality in the distribution grid?

This thesis looks at how a co-simulation framework can be used to deal with the voltage at a point of common coupling (PCC). The regulation on quality of electricity supply states that the voltage has to be within $\pm 10\%$ of nominal voltage in the low voltage (LV) network. To give the DSO a margin, a voltage range of $\pm 5\%$ was used in this thesis.

Co-simulation is a way to synchronize two or more algorithms using two or more platforms. The different algorithms exchange data with each other on a co-simulation platform. The reason co-simulation is used is to reduce computational time. MATLAB is used as the co-simulation platform, as it exchanges data between the different models. There is an optimization model in Python that minimizes the cost of electricity imported by charging and discharging the battery, and a Simulink model that uses the Python output for simulating the impact on the power grid. To simulate different scenarios, different battery sizes and power peaks were used. The power peaks were generated by taking the hourly metering, multiplying it by a power peak factor for a short time so that the hourly metering stayed the same.

There are three cases: a base case, a power peak case and a battery case. All three cases were simulated for one day in all four seasons of the year. The optimization decides first how the spot price of electricity, load and PV impact the charging/discharging of the battery and grid exchange. The output from the optimization is used in the Simulink simulation, where the voltage is the output. The co-simulation platform analyses the simulated voltage. If there is a voltage violation the maximum power allowed at PCC is reduced. After the maximum power allowed at PCC is reduced, there is a new iteration of optimization and Simulink simulation. The co-simulation iterates until there is a solution without voltage violation, or the optimization is unable to find a solution. Because of the grid tariff on import, the battery is used to store the excess power when residual load is negative. When the PV generation is low, the battery was used to buy electricity when it was cheap, and use it later in the day when the prices were higher. The results show that co-simulation can be used to improve the quality of power supply. With a larger battery, there is a greater chance of the optimization to find a feasible solution and voltage within the given range. Although a larger battery makes a feasible solution more likely, a larger battery cost much more. With higher power peak factors, the co-simulation had to do more iterations to find a valid solution, and it was not able to find a solution during the days with low PV generation.

Co-simulation can be used to coordinate a battery optimization model and a load flow simulation to improve voltage quality in the distribution grid by the two models exchanging data on a co-simulation platform. By implementing a stepwise decrease of maximum power at PCC when the voltage quality is violated, the two models adapt and change charging and discharging patterns for the battery.

Sammendrag

Økningen av distribuerte energi ressurser slik som solcellepanel (PV) og effektkrevende apparater har skapt nye utfordringer som leveringskvaliteten på spenningen for distribusjonsnett, og det er kanskje mulig å bruke batterier for å løse dem. I Norge er det forskriften om leveringskvalitet i kraftsystemet bestemmer hva spenningen skal være hos forbrukeren. Tradisjonelt har nettselskapene (DSO) oppgradert infrastrukturen for å forbedre spenningskvaliteten. Denne masteroppgaven prøver å svare på spørsmålet: Hvordan kan samsimulering koordinere an batterioptimeringsmodell og en lastflyt simulering for å forbedre spenningskvaliteten i distribusjonsnett?

Denne masteroppgaven ser på hvordan et samsimuleringsrammeverk kan brukes til å håndtere spenningen i et felles tilknytningspunkt (PCC). Forskriften om leveringskvalitet sier at spenningen må være $\pm 10\%$ av nominell spenning i lavspenningsnett. $\pm 5\%$ av nominell spenning er brukt i denne oppgaven for å gi nettselskapene en margin.

Samsimulering er en måte å synkronisere to eller flere algoritmer som bruker to eller flere plattform, og samsimulering brukes grunnet redusert simuleringstiden. MATLAB er brukt som samsimuleringsplattform siden den utveksler data mellom de forskjellige modellene. Det er en optimeringsmodell i Python som minimerer strømkostnaden ved å lade opp og lade ut et batteri, og en lastflyt modell i Simulink som bruker resultatet fra Python til å simulere påvirkning på distribusjonsnett. Forskjellige batteri størrelser og effekttopper ble brukt for i ulike scenarier. Effekttoppene ble laget ved å multiplisere timeforbruket med en effekttoppfaktor i en kort tid slik at timeforbruket forblir det samme.

Det er tre scenarier: et standard scenario, et effekttopp scenario og et batteri scenario. Alle tre scenariene ble simulert for en dag i alle fire årstidene. Først finner optimeringsmodellen ut hvordan spot pris på strøm, last og PV påvirker opp og utladingen av batteriet og kraftutvekslingen med strømmettet. Simulink bruker resultatet fra optimeringsmodellen for sin simulering, og resultatet fra Simulink er spenningen i strømmettet. Samsimuleringsplattformen analyserer den simulerte spenningen. Hvis det brudd i spenningskvaliteten reduseres maksimalt tillatt effekt i PCC, og en ny iterasjon av optimering og Simulink simulering starter. Samsimuleringen iterer helt frem til spenningskvaliteten er godkjent, eller optimeringsmodellen ikke får et svar. På grunn av nettleien på import av strøm brukes batteriet til å lagre overskuddsstrømmen fra PV. Når det var lite produksjonen fra PV ble batteriet brukt til å lade opp batteriet ved lave strømpriser, og lade ut når det var høye strømpriser. Resultatene viser at samsimulering kan brukes til å forbedre spenningskvaliteten. Et større batteri gir større sannsynlighet for at optimeringsmodellen får et svar og en spenning $\pm 5\%$ av nominell spenning. Selv om et større batteri gir større sannsynlighet for bedre spenningskvaliteten, koster et større batteri mye mer. Når det var høye effekttopper brukte samsimuleringsmodellen flere iterasjoner før den fant et svar, og med dager med lite produksjon fra PV var det ingen løsning.

Samsimuleringsrammeverket kan brukes til å koordinere en optimeringsmodell for batteri og en lastflyt simulering for å forbedre spenningskvaliteten i distribusjonsnett ved data utveksling mellom de to modellene. Ved å implementere en stegvis reduksjon av tillatt kraft i PCC når spenningskvaliteten var for dårlig endrer opp og utladingen av batteriet slik at spenningskvaliteten blir innenfor forskriften.

Preface

This master's thesis concludes my master's degree within Energy and Environmental engineering at the Department of Electric Power Engineering at the Norwegian University of Science and Technology (NTNU).

It was supervised by Professor Hossein Farahmand (NTNU) and co-supervised by Kjersti Berg (NTNU). I would like to express my deepest appreciation to my supervisors for your help and support during my work with this master's thesis and the preceding specialization project. Your guidance helped me navigate the different aspect of writing a master's thesis. I want to thank Merkebu Zenebe Degefa and Rubi Rana from SINTEF for invaluable help. I thank you for helping me to develop and understand the models in this master's thesis.

Thank you to my fellow students for the fun times these years, and especially the last year.

I want to thank my family and friends for their encouragement and support during the last five years. They have endured constant lecturing on what I have learned, and I thank you for listening even though you did not understand anything.

Trondheim, May 2022
Runar Hillestad

Abbreviations and nomenclature

Abbreviations

| | |
|-------------|--|
| PV | Photovoltaic |
| PCC | Point of common coupling |
| DSO | Distribution system operator |
| FINE | Flexible Integration of Local Energy Community |
| LV | Low voltage |
| IEC | International Electrotechnical Commission |
| HV | High voltage |
| NVE | Norges vassdrags- og energidirektorat |
| EV | Electric vehicles |
| DSSE | Domain specific systems engineering |
| SGAM | Smart grid architecture model |
| HEMS | Home energy management system |
| HVAC | Heating, ventilation, and air conditioning |
| PF | Power factor |

Nomenclature

| | | |
|-----------|--|-------------|
| P_t | Electricity spot price in hour t | $[NOK/kWh]$ |
| i_t | Power imported from the grid in hour t | $[kWh]$ |
| e_t | Power exported from the grid in hour t | $[kWh]$ |
| c_t | Charging of the battery in hour t | $[kWh/h]$ |
| d_t | Discharging of the battery in hour t | $[kWh/h]$ |
| L_t | Load for the house in hour t | $[kWh/h]$ |
| s_t | State of charge for the battery in hour t | $[kWh/h]$ |
| η | Round-trip efficiency of the battery | $[\%]$ |
| R_{max} | Maximum rate for charging/discharging the battery | $[kWh/h]$ |
| α | Grid tariff for electricity | $[NOK/kWh]$ |
| S_{max} | Maximum charge of the battery | $[kWh]$ |
| PV_t | Electricity generated by the PV in hour t | $[kWh/h]$ |
| I_{max} | Maximum power that can be imported from the power grid in hour t | $[kWh]$ |

Table of Contents

| | |
|--|-------------|
| List of Figures | xi |
| List of Tables | xiii |
| 1 Introduction | 1 |
| 1.1 Motivation | 1 |
| 1.2 Objective and Scope | 1 |
| 1.3 Contribution | 2 |
| 1.4 Structure | 2 |
| 2 Background | 5 |
| 2.1 Quality of voltage supply | 5 |
| 2.2 PV and battery in Norway | 5 |
| 2.3 Power resolution | 7 |
| 2.4 Co-simulation | 8 |
| 3 Methodology | 11 |
| 3.1 MATLAB as co-simulation platform | 11 |
| 3.2 Optimization | 11 |
| 3.3 Simulink model | 13 |
| 3.3.1 Upper layer | 14 |
| 3.3.2 Lower layer | 15 |
| 3.4 Co-Simulation setup | 18 |
| 4 Co-simulation case study | 21 |
| 4.1 Setup for the cases | 21 |
| 4.1.1 Setup | 21 |
| 4.1.2 Choise of days | 22 |
| 4.2 Case results | 26 |
| 4.2.1 Base case results | 29 |
| 4.2.2 Power peak results | 35 |
| 4.2.3 Power peak larger battery | 41 |

| | | |
|----------|---|-----------|
| 4.3 | Summary | 47 |
| 5 | Discussion | 51 |
| 5.1 | Base case | 51 |
| 5.2 | Power peaks and battery cases | 52 |
| 5.3 | Chosen days | 52 |
| 5.4 | Spot price | 53 |
| 5.5 | Voltage requirements | 53 |
| 5.6 | Battery cost | 53 |
| 6 | Conclusion and future work | 55 |
| 6.1 | Conclusion | 55 |
| 6.2 | Future work | 56 |
| | Bibliography | 57 |
| A | Appendix | 61 |
| A.1 | Simulink setup | 61 |
| A.2 | Power peaks spring and autumn | 62 |
| A.2.1 | Power peak 2 | 63 |
| A.2.2 | Power peak 2.5 | 65 |
| A.2.3 | Power peak 3 | 67 |
| A.3 | Power peaks with larger battery spring and autumn | 68 |
| A.3.1 | Power peak 2 | 69 |
| A.3.2 | Power peak 2.5 | 71 |
| A.3.3 | Power peak 3 | 73 |
| A.4 | Summary of spring and autumn voltages | 75 |

List of Figures

| | | |
|----|---|----|
| 1 | Installed grid connected PV in Norway | 6 |
| 2 | Battery price forecast | 6 |
| 3 | Different power resolutions | 7 |
| 4 | Co-simulation vs hybrid and parallel simulation | 8 |
| 5 | Matlab model | 11 |
| 6 | Overview of variables and parameters | 12 |
| 7 | Upper layer power system and connection between MATLAB and Simulink | 14 |
| 8 | Lower layer set up for Simulink | 16 |
| 9 | Power peaks | 17 |
| 10 | The flow in co-simulation case | 19 |
| 11 | All the days in December compared to the 21 st | 23 |
| 12 | All the days in June compared to the 16 th | 24 |
| 13 | All the days in April compared to the 21 st | 25 |
| 14 | All the days in October compared to the 16 th | 26 |
| 15 | The results from the winter simulation, December 21 st | 27 |
| 16 | Base case winter | 28 |
| 17 | The results from the spring simulation, April 21 st | 30 |
| 18 | Base case spring | 31 |
| 19 | The results from the summer simulation, June 16 th | 32 |
| 20 | Base case summer | 33 |
| 21 | The results from the autumn simulation, October 16 th | 34 |
| 22 | Base case autumn | 35 |
| 23 | Winter: Power peak 2, first and last simulation | 36 |
| 24 | Summer: Power peak 2, first and last simulation | 37 |
| 25 | Winter: Power peak 2.5, first and last simulation | 38 |
| 26 | Summer: Power peak 2.5, first and last simulation | 39 |
| 27 | Winter: Power peak 3, first and last simulation | 40 |
| 28 | Summer: Power peak 3, first and last simulation | 41 |
| 29 | Winter: Power peak 2 with a larger battery, first and last simulation | 42 |

| | | |
|----|---|----|
| 30 | Summer: Power peak 2 with a larger battery, first and last simulation | 43 |
| 31 | Winter: Power peak 2.5 with a larger battery, first and last simulation | 44 |
| 32 | Summer: Power peak 2.5 with a larger battery, first and last simulation | 45 |
| 33 | Winter: Power peak 3 with a larger battery, first and last simulation | 46 |
| 34 | Summer: Power peak 3 with a larger battery, first and last simulation | 47 |
| 35 | From MATLAB to Simulink, two vectors | 61 |
| 36 | Timestamp | 62 |
| 37 | Spring: Power peak 2, first and last simulation | 63 |
| 38 | Autumn: Power peak 2, first and last simulation | 64 |
| 39 | Spring: Power peak 2.5, first and last simulation | 65 |
| 40 | Autumn: Power peak 2.5, first and last simulation | 66 |
| 41 | Spring: Power peak 3, first and last simulation | 67 |
| 42 | Autumn: Power peak 3, first and last simulation | 68 |
| 43 | Spring: Power peak 2 larger battery, first and last simulation | 69 |
| 44 | Autumn: Power peak 2 larger battery, first and last simulation | 70 |
| 45 | Spring: Power peak 2.5 larger battery, first and last simulation | 71 |
| 46 | Autumn: Power peak 2.5 larger battery, first and last simulation | 72 |
| 47 | Spring: Power peak 3 larger battery, first and last simulation | 73 |
| 48 | Autumn: Power peak 3 larger battery, first and last simulation | 74 |

List of Tables

| | | |
|---|--|----|
| 1 | Setup for the optimization for all cases | 21 |
| 2 | Setup for the Simulink model for all cases | 22 |
| 3 | Summary of voltage for the winter simulations for the first and last iteration . . . | 48 |
| 4 | Summary of voltage for the summer simulations for the first and last iteration . . . | 48 |
| 5 | Cost in NOK for power with different maximum power at PCC for a battery of 3.3 kWh | 48 |
| 6 | Cost in NOK for power with different maximum power at PCC for a battery of 15 kWh | 49 |
| 7 | Summary of voltage for the spring simulations for the first and last iteration | 75 |
| 8 | Summary of voltage for the autumn simulations for the first and last iteration . . . | 75 |

1 Introduction

The introduction section explains the motivation for this thesis, the objective and scope, the contributions this thesis brings and the structure for the thesis. Some text in Section 1.1 is taken from the specialization project [1].

1.1 Motivation

In recent years photovoltaic cells (PV), home batteries and other forms of decentralized energy resources (DER) have become cheaper to produce [2, 3, 4], which has led to many households buying and using DER [5]. The flow of power and the load demand from the power grid is changing because of the power production at the end user. The change in power flow brings some new challenges to the power quality [6]. In Norway, there are regulations controlling what the voltage has to be at the end user, called the Norwegian regulation on quality of electricity supply [7].

This master thesis is done in collaboration with SINTEF and their FINE (Flexible Integration of Local Energy Community) project. FINE is a project looking at how local energy communities can be used in the Norwegian electricity distribution system [8].

With the increase in PV, home battery and other forms of DER, some consumers become prosumers in the market. To be able to distribute the excess electricity, there needs to be a market put in place with market mechanisms and a structure of how the electricity is to be distributed and if the power grid can manage that. There have been many papers looking at either the Norwegian regulation on quality of electricity supply or the power grid aspects of the prosumer selling the electricity back to the grid. However, there are no papers looking at both aspects at the same time using co-simulation. To be able to analyze the effect on the power grid, multiple s have to be used. Simulation of the power grid has to be done on a small timescale, while markets are cleared on an hourly basis. To simulate this efficiently, co-simulation has a good use case where one simulation will handle the optimization of charging/discharging the battery and another simulation will handle the power grid. The two models exchange data after their separate simulations and then change parameters between each simulation until the data from both simulations are acceptable.

1.2 Objective and Scope

The objective of this thesis is to find out if a co-simulation model with two different solvers that runs separate models can have an impact on the power quality in the power grid. One model optimizing the energy use in the household and one model simulating the impact on the power grid.

The most crucial question that the thesis should address is as follows: How can a co-simulation framework coordinate a battery optimization model and a load flow simulation to improve voltage quality in the distribution grid?

This question is answered in three steps:

-
1. **Background for co-simulation, home battery, PV and voltage quality.** To be able to know where to start, literature review on different types of co-simulation was done. It was important to understand the different use cases, and how to use co-simulation properly in for a power grid simulation. The development of home battery and PV was looked at to understand the impact they can have on the voltage. The regulation regarding the quality of electricity in Norway was reviewed to understand the problems for the distribution system operator (DSO).
 2. **Make a co-simulation model.** Take inspiration from different optimization, simulation and co-simulation models. The optimization and power grid simulation models were made put together with a co-simulation platform for them to be able to work together. The optimization model is made to minimize the cost on the battery, the power grid simulation outputs the voltage and the co-simulation platform exchanges the data and evaluates the voltage.
 3. **Simulate the impact of the household on the low voltage network with co-simulation.** The co-simulation is set up with different cases, one base case and two cases with power peaks. The two power peak cases have different battery sizes, to see the effect on the battery size on the voltage.

1.3 Contribution

To understand the use of co-simulation in the power grid, existing literature was reviewed. There were many papers on the use of co-simulation on the market aspect of local energy production, and papers on the impact on the low and medium voltage power system. In [9], they set up a co-simulation model for monitoring the voltage in real time using smart metering connected to the Internet in Sweden. The authors found a cheap and easy way of monitoring the voltage by using two model, one for power process and the other for communication network.

This thesis' contribution is to show how co-simulation can be used to find a way for a household with battery and PV to have a satisfying quality of voltage supply by making two models that simulate the voltage in the low voltage network (LV). To do that, two models were made, one optimization model to find out when the battery should charge and discharge and one model to simulate the impact on the LV. They communicated using a co-simulation platform, where data is exchanged and voltage evaluated. If the data is not within the given range, the optimization model changes. This happens until voltage is within the given range or the optimization model cannot find a solution.

1.4 Structure

Background Section 2 presents the background. The section will explain what quality of voltage supply is, and the regulation the DSO needs to follow. The development of PV and battery in Norway, and how it is used in a typical Norwegian household is reviewed. Further, the difference in hourly metering and intra-hourly metering, and how different time resolution for metering impacts the voltage simulation, explored. Co-simulation is defined and explained in the background section, alongside literature review on how co-simulation have been used in a power system.

Methodology Section 3 is the methodology. There are two models in different software programs, one optimization model in Python that determines when the battery charges and discharges. The other model is a simulation in Simulink, that outputs the voltage. It shows the method used in this report to solve a use case. Section 3 describes the optimization model and MATLAB/ Simulink model and how they work together through the co-simulation script.

Co-simulation case study Four days were used for the case study, one for each season of the year. The results from the optimization and different cases are displayed in Section 4. There are three different cases, where one is the base case for the chosen days. There are two cases with power peaks to simulate the intra-hourly metering, and one with the original battery and one with a big battery.

Discussion The results from the co-simulation cases are discussed in Section 5. The differences in results of the co-simulation for winter and summer, the difference in results for the small and big battery, are discussed. This section further discusses the choice of days within the four seasons and compare them to other days in the month, the benefit for the household and the DSO by doing co-simulation in regard to the voltage quality and if the power peak factors are relevant for a Norwegian power system.

Conclusion and future work A conclusion and future work is in Section 6.

2 Background

This background section will be explaining what quality of voltage supply is and the Norwegian laws regulating it. Additionally, it will look at how PV and home batteries are affecting the power grid, time resolutions for power generation and consumption for the DSO as well as what co-simulation is and how it is used for in power grid application.

2.1 Quality of voltage supply

In Norway, there are regulations, the Norwegian regulation on quality of electricity supply [7], concerning the quality of the voltage and power supplied from the power grid to the consumer. The DSO are the companies that are required to make sure that the voltage is within $\pm 10\%$ of nominal voltage. § 3-3 [7] states that it is a violation if the voltage is within $\pm 10\%$ of nominal voltage averaged over a minute in the LV network. LV is defined by International Electrotechnical Commission (IEC) as voltage between 50 and 1000 V [10]. A LV in Norway is the last part of the distribution grid and is 230 V for residential homes [11]. The voltage in the LV network changes with the load and power generation within the LV network, where the DSO has control. If the law is broken, the DSO will be fined. It is therefore in the DSO's interest to make sure that the voltage is as close to the nominal voltage as possible. Traditionally, the power has been produced at large power plants, then transported over high voltage (HV) networks, transformed down to the LV network, and then used. In the last couple of years, DER has become a bigger part of the power generation in Norway [12]. A report from NVE (Norges vassdrags- og energidirektorat) assumes that some DSOs in Norway will struggle with keeping the voltage within the $\pm 10\%$ of nominal voltage with the increase of DER in the LV network [6]. The report outlines problems with DER in the form of potential overvoltage during the summer months and undervoltage in the winter months, due to the fact that PV produces the most power in the summer. Some LV networks in Norway are not built to be able to have a high penetration of DER. The increase in electric vehicles (EV), and other power consuming loads into the LV distribution network has an effect on the voltage quality [13, 14].

2.2 PV and battery in Norway

As more and more PV are connected to the Norwegian LV networks [5], as seen in Figure 1, the voltage in the LV networks becomes more volatile. Studies have been done to find a PV penetration limit in different LV networks [15] [16]. The PV penetration limit varies from network to network, depending on the topology and sun coverage in the area. With PV, there are also many houses that acquire a home battery, and the installed capacity is predicted to increase in the future [17].

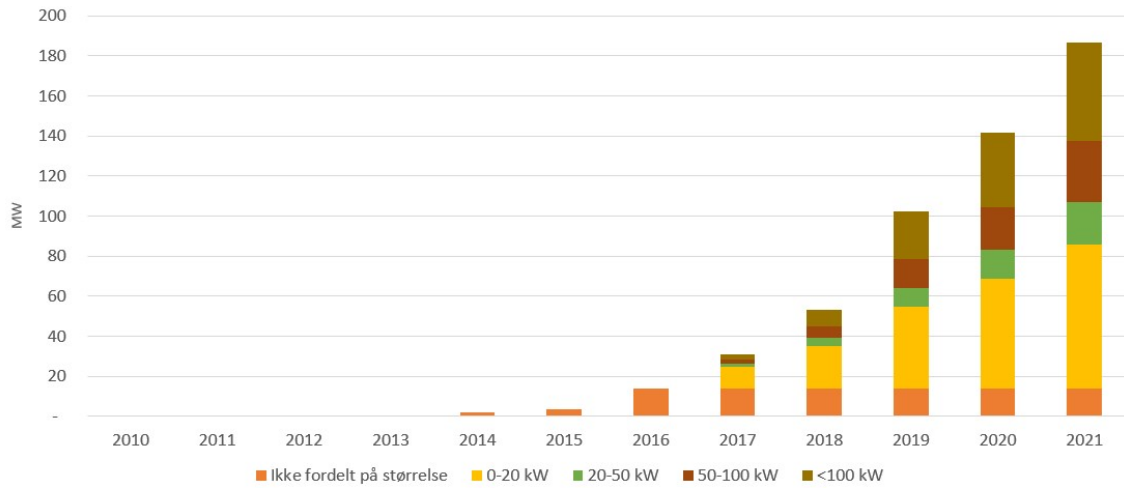


Figure 1: PV installation in Norway [5]

There has not been an increase in home batteries in Norway, but NVE assumes that batteries will be an important part of the power system in the future [18] as that batteries are predicted to become much cheaper. Figure 2 is taken from a review of battery price forecasting [19]. The black line in the figure is a regression of all the different forecast models and illustrates the expected battery price until 2050. The graph clearly shows that the battery price is expected to decrease in the next 3 decades.

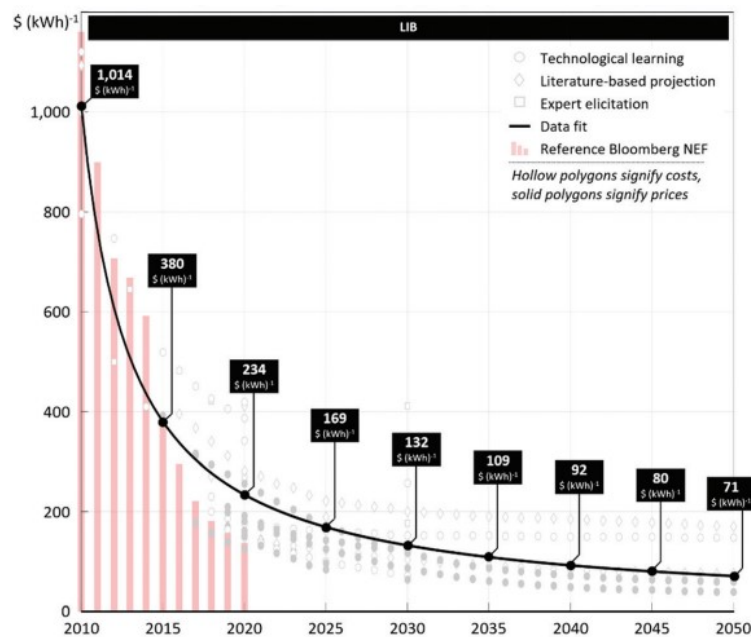


Figure 2: Battery price forecast [19]

It is possible to get home batteries in all sizes, and the size of any given home battery is determined by several factors. Sonnen, a German battery manufacturer, has different batteries ranging from 2 kWh to 22 kWh [20], and a Tesla Powerwall has a capacity of 13.5 kWh [21]. With batteries, the load profile changes due to the charging and discharging of the battery. The battery is used to charge when there is excess power from solar, but also when the price is the cheapest [22]. With

more people charging their batteries when it is cheap, more power is used in the LV network. According to the NVE report about the quality of voltage [6], PV production affects the load curves more in the summer than the winter as that there is more sunlight in the summer. The increased difference in the load curves makes it hard for the DSOs to know when and where to upgrade the LV network.

2.3 Power resolution

In Norway, electric energy consumption from the power grid is measured and sent to the DSO on an hourly basis with an hourly time resolution [23], called hourly metering. The DSO taxes the usage of power with a grid tariff based on how much power the consumer uses within the hour. Power can not be measured accurately over an hour, and power is defined as [24] work done per time unit or energy used per time unit. The measurement the DSO has is the power average for the hour, while the power is instantaneous and can vary within the hour. The LV network becomes affected by the instantaneous power, and the voltage in the LV network varies with the power usage. The DSO therefore need to look at the power usage within the hour to monitor the voltage level.

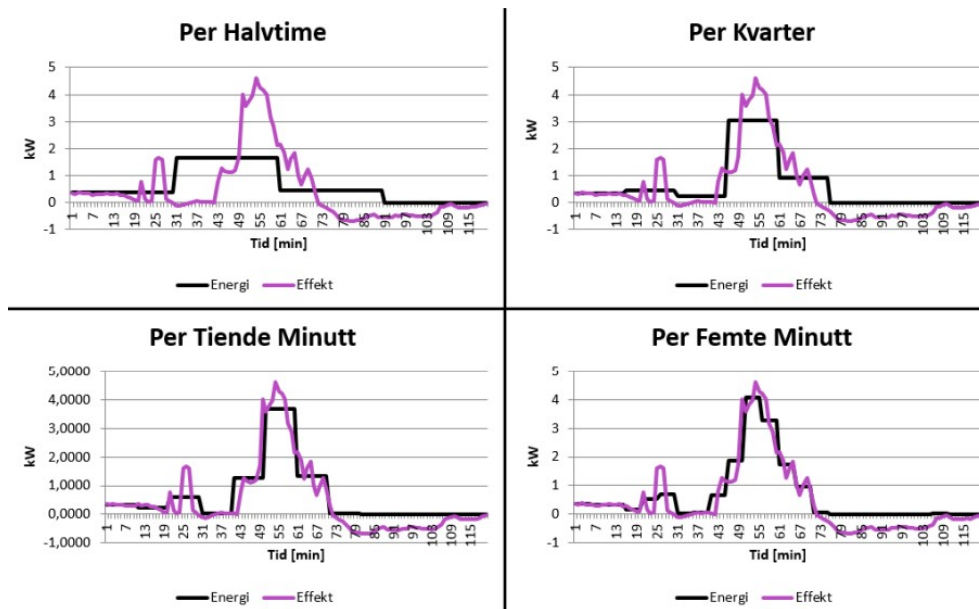


Figure 3: Different power resolutions [25]

It is not realistic that a household uses the hourly average power constant the entire hour, and it will therefore vary with power peaks for a fraction of the time. To look at a part of an hour is called intra-hourly metering. Since the DSO needs to keep the voltage $\pm 10\%$ of nominal voltage averaged over a minute, the smallest time resolution needed is one minute. The DSOs in Norway does not have access to the minute resolution and can only look at the hourly energy usage for each individual house. The benefit of using smaller time regulation is that the intra-hourly metering becomes much closer to the actual power usage. In Figure 3 taken from [25], there are four different time steps used. The 30-min resolution does not catch the power peak between 50-60 min, the 15-min resolution is closer. However, it is not until the 10-min resolution the peak is displayed closely. The 5-min resolution is almost perfectly displaying the power peak.

2.4 Co-simulation

For this thesis, co-simulation is used for an optimization model and a simulation model to be able to work together. Co-simulation is used for the two models to exchange data, to improve the simulated voltage level.

According to [26], co-simulation is a way to synchronize two or more algorithms on different platforms (sub-simulators) into one simulation. This is done via the co-simulation platform, where the different models are synchronized and exchange data. When the sub-simulators synchronize, there is an exchange of information between the sub-simulations. Outside the synchronization, there is no exchange of information between the models. This makes co-simulation a highly flexible way when dealing with complex systems with multiple simulations that need to exchange information.

Co-simulation is different from hybrid and parallel simulation by simulating in different programs, and being co-dependent on the result from the other simulation [27]. Parallel simulation uses many solvers for one model, while hybrid simulation uses more than one solver for one model. This is shown in Figure 4 taken inspiration from [27].

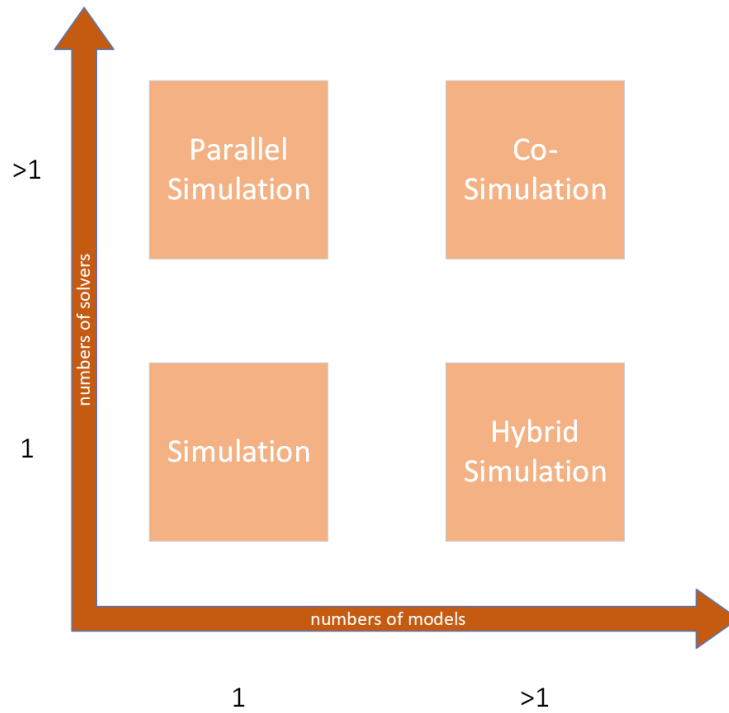


Figure 4: Co-simulation vs hybrid and parallel simulation [27]

There are many ways to use co-simulation. This section is a literature review on different ways co-simulation has been used in power grid applications. A big part of the literature is on power market, PV power generation and energy community. Power market and energy community is not a part of this thesis, but the literature provides a good understanding on how co-simulation can be used. Ref. [28] uses co-simulation for Smart Grid applications. The authors used co-simulation to combine domain specific systems engineering (DSSE) and smart grid architecture model (SGAM) to be able to look at the electric vehicle charging patterns and the utilization of PV generated electricity. The co-simulation platform Mosaik was used to help synchronize and

exchange data. Mosaik is made specifically for smart grid application. In the study, there were 30 EV's, 50 households and 30 PV with a price simulation generation. Three time steps are used, fifteen minutes, three minute and one minutes for different part of the system.

In [29] they have used co-simulation to be able to have a fast and reliable market clearing for the energy sale in the microgrid, and also have simulated the home energy management system (HEMS). One model looked at the market platform, HEMS and billing, while the other model looked at the real life conditions of the system such as weather, building models, physical devices and controllers.

The co-simulation platform HELICS was used in [30] to simulate 5 different entities in the energy market, whilst using high-quality models that need to operate on a small timescale (OpenDSS). They integrated different models. One captures thermal building performance with HVAC (Heating, ventilation, and air conditioning). All the flexible assets in the system are controlled by the HEMS, which this is modeled in the second model. The last model is one of the bidding agents that takes into account all the flexible assets and PV. Because of the complexity in each model, co-simulation made the computing time short compared to hybrid simulation.

Ref. [31] used co-simulation to simulate the peer-to-peer energy trading simulation and the electricity distribution network. They used a typical European suburb to see if a decentralized trading would have an impact on the power grid. The result was lower reliance on grid import of electricity. However, they did not have a big enough sample size to conclude how a large-scale adoption of local production and distribution would impact the system. In Ireland the EnerPort project [32] looked at how blockchain and peer-to-peer could be used for power trading platform. Blockchain is used to keep a public ledger of all the trades that occur. The authors list many reasons for peer-to-peer trading such as ease of trading, no third party involvement because the blockchain is proof of the trade, assured payment and many more. Ref. [33] looks at how to set up a co-simulation framework for a blockchain based market.

In [9], they set up a co-simulation model for monitoring the voltage in real time using smart metering connected to the Internet in Sweden. The authors found a cheap and easy way of monitoring the voltage by using two models. One was for power process and the other for communication network. There is a need for monitoring the power quality in smart grid projects, and make a platform to relay the correct information from the metering to the DSO. The platform therefor makes it possible to do real time analysis and communication in the LV, and compare it to the strategies.

The paper [34] uses co-simulation to analyze PV rich communities, and the impact of the PV generation on the distribution grid. They have one model for the PV generation by use of weather data to predict the volatility for the PV generation. They then use flexible thermal loads to cover the volatility, to stabilize the voltage in the distribution grid. Instead of charging and discharging a battery, they heat up the buildings with the excess power.

3 Methodology

This section presents the methods and models used to be able to have co-simulation for a prosumer in the LV distribution grid. The section is based on [1], the optimization model is the same as in the specialization model, whilst the Simulink is based on the model from the specialization model. The house has power generation from PV, a battery, and is connected to the power grid, ref Figure 3.2. The house is not connected to any other participants in the local energy community. The model in Section 3.2 dictates how the battery charges and discharges. In Section 3.1 the impact on the power grid in point of common coupling (PCC) is explained, and in Section 3.3 the model for simulating how the power grid is affected by the house at PCC is described. At PCC, the battery and the house are two separate loads that simulate the charging and discharging from the battery and PV generation and load for the household. The models in Section 3.2, 3.1 and 3.3 are inspired by the models described in [35].

3.1 MATLAB as co-simulation platform

MATLAB is used as the co-simulation platform. The data exchange between Python and Simulink is done with in MATLAB. Figure 5 is based on a figure from [35]. The figure illustrates how MATLAB have different functions within the framework. Both Simulink and the script examined in Section 3.4 are done within MATLAB. The optimization model in Python is started from MATLAB, and the results are imported to Simulink through MATLAB. Python runs the optimization for 24 hours at the time. If the Simulink simulation is over 24 hours, the MATLAB runs the optimization model multiple times.

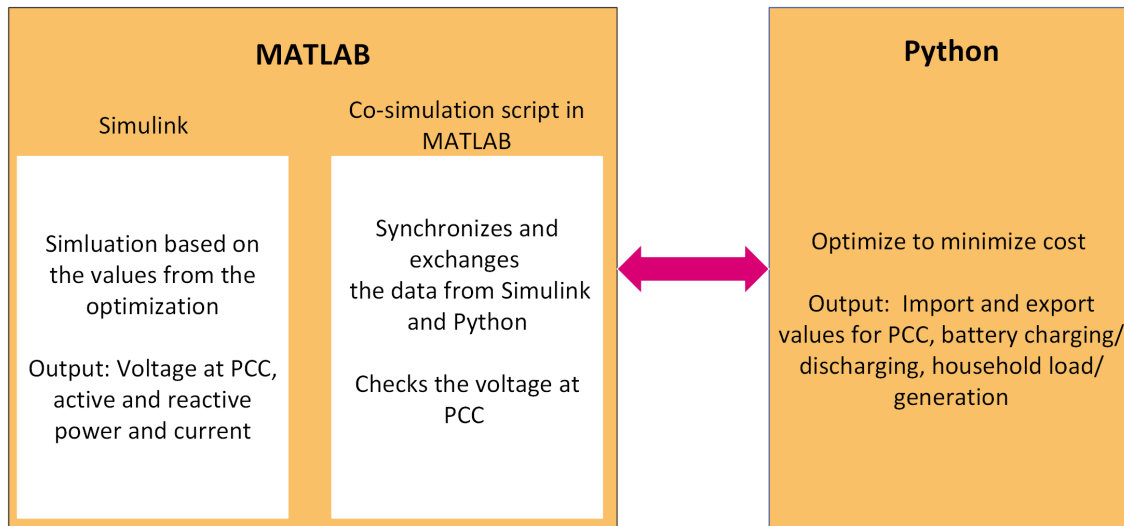


Figure 5: Co-simulation model based on [35]

3.2 Optimization

The model below, (1), is an optimization model to minimize the cost for using electricity for a household. This is done with regard to import and export from the power grid, PV generation and battery storage. Figure 6 shows where the variables and parameters are used.

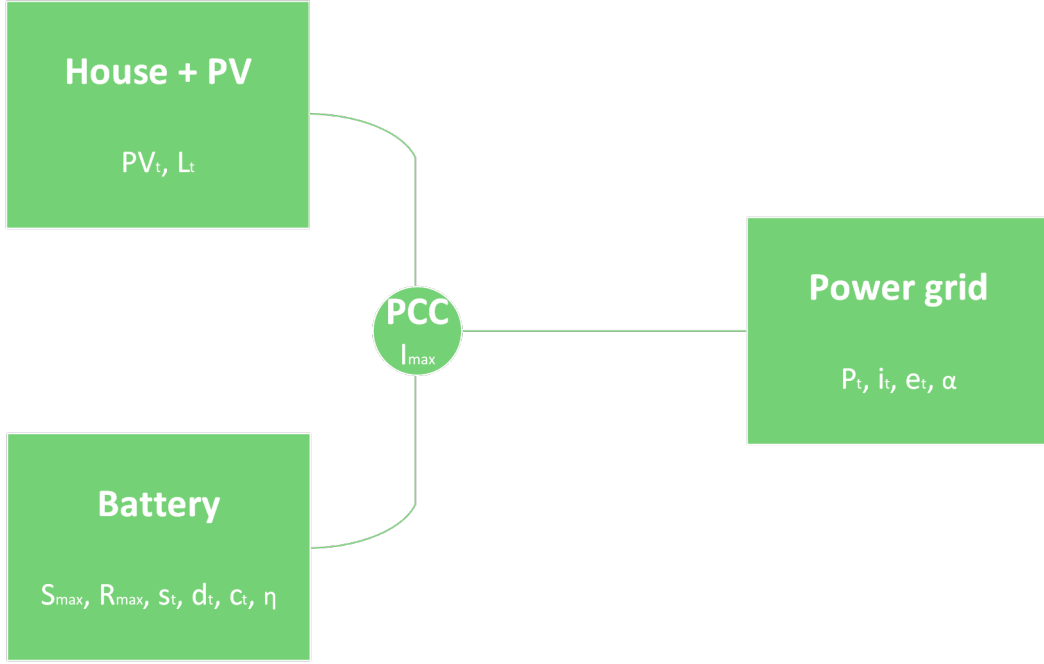


Figure 6: Overview of variables and parameters

$$\begin{aligned}
\min \quad & \sum_{t \in T} ((P_t + \alpha) \cdot i_t) - \sum_{t \in T} (P_t \cdot e_t) & (1a) \\
\text{s.t.} \quad & \\
& \sum_{t=1}^T c_t \cdot \sqrt{\eta} = \sum_{t=1}^T \frac{d_t}{\sqrt{\eta}} & (1b) \\
& c_t \leq R_{max} & \forall t \quad (1c) \\
& d_t \leq R_{max} & \forall t \quad (1d) \\
& d_t \leq \frac{s_t}{\eta} & \forall t \quad (1e) \\
& s_1 = \frac{S_{max}}{2} & (1f) \\
& s_{24} = s_1 & (1g) \\
& s_t = s_{t-1} + c_t \cdot \sqrt{\eta} - \frac{d_t}{\sqrt{\eta}} & t > 1 \quad (1h) \\
& d_t + PV_t - e_t + i_t = L_t + c_t & \forall t \quad (1i) \\
& i_t \leq I_{max} & \forall t \quad (1j) \\
& 0 \leq s_t \leq S_{max}, c_t \geq 0, d_t \geq 0, i_t \geq 0, e_t \geq 0 & \forall t \quad (1k)
\end{aligned} \tag{1}$$

The corresponding notation is the following:

- P_t is the electricity spot price in hour t [NOK/kWh]
- i_t is the power imported from the grid in hour t [kWh]
- e_t is the electricity exported from the grid in hour t [kWh/h]
- c_t is the charging of the battery in hour t [kWh/h]

-
- d_t is the discharging of the battery in hour t [kWh/h]
 - L_t is the load for the house in hour t [kWh/h]
 - s_t is the state of charge for the battery in hour t [kWh/h]
 - η is the round-trip efficiency of the battery [%]
 - R_{max} is the maximum rate for charging/discharging the battery [kWh/h]
 - α is the grid tariff for electricity [NOK/kWh]
 - S_{max} is the maximum charge of the battery [kWh]
 - PV_t is the electricity generated by the PV in hour t [kWh/h]
 - I_{max} is the maximum power that can be imported from the power grid in hour t [kWh]

Constraint (1a) is the objective function. It minimizes the cost for purchasing electricity. The grid tariff is applied when you buy the electricity, but not when you sell. Both an import variable (i_t) and an export variable (e_t) are needed because of the different cost associated with the different variables. The constraint in (1b) makes sure that the amount of electricity that is charged in the battery is the same that is discharged when efficiency is taken into account. Constraint (1c)-(1e) make sure that charging and discharging do not exceed the maximum ratings or the amount that is in the battery. The model simulates for 24 hours at the time, and the battery has to be set at the same level for the start and the end of the simulation so that there is no free energy in the system. To make sure that the battery is at half charge at the start and end of each day, constraints (1f) and (1g) are implemented. Constraint (1h) is there to ensure that the state of charge for the battery is the difference of the charging/discharging and the previous hour's state of charge. The power balance is controlled in (1i). Constraint (1j) is there to make sure that the voltage is within the given parameters and is regulated in the co-simulation process by regulating the amount of power at PCC. It is important that the state of charge for the battery is between or equal to 0 and max state of charge. Charging, discharging, import and export all have to be higher or equal to 0, (1k).

3.3 Simulink model

The Simulink model is simulates the voltage on the power grid from the battery charging and discharging. A slight change in the charging/discharging from the battery might lead to different values of the voltage at PCC. The Simulink model is set up in two layers. The upper layer is the model of the power grid and where the communication between MATLAB and Simulink happens. Figure 7 shows the setup for the upper layer and is divided in three parts. Each part is described in Section 3.3.1. The second layer is the lower layer shown in Figure 8, and is described in Section 3.3.2. The connection between the two layers is described in Section 3.3.1. The lower layer is divided into ten parts, described in Sections 3.3.2.

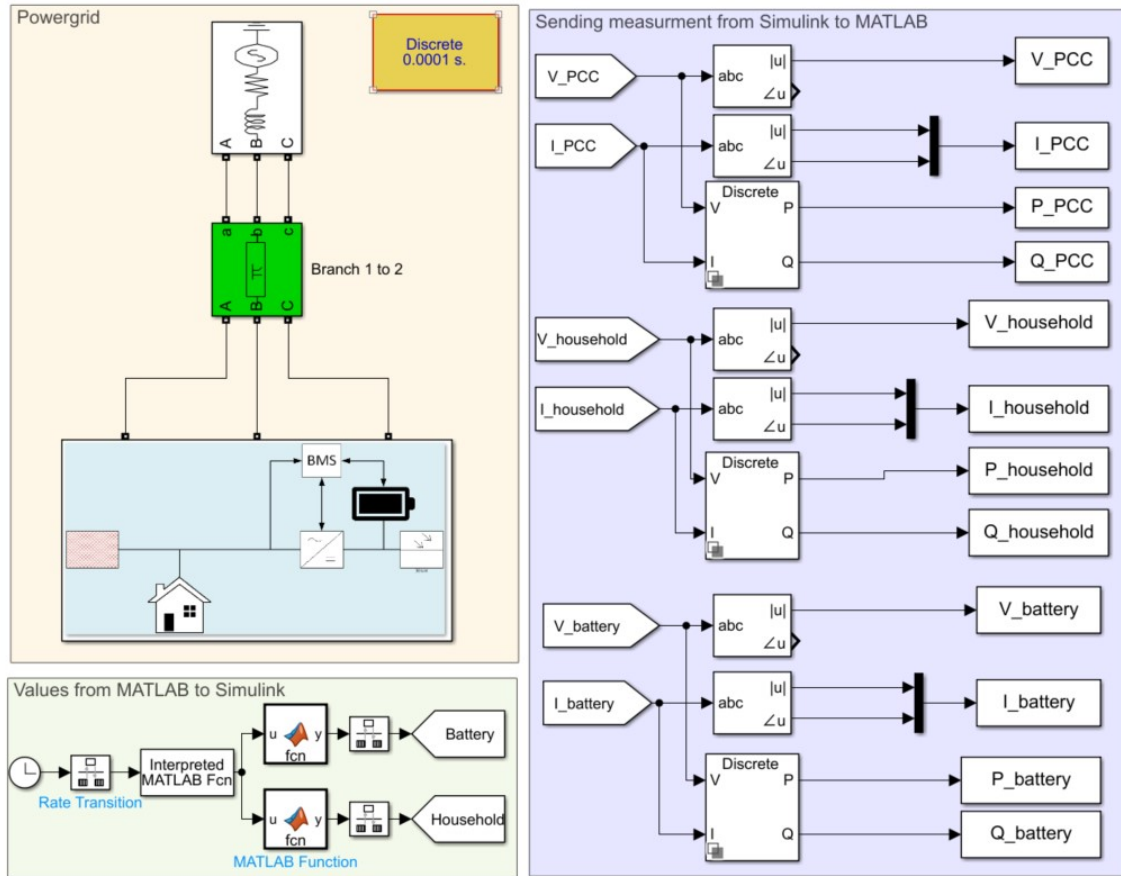


Figure 7: Upper layer power system and connection between MATLAB and Simulink

3.3.1 Upper layer

An explanation on "Values from MATLAB to Simulink" can be found in Appendix A.1.

Power grid

The power grid part in Figure 7 has four blocks. At the top center there is a power source of 400V (line-line) with internal impedance. The green block is a representation of the impedance on the line from the power source to the house. Line impedance is there to represent the voltage drop from a real line. The impedance is given in positive and zero sequence resistance, inductance and capacitance per kilometer. The length and frequency of the line are inputs. The large block at the bottom of the figure is the subsystem that is shown in Figure 8 and described in Section 3.3.2. The values from the power grid are sent to the area marked "From power grid" in Figure 8. The fourth block is not connected to any other block. It is the timer for the whole simulation. It is set to "Discrete 0.0001s". Simulink works in seconds, but for this simulation the unit is hours.

Sending measurement from Simulink to MATLAB

The measurement from the lower layer is sent to the six From blocks to the left in the purple area to the right in Figure 7. From the three measurements, a voltage and a current value are sent.

There are three parallel processes happening, one for each of the measurement points. The same happens for all. The two top blocks are sequence analyzers. It takes the positive sequence from the voltage or current measurements and analyses that. For the voltage, it sends the magnitude of positive sequence to the next block. While for the current, it sends both magnitude and angle. The reason to get both the magnitude and angle is to make the direction of the current visible. As the magnitude is always positive, the angle is measured to see if the current is going into the loads in "Three-phase dynamic loads for house and battery". This is not needed for the voltage, since that is always positive. Under the sequence analyzers, there is a block that calculates the active and reactive power from the voltage and current measured. The blocks to the right are To Workspace blocks and sends the values from Simulink to MATLAB.

3.3.2 Lower layer

The lower level model is shown in Figure 8. It has ten parts. There are two power peak parts, which are identical, one for household load/generation and one for battery charging/discharging. The yellow block "From Power grid" is the connection between the upper and lower layer. The three lines that goes into the bottom block in the upper layer are the three lines that start in the yellow area. An explanation on "Timestamp" can be found in Appendix A.1.

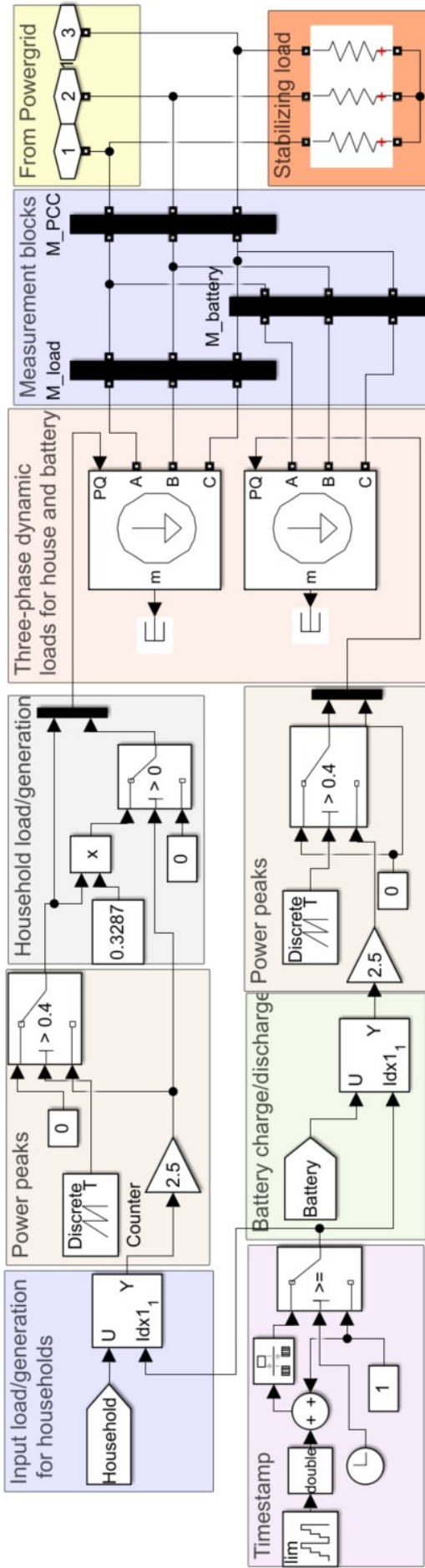


Figure 8: Lower layer set up for Simulink

Input load/generation for households

The MATLAB outputs come as a vector into the Simulink model from the From block labeled Household in Figure 8. In a simulation, a vector of values can be interpreted different ways. The block to the right in the violet area is a selector block. It takes the vector from Household and matches it with the other side connected to the selector. In this case, the output from Timestamp, the hour of the day. Hence, the output from the selector block will be the vector value where the index position matches the hour of the day. The first vector value in hour 1, the second vector value in hour 2 and so on.

Power peaks

There is not always a continuous power flow within any given hour, as explained in Section 2. The values from the optimization in Python are given in an hourly average for every hour. Power is used/produced instantaneous. To simulate that instantaneous power peaks, the hourly average is multiplied by a factor for a shorter time. To make sure that the hourly average is the same with and without power peaks, the time is inversely proportional to the factor. In Figure 9 there are four blocks that switches on and off the power to simulate power surges within the hour. The block to the right is a switch that turns on and off the power. The triangle in the bottom is a gain block. It takes the power from "Input load/generation" for the household and gains it by a factor, or "Battery charge/discharge for the battery and gain it by a factor. In Figure 9 that factor is 5. The switch turns off after $1/factor$. In the figure, that time is $1/5$ of an hour. The "Discrete" block keeps track of time within the hour. It sends a continuous increasing signal from 0 to 1 in every hour. The block in the top is a block that gives a constant power. As this configuration of blocks is simulating a surge and then turning off, the constant block is 0.

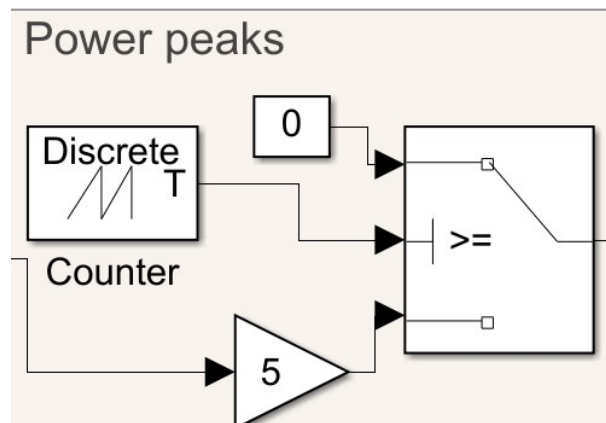


Figure 9: Power peaks

Household load/generation

The reactive power for the household is set to a constant factor of the active power. With a power factor (PF) of 0.95, the reactive power is 32.87 % of the active power (see eq. (2)). The block in the middle of the gray area in Figure 8 is a multiplier, and it takes the active power and multiplies it with 0.3287 to get the reactive power. The black block to the right in the gray area is a multiplexer, and it takes two signals and sends them together as two signal on top of each other. Both active

and reactive power. This is done because the dynamic loads discussed in "Three-phase dynamic loads for house and battery" needs the active and reactive power together in the same input.

$$Q = P * \tan(\arccos(PF)) \quad (2)$$

Where Q is reactive power, P is active power and PF is the power factor.

Battery charge/discharge

To the right in the green area in Figure 8 is a From block that is corresponding to the Goto block described in "Values from MATLAB to Simulink". The selector block and mux works the same way as described in "Input load/generation for households".

Three-phase dynamic loads for house and battery

The active and reactive power for the battery and household come from "Battery charge/discharge" and "Household load/generation". There are two three-phase dynamic loads, one for the battery and one for the household. They are connected in parallel with the three phases from the power grid, and have an input for active and reactive power "PQ". The output to the left in Figure 8 is not used further and is connected to a terminal block.

Measuring blocks

There are three measurement blocks in Figure 8, one for PCC, one for the household and one for the battery. The measurement block measures the phase to ground voltage for each of the phases. In each block, there are two Goto blocks that sends the values to a corresponding From block in "Sending measurement from Simulink to MATLAB". The active and reactive calculations in "Sending measurement from Simulink to MATLAB" are phase to phase calculation, so the measurement blocks also send that.

Stabilizing load

The orange area in the bottom right of Figure 8 is a stabilizing load. There are three resistive loads, one for each phase. They are connected in a Y formation. The load is in parallel to the three-phase dynamic loads for house and battery. Due to the large resistance, there is almost no current going through the load.

3.4 Co-Simulation setup

Co-simulation is set up through a script in MATLAB, and the script starts the optimization model and the Simulink simulation. The results from Simulink are processed in the script. The voltage at PCC during the simulation period is analyzed by the co-simulation platform, the lowest and highest voltage is saved. If the voltage is outside given parameters, $\pm X$ percent of nominal voltage, there is a voltage violation. The highest and lowest voltage values for the simulation are compared

to the minimum and maximum values that the voltage can be. If Eq. (3) and Eq. (4) are satisfied, the process is complete. However, if one or both of the constraints are violated, the imported power constraint changes. This is done by increasing or decreasing imported power by a given amount and repeating the optimization and Simulink process. This is repeated until both Eq. (3) and Eq. (4) are satisfied.

$$voltage_{top} \leq nominalvoltage * (1 + X\%) \tag{3}$$

$$voltage_{bottom} \geq nominalvoltage * (1 - X\%) \tag{4}$$

The entire co-simulation process is shown in Figure 10.

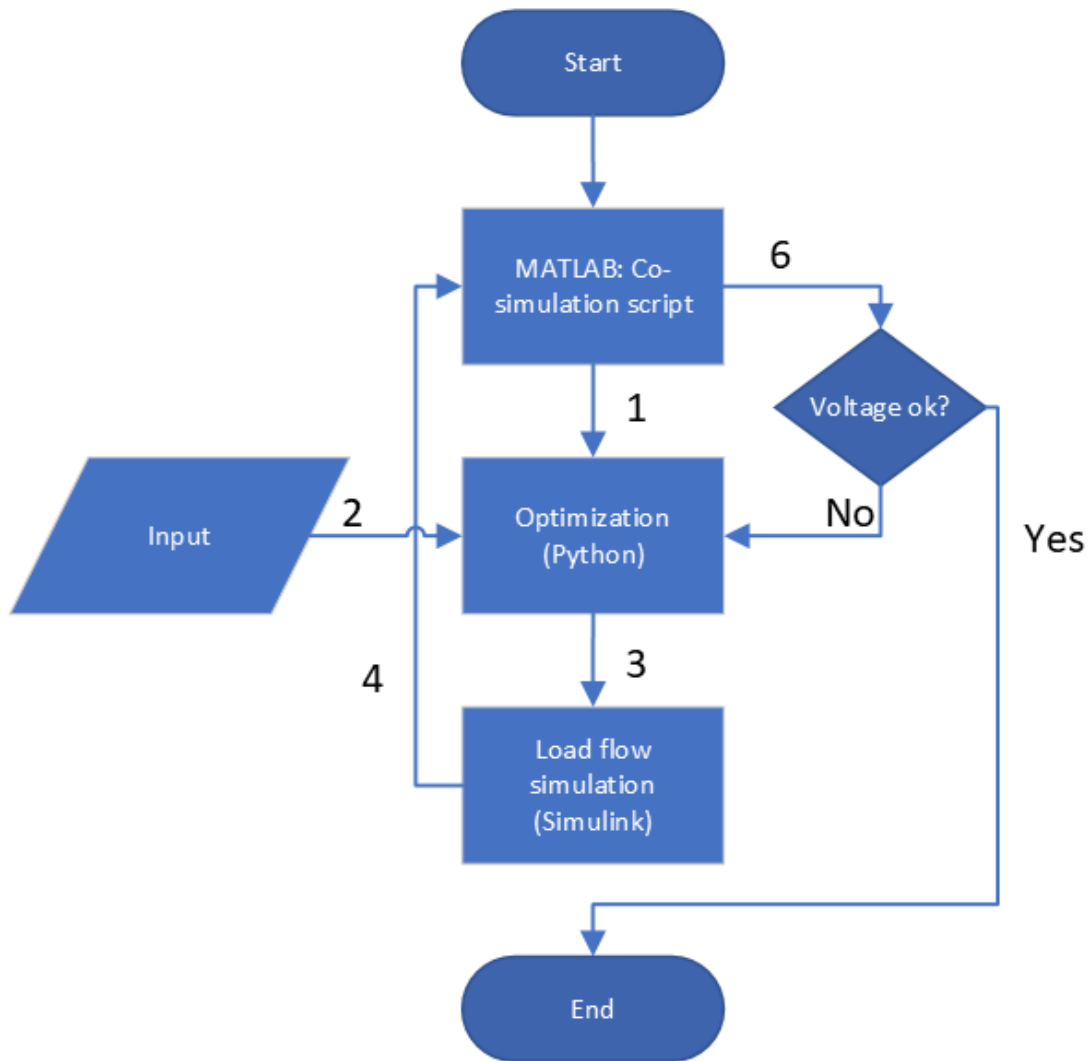


Figure 10: The flow in co-simulation case

The co-simulation have the following steps:

Step 1: The co-simulation script starts the optimization.

Step 2: All the data is collected from CSV files.

Step 3: When the optimization is done, the values are exported to Simulink through the co-simulation platform.

Step 4: The Simulink results are export to MATLAB.

Step 5: Checks if eq. (3) and (4) are satisfied. If the voltage is too high or low, the I_{max} in optimization model is lowered by a step with a predetermined step size. Then the process continues from Step 2.

4 Co-simulation case study

This section showcases a case study of a house with the models from Section 3. Some parts of this section is based on [1]. There are four base case results: Winter, spring, summer and autumn in the optimization and simulations. Six results with a battery of 3.3 kWh: Power peaks for winter and summer. Six results with a battery of 15 kWh: Power peaks for winter and summer. The 16 results illustrate how the model operates with different input data at different parts of the year.

The data set that has been used for this case study contains values for 99 houses from Steinkjer in 2015, and was given by SINTEF Energy Research as a part of the FINE research project [8]. Only the data for one house is used. The data for load is given for an entire year in an hourly resolution. The PV is from a 3 kWp panel, the power generation is simulated for every hour in the year. The price is taken from Nord Pool price zone NO3/Trondheim every hour in 2015 [36].

4.1 Setup for the cases

Three cases are defined. A base case where the hourly metering data is used for the entire hour (power peak factor is 1), and the battery is 3.3 kWh power peak cases where three different power peak factors have been used, 2, 2.5 and 3 with the battery of 3.3 kWh. The battery case where power peak 2, 2.5 and 3 is used with a larger battery of 15 kWh.

4.1.1 Setup

The setup for the optimization model is found in Table 1. The grid tariff, round trip efficiency for the battery and max power at PCC is the same for all three cases. The battery capacity and max rate of charging/discharging is different for the battery case.

Table 1: Setup for the optimization for all cases

| | Base case | Power peak | Battery case |
|--|-----------|------------|--------------|
| Grid tariff (α) ^a | 0.206 | 0.206 | 0.206 |
| Round trip efficiency for the battery (η) | 95% | 95% | 95% |
| Battery capacity (S_{max}) | 3.3 | 3.3 | 15 |
| Max rate of charging/discharging (R_{max}) | 1.6 | 1.6 | 4.5 |
| Max power at PCC (I_{max}) | 4.5 | 4.5 | 4.5 |

^a This grid tariff is lower than the actual tariff from 2015 [37]

The setup for the Simulink model is found in Table 2. The data resolution, power line length, stabilizing loads and allowed voltage range are the same for all three cases. The base case does only use power peak factor 1 without step size because there is no need for change in I_{max} .

Table 2: Setup for the Simulink model for all cases

| | Base case | Power peak | Battery case |
|---|------------------|-------------------|---------------------|
| Data resolution (data points/hour) | 10 000 | 10 000 | 10 000 |
| Power line length (km) | 4 | 4 | 4 |
| Stabilizing load (kohm/phase) | 10 | 10 | 10 |
| Power peak factors | 1 | 2, 2.5, 3 | 2, 2.5, 3 |
| Voltage range compared to nominal voltage | $\pm 5\%$ | $\pm 5\%$ | $\pm 5\%$ |
| Step size for lowering I_{max} (kwh/h) | N/A | 1, 1.25, 1.5 | 1, 1.25, 1.5 |

4.1.2 Choise of days

The simulation of the optimization model in the Python script was done for each season of the year, December 21st, April 21st, June 16th and October 16th.

The active power load and PV generation all the days in December, compared to the 21st in Figure 11.

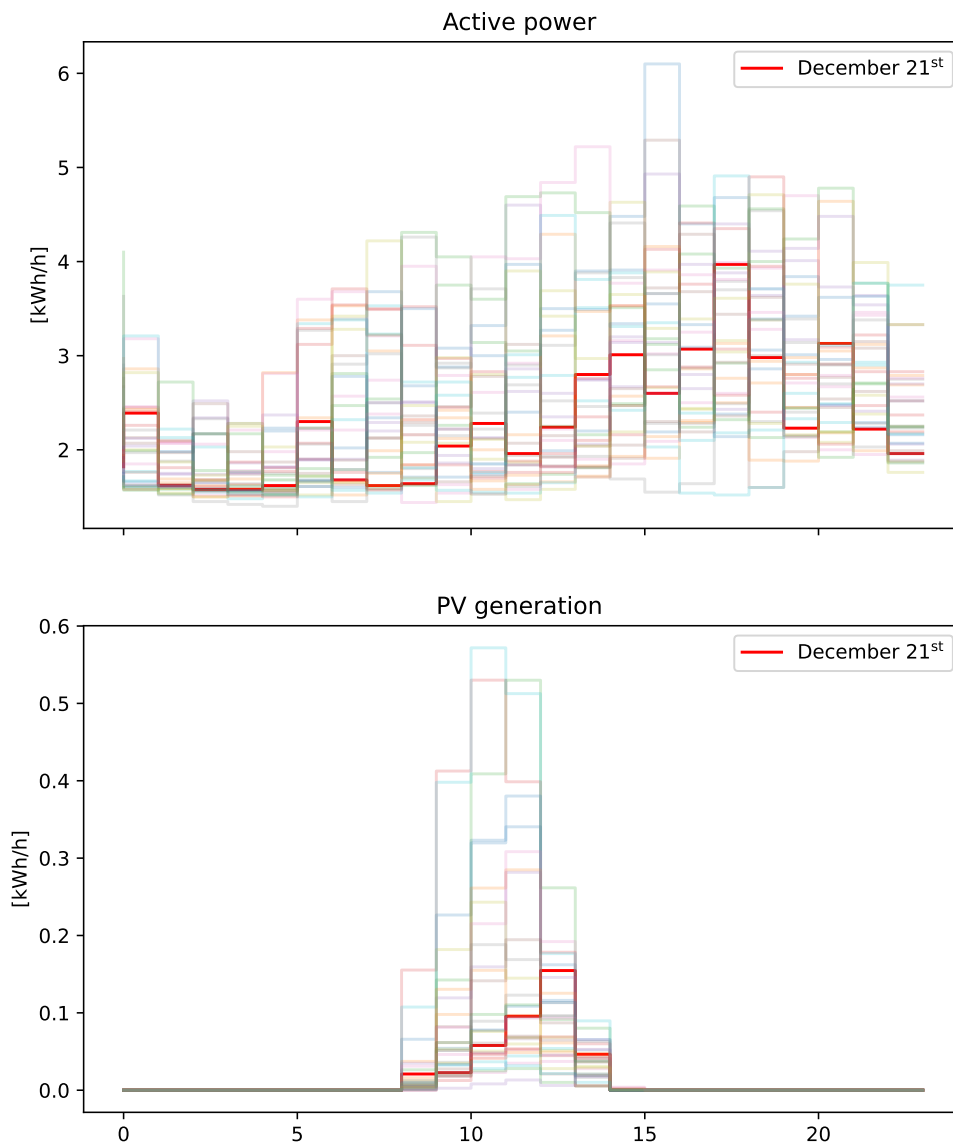


Figure 11: All the days in December compared to the 21st

The active power load and PV generation all the days in June compared to the 16th

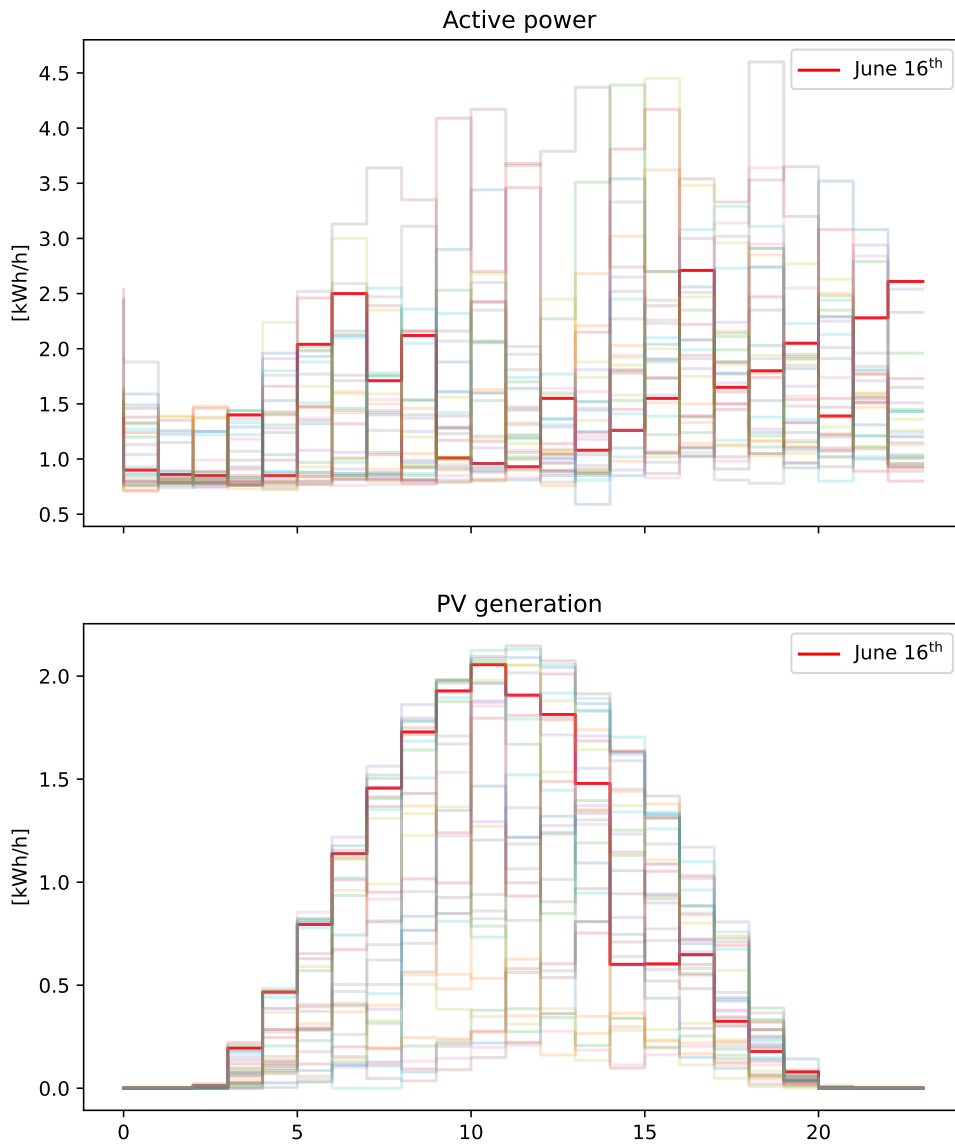


Figure 12: All the days in June compared to the 16th

The active power load and PV generation all the days in April, compared to the 21st in Figure 13.

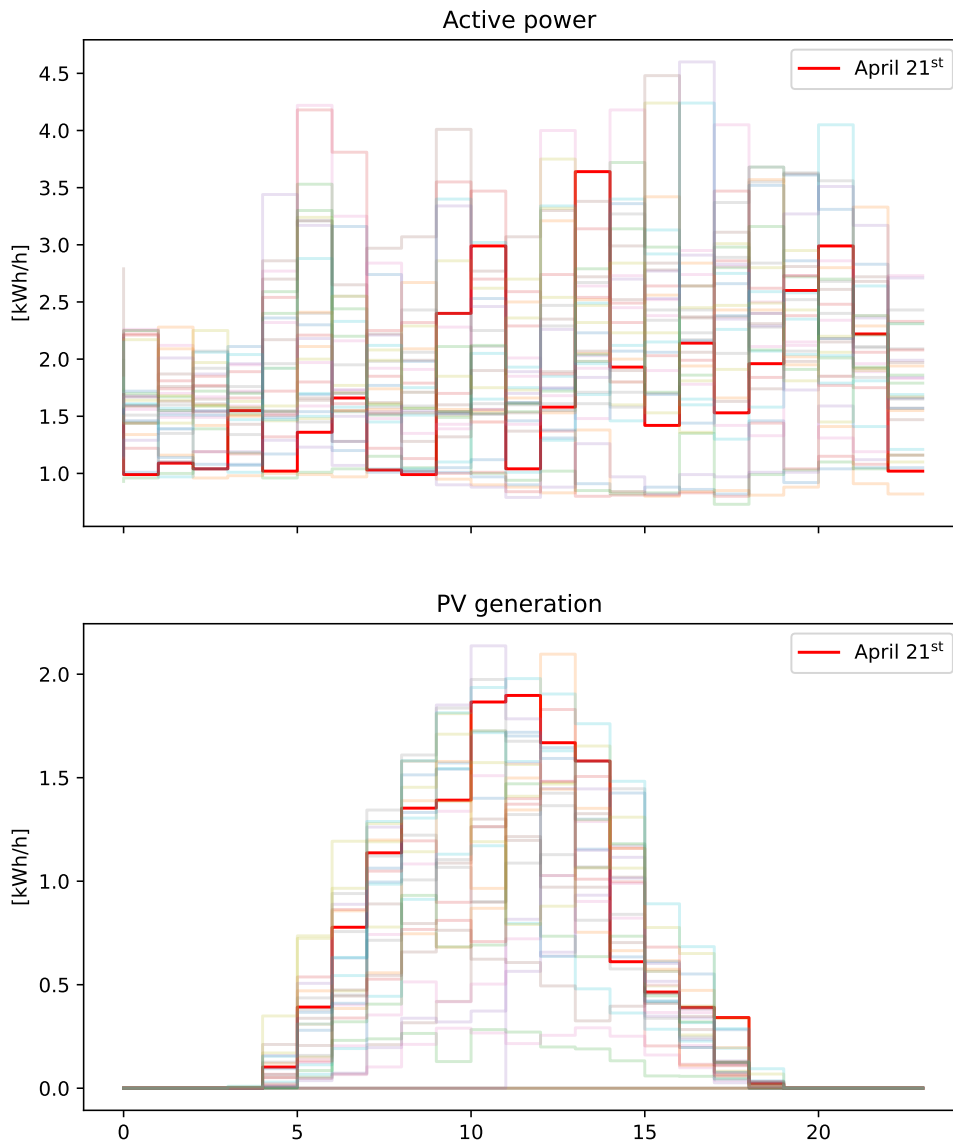


Figure 13: All the days in April compared to the 21st

The active power load and PV generation all the days in October compared to the 16th in Figure 14.

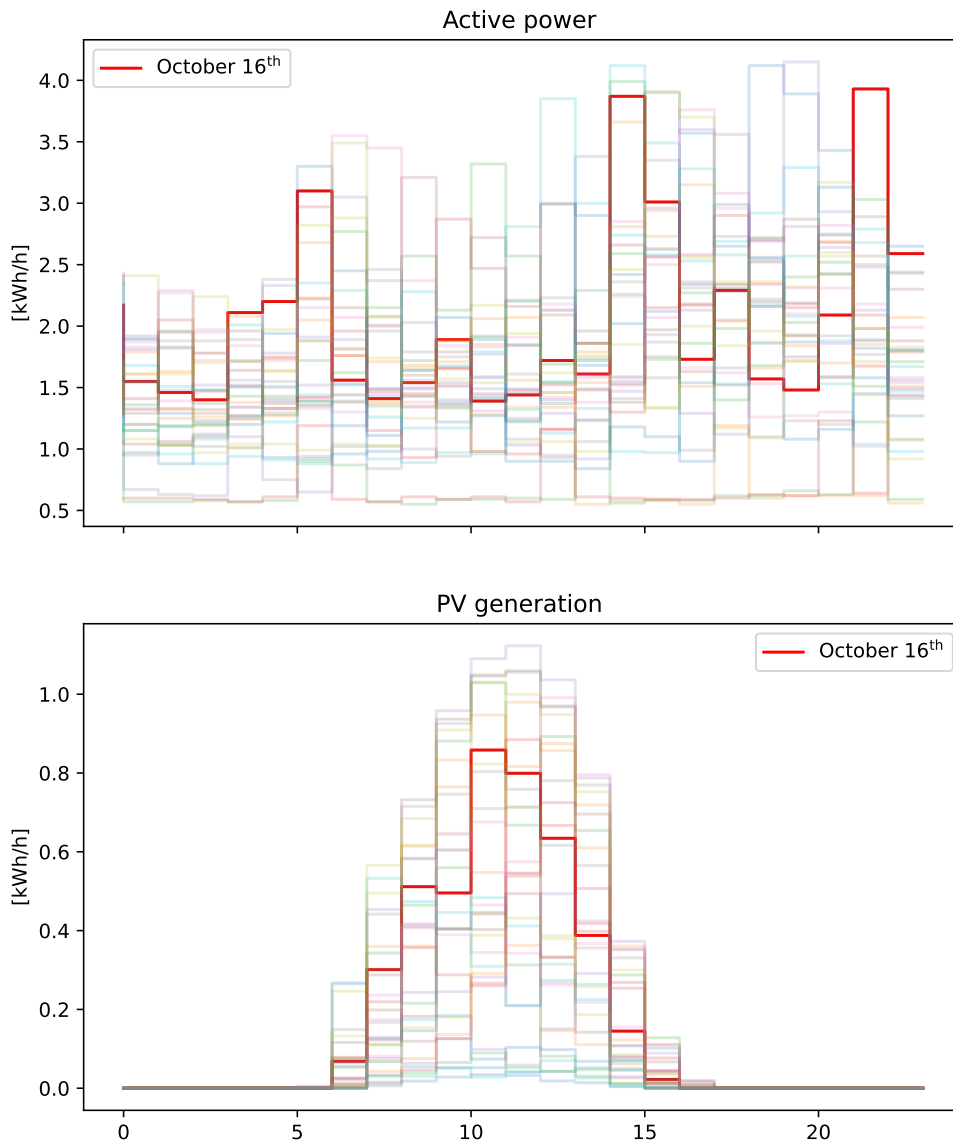


Figure 14: All the days in October compared to the 16th

4.2 Case results

The optimization and Simulink setup and results for each season of the base case are presented in this section. The power peak results for winter and summer are presented in this section. The power peak results for spring and autumn are in Appendix A.2 and A.3. A summary of the lowest voltages can be found in Tables 3 and 4.

In the figures for the optimization, there are four different graphs:

- Price
- Load curve
- State of charge for the battery
- Grid exchange

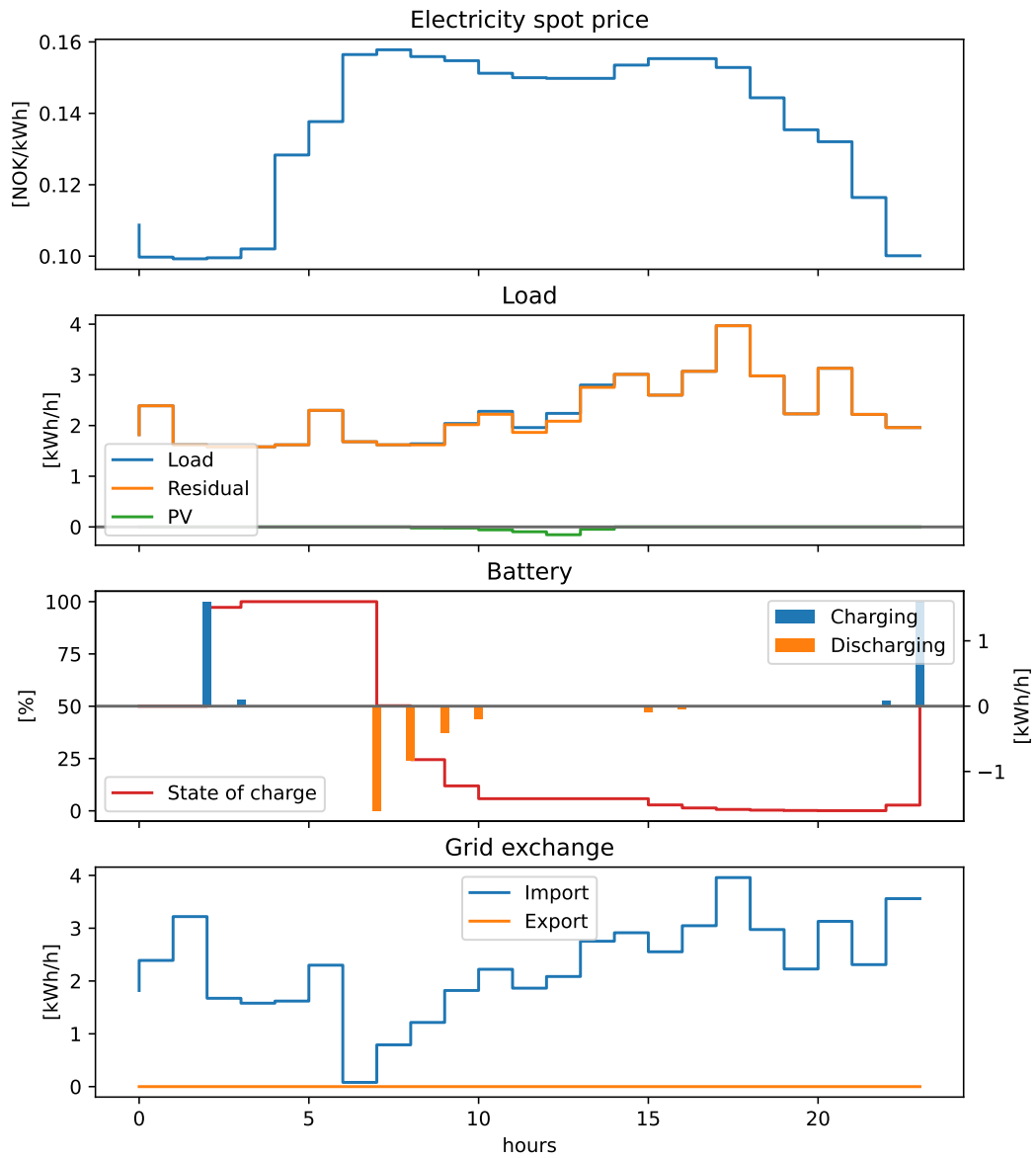


Figure 15: The results from the winter simulation, December 21st

For each of the base case plots, the measurements for battery, household and PCC is shown for each graph. The current in the plots has the convention of positive current is charging/load, and negative is discharging/generation from the battery or household.

In the figures of Simulink simulations, there are four different graphs.

- Current
- Voltage
- Active power
- Reactive power

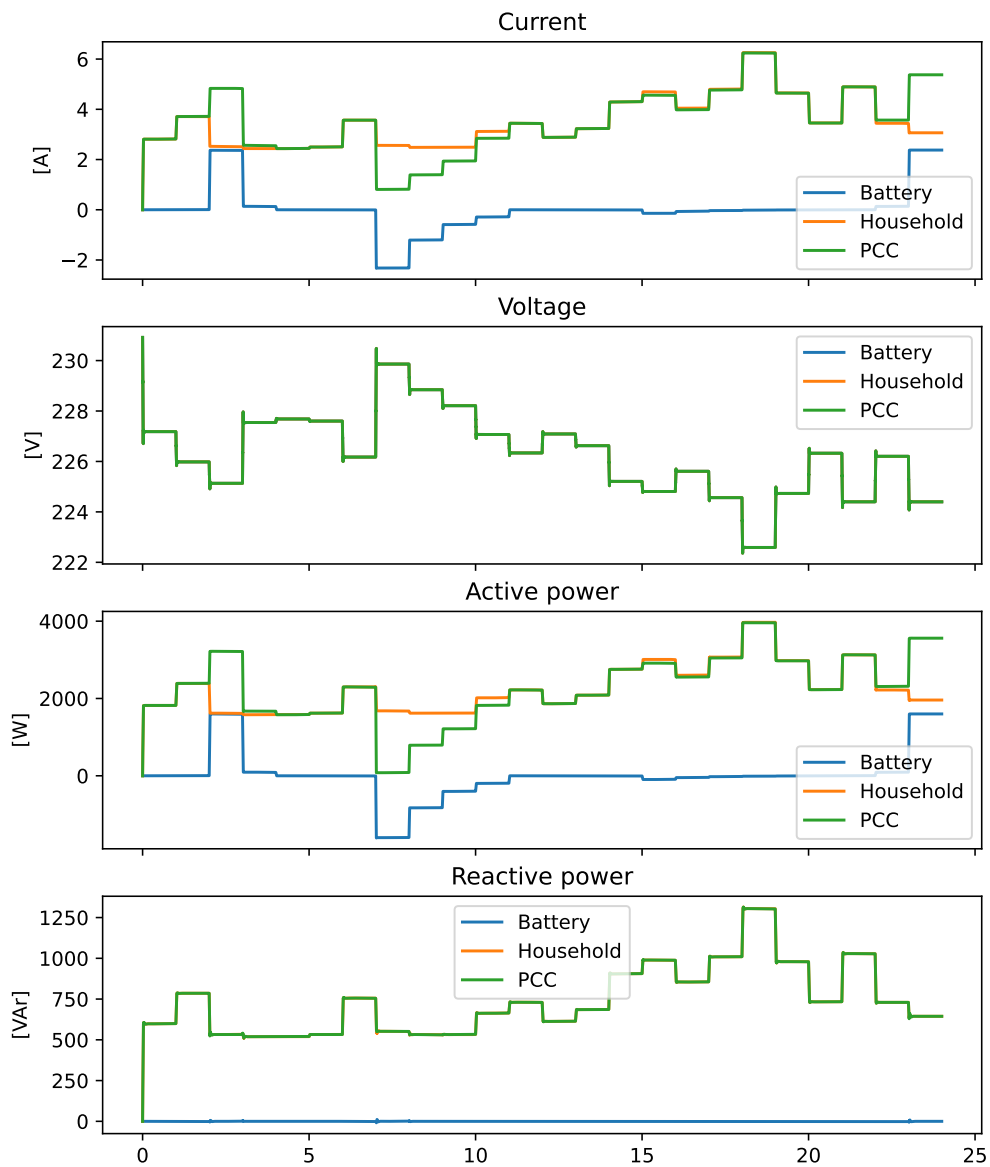


Figure 16: Base case winter

For each graph, there are three lines. The blue line is the battery, the orange is household and green is the measurement at PCC. The current and active power are inputs from the optimization, the reactive power is calculated to be 32.87% of the active power. The only output that is not given is the voltage, and that is what is interesting from the Simulink simulations.

The voltage graph only has one visible line. This is due to all the measuring points being in parallel, so the voltage is the same at all the three measuring points. At PCC, current and active power are the sum of current and active power of the battery charging/discharging and household load/generation.

The active power at PCC for each season in the base case is the same as the "Grid exchange" in the Figures 15-21. The base case has a power peak factor of 1 (see "Power peaks" in Section 3.3.2), giving it a constant power for the entire hour. Active power for the battery for each season are the same as "Battery" in the same figures because of the data input for the simulation is output from

the optimization.

The voltage in the graphs have spikes when there is load change, with a resolution of 10 000 measurements every hour there are often just a few measurements of a low or high voltage. This is due to the optimization being in hourly resolution, while Simulink has a resolution of $\frac{1}{10000}$. That will result in spikes in the figures.

4.2.1 Base case results

The results from the optimization are found in Figures 15, 17, 19 and 21. The results from the Simulink are found in Figures 16, 18, 20 and 22.

The price curve presents the spot price for the given day. The load graph has three different lines, one for the load for the house, one for the power generated from the PV and one for the residual load (load subtracted PV generation). The PV generation is shown as negative here to better display the impact on residual load, whilst it is positive in the optimization problem. The graph displaying the state of charge in the battery has two y-axes. The one on the left demonstrates the state of charge in the battery given by the red line, and the right axis demonstrates the charging and discharging of the battery. The convention of charging being positive and discharging being negative is used here to clearly show charging and discharging. However, it should be noted that in the optimization problem, both charging and discharging is positive. The grid exchange graph demonstrates the amount of power needed to import or export from the power grid for the house in the given hour, however it should be noted that in the optimization problem both import and export is positive.

In the optimization results figures, hourly values are used and therefore used stepwise graphing is used to show how the values change per hour.

The winter simulation in Figure 15 has an electricity spot price between $0.10 \frac{NOK}{kWh}$ and $0.16 \frac{NOK}{kWh}$, where the price is stable around $16 \frac{NOK}{kWh}$ from 07:00 to 19:00. The PV power generation is close to zero the entire day. The battery has two major charges at 03:00 and 23:00, and discharging between 06:00 and 09:00. There is import from the power grid the entire day, with the lowest at 06:00, close to 0 kWh/h import.

In Figure 16, the voltage the entire day is close to 230V, with spikes at the hour mark. It is lowest at 18:00 close to 227.5V and highest at 00:00 231V ($\frac{400}{\sqrt{3}}$ V). The reactive power for the Household and PCC are the same, 32.87 percent of the active household power.

The spring simulation in Figure 17 has an electricity spot price between $0.195 \frac{NOK}{kWh}$ and $0.225 \frac{NOK}{kWh}$. The PV generates electricity between 04:00 and 18:00. From 07:00 to 09:00, and 11:00 to 13:00, the residual load is below 0 kW. The battery is charged at 02:00 and is charged and discharged between 06:00 and 13:00. The import from the power grid is 0 kW between 05:00 and 09:00, and 11:00 and 13:00.

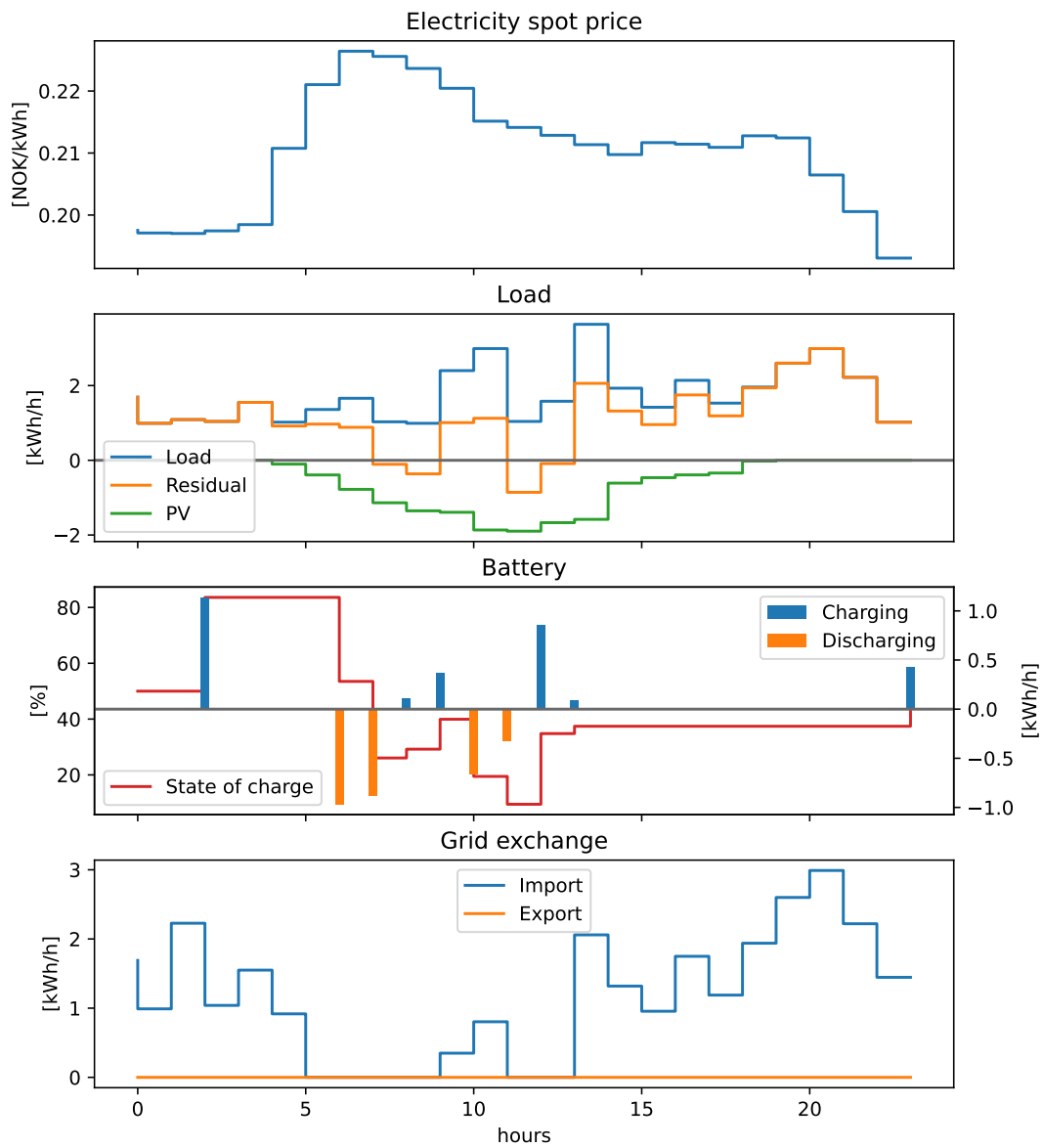


Figure 17: The results from the spring simulation, April 21st

In Figure 18, the voltage the entire day is close to 230V, with spikes at the hour mark. It is lowest at 21:00 close to 228V and highest at 12:00 231V. The reactive power for the Household and PCC are the same, 32.87 percent of the active household power.

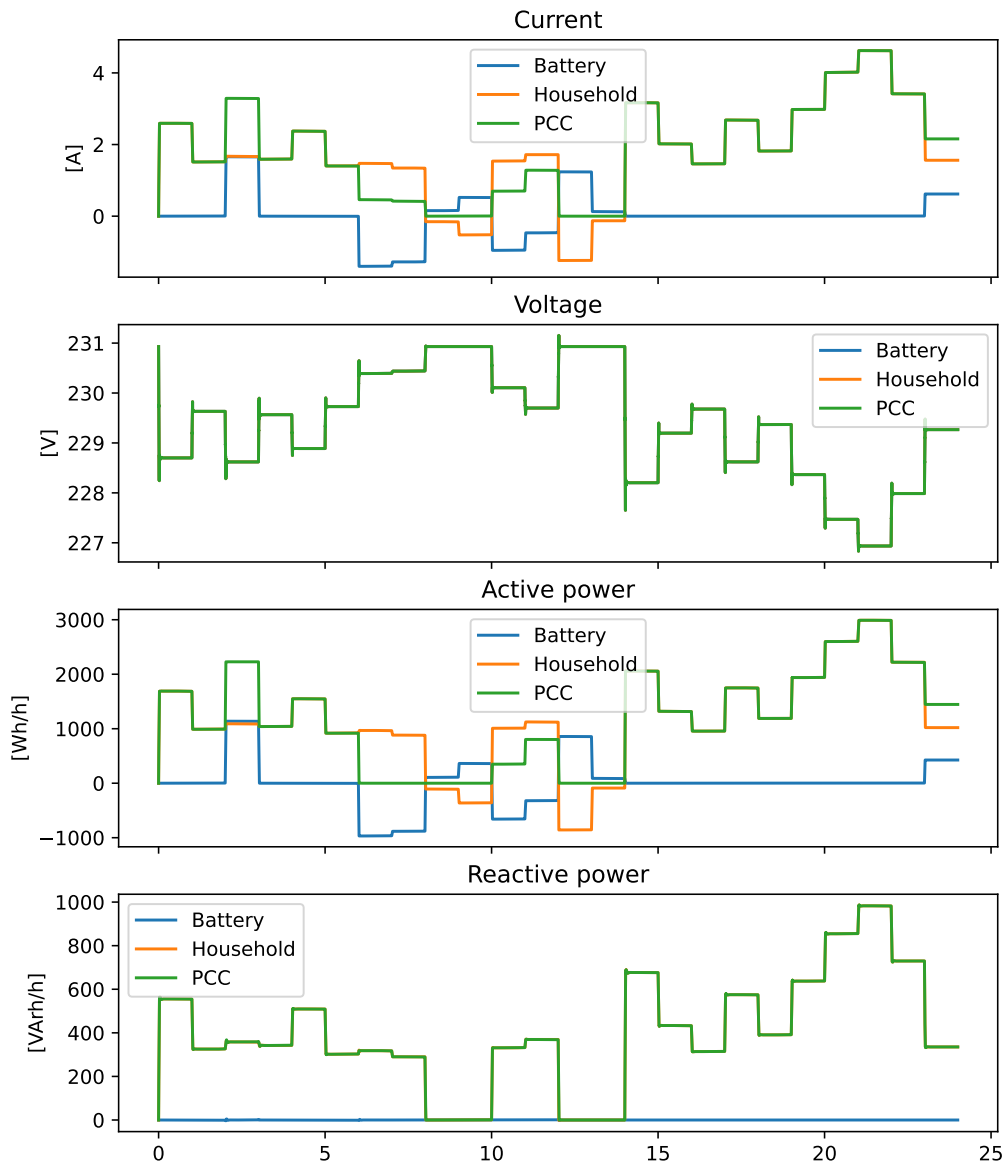


Figure 18: Base case spring

The summer simulation in Figure 19 has an electricity spot price between $0.09 \frac{NOK}{kWh}$ and $0.20 \frac{NOK}{kWh}$, with the peak around 06:00 to 10:00. There is PV generation between 03:00 and 20:00, and the residual load is negative between 09:00 and 14:00. The battery has three periods when it charges and two periods when it discharges though the day, alternating between charging and discharging. It is charging 02:00-03:00, 10:00-15:00 and 24:00, and discharging 06:00-10:00 and 15:00-20:00. The grid exchange is close to 0 kW from 04:00 until 16:00, with an export from 09:00 to 10:00.

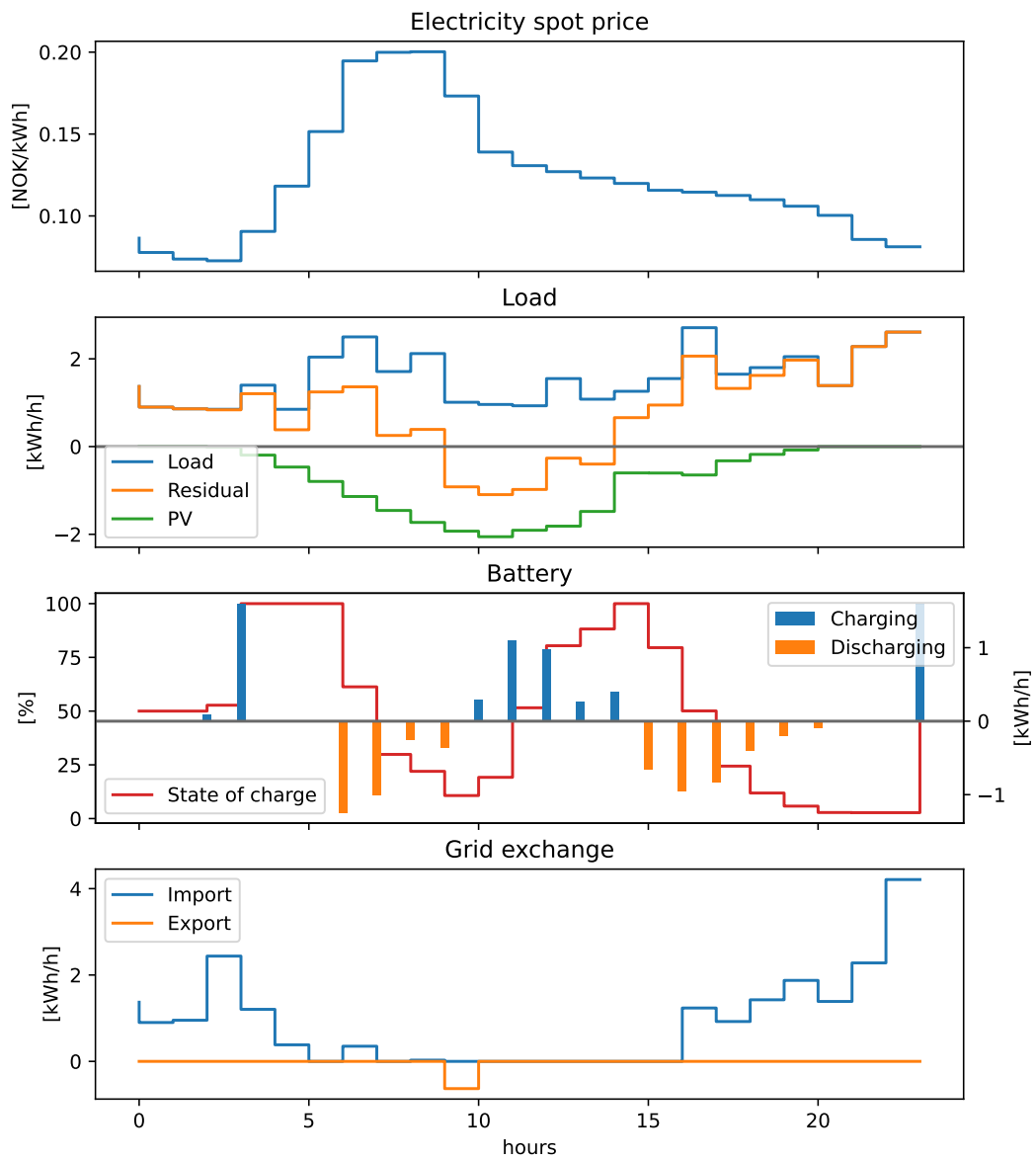


Figure 19: The results from the summer simulation, June 16th

In Figure 20, the voltage the entire day is close to 230V, with spikes at the hour mark. It is lowest at 24:00 close to 229.5V and highest at 11:00 232V.

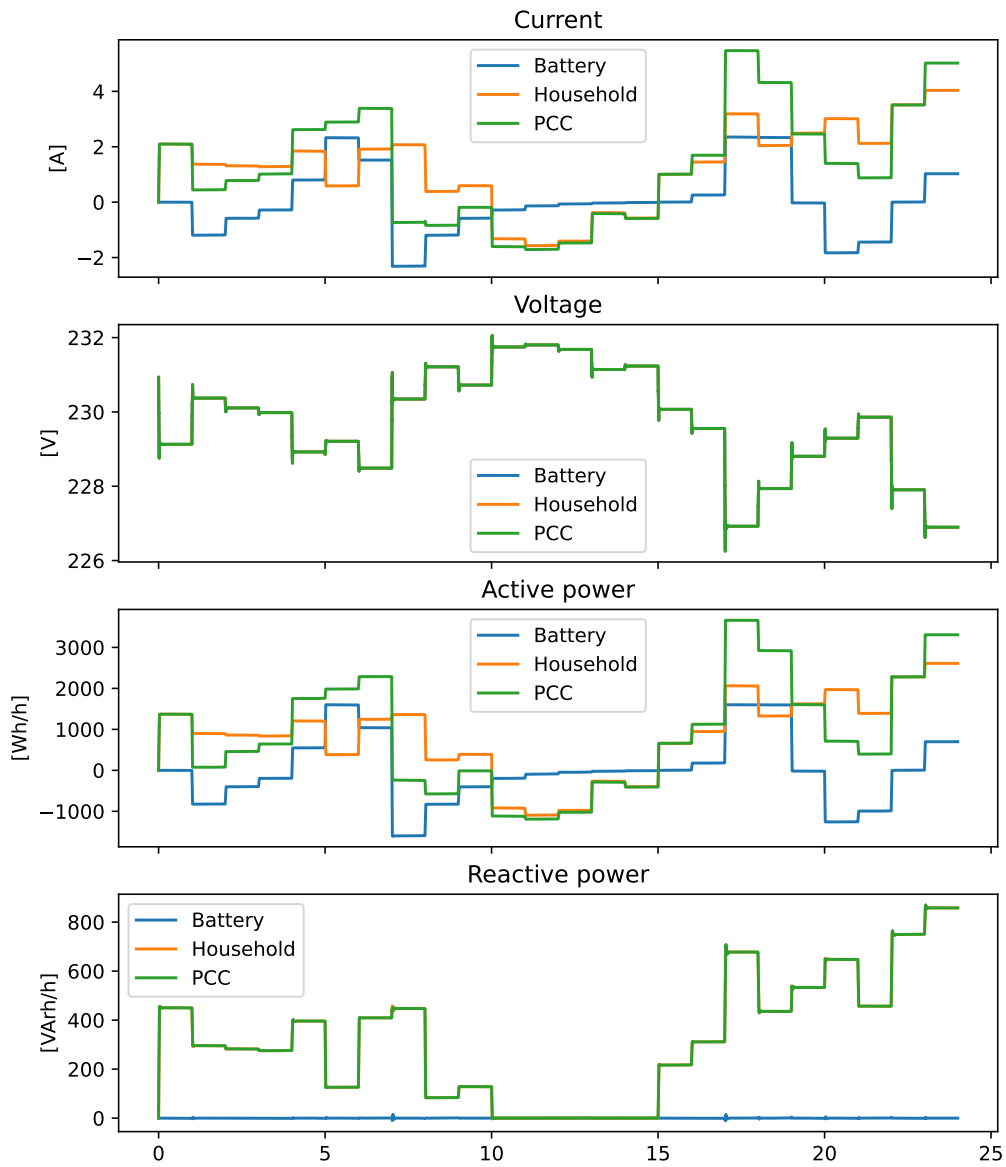


Figure 20: Base case summer

The autumn simulation in Figure 21 has an electricity spot price $0.20 \frac{NOK}{kWh}$ and $0.225 \frac{NOK}{kWh}$. PV generation happens from 06:00 to 15:00. The battery has two big changes in state of charge, one charge at 01:00 and a discharge at 06:00. Power is imported throughout the entire day.

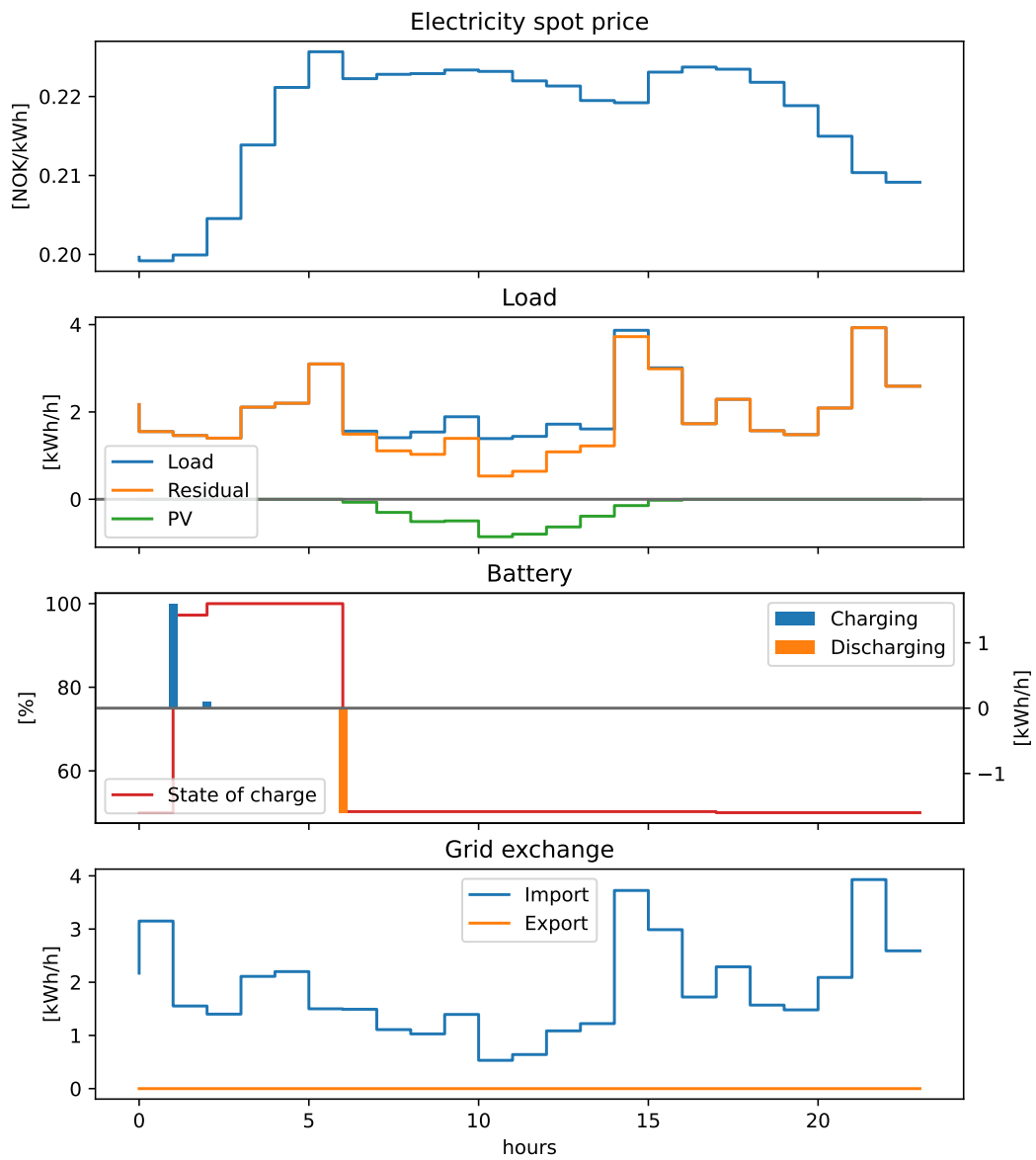


Figure 21: The results from the autumn simulation, October 16th

In Figure 22, the voltage the entire day is close to 230V, with spikes at the hour mark. It is lowest at 22:00 close to 227.5V and highest at 00:00 231V.

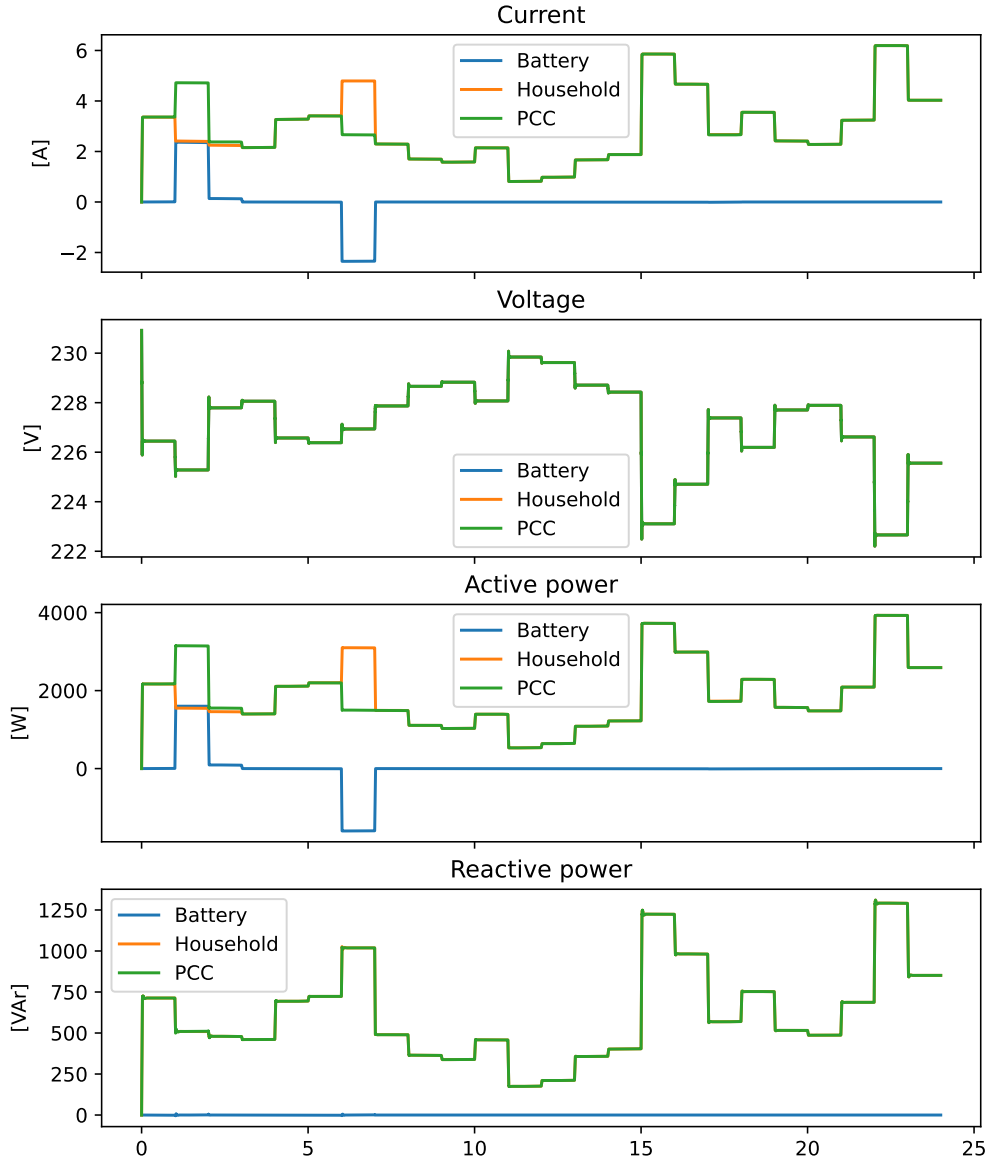


Figure 22: Base case autumn

4.2.2 Power peak results

The optimization model uses the same output for each power peak factor with the same step size. The step sizes begin with 4.5 and decreases with 0.5 for each iteration.

Power peak 2

With the power peak factor at 2, the power is 2 times as high as the base case for a $\frac{1}{2}$ of an hour. The voltage can be within the range of eq. (5). The maximum power at PCC (I_{max}) starts at, $4.5kW * 2 = 9kW$ since that is higher than any power during the base case. If the voltage constraint, eq. (5) is violated, I_{max} is lowered by a step size of $0.5kW * 2 = 1kW$.

The winter simulation in Figure 23 presents the first and last simulation in the co-simulation

iteration. The active power in the first iteration was lower than I_{max} the entire day, and the voltage constraint was violated at 18:00. The last iteration had an I_{max} of 7kW. The voltage constraint was not violated during that day.

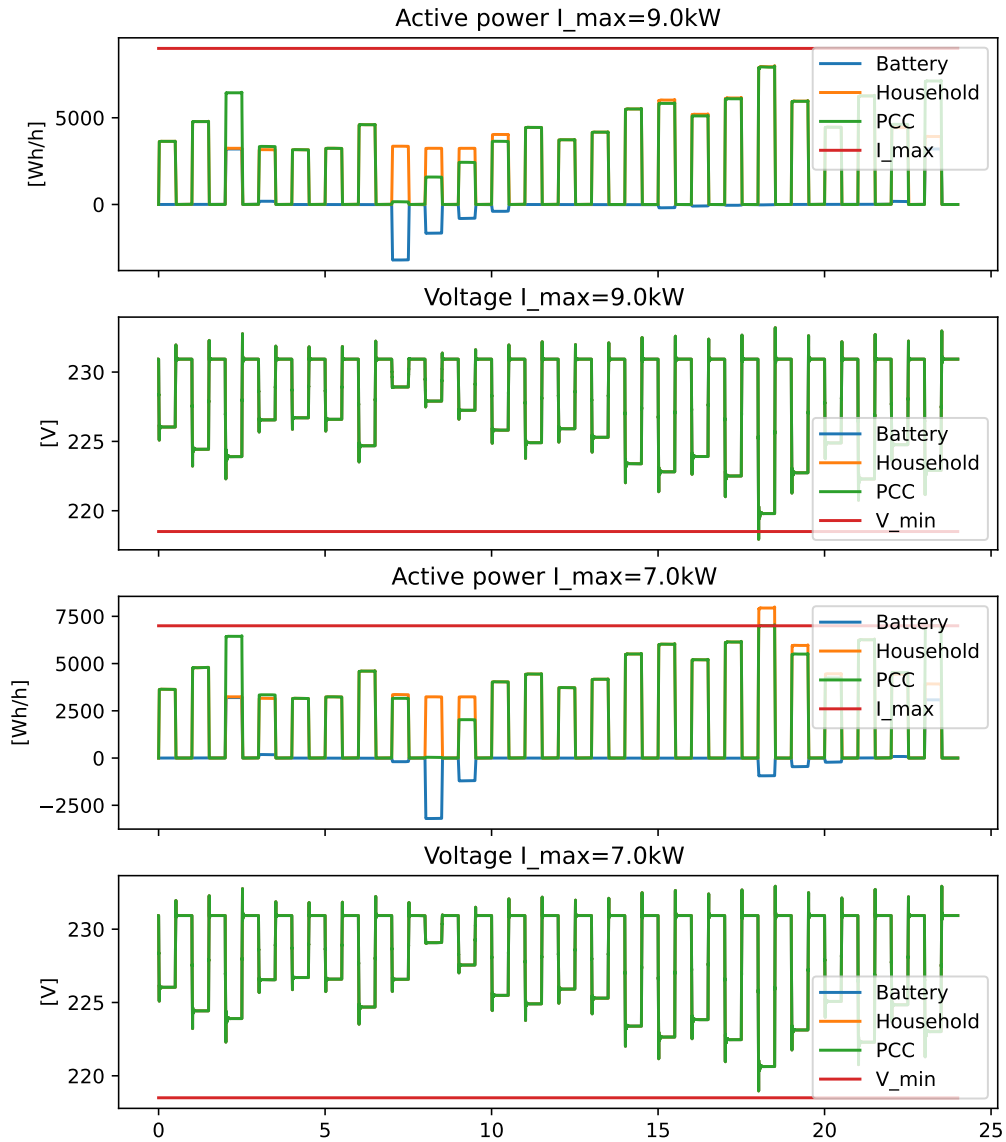


Figure 23: Winter: Power peak 2, first and last simulation

The summer simulation in Figure 24 had one iteration. The first and the last iteration is the same since the voltage constrain was not violated with a power peak factor of 2 for the summer day.

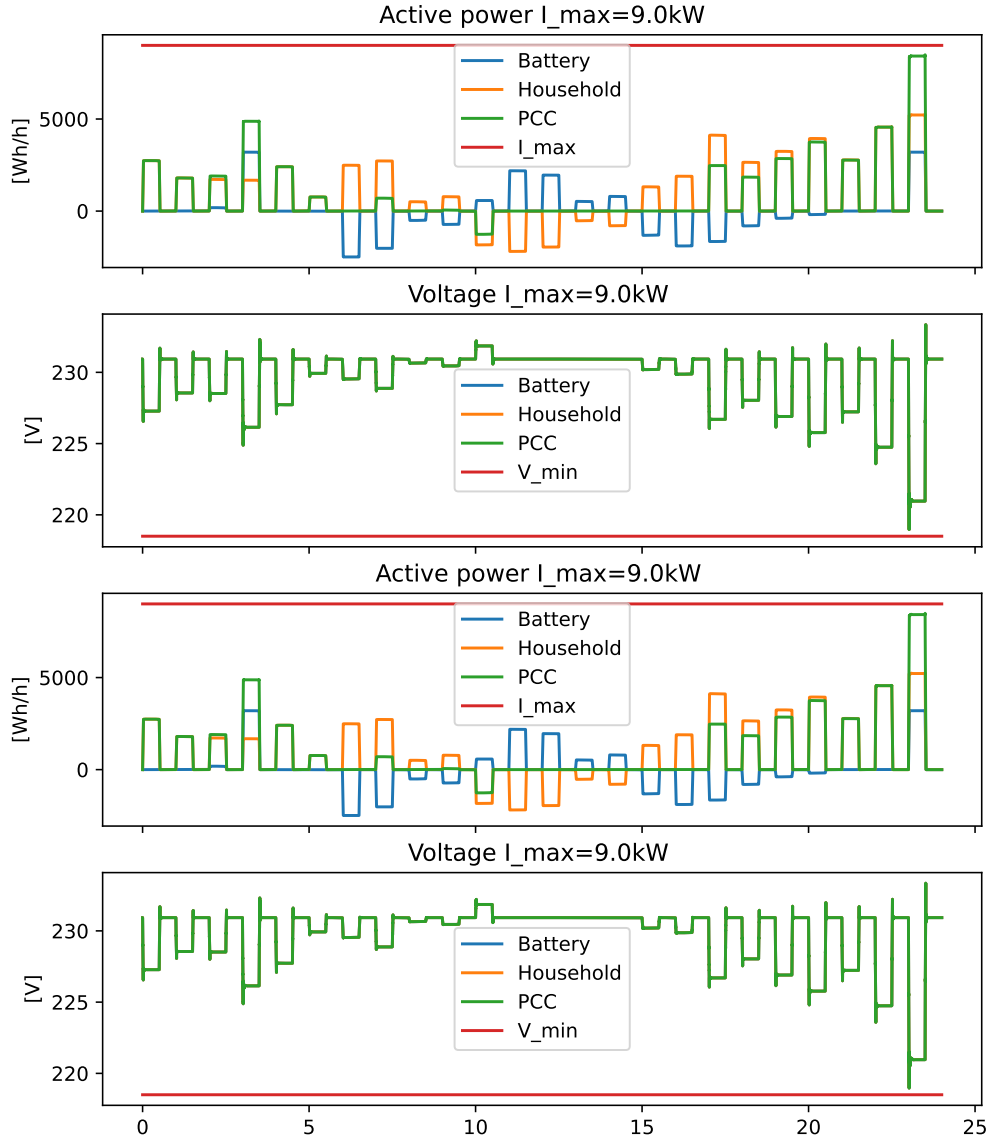


Figure 24: Summer: Power peak 2, first and last simulation

Power peak 2.5

With the power peak factor at 2.5, the power is 2.5 times as high as the base case for a $\frac{1}{2.5}$ of an hour. The voltage can be within the range of eq. (5). The maximum power at PCC (I_{max}) starts at, $4.5kW * 2.5 = 11.25kW$ since that is higher than any power during the base case. If the voltage constraint, eq. (5) is violated, I_{max} is lowered by a step size of $0.5kW * 2.5 = 1.25kW$.

The winter simulation in Figure 25 presents the first and last simulation in the co-simulation iteration. The active power in the first iteration was lower than I_{max} the entire day, and the voltage constraint was violated at 18:00 and 21:00. The last iteration had an I_{max} of 7.5kW. The voltage constraint was violated once at 18:00. The co-simulation stopped at I_{max} of 7.5kW because the optimization model was not able to find a result with I_{max} of 7.5kW.

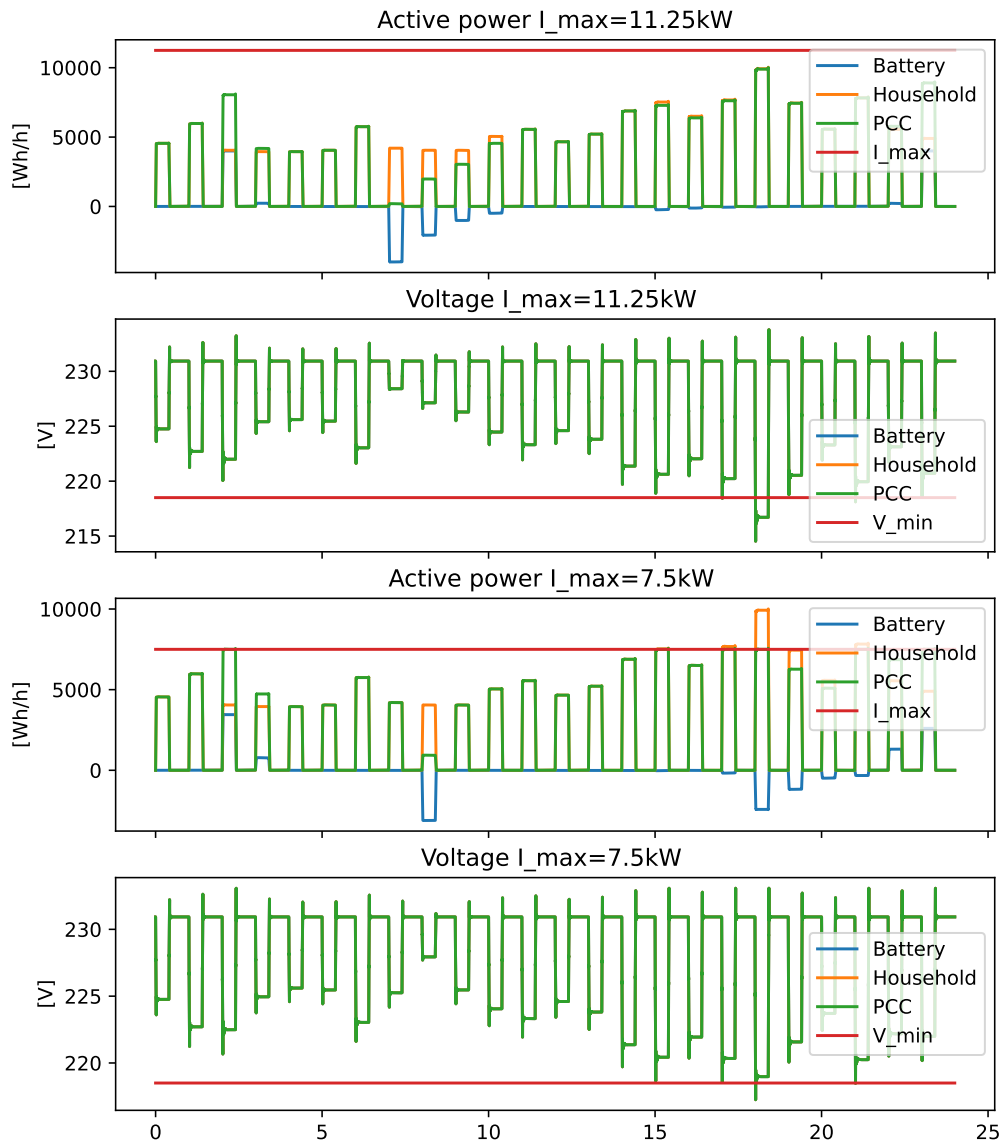


Figure 25: Winter: Power peak 2.5, first and last simulation

The summer simulation in Figure 26 presents the first and last simulation in the co-simulation iteration. The iteration did not use the maximum power at PCC for the first iteration, and the voltage constraint was violated at 23:00. The last iteration was with I_{max} of 7.5kW.

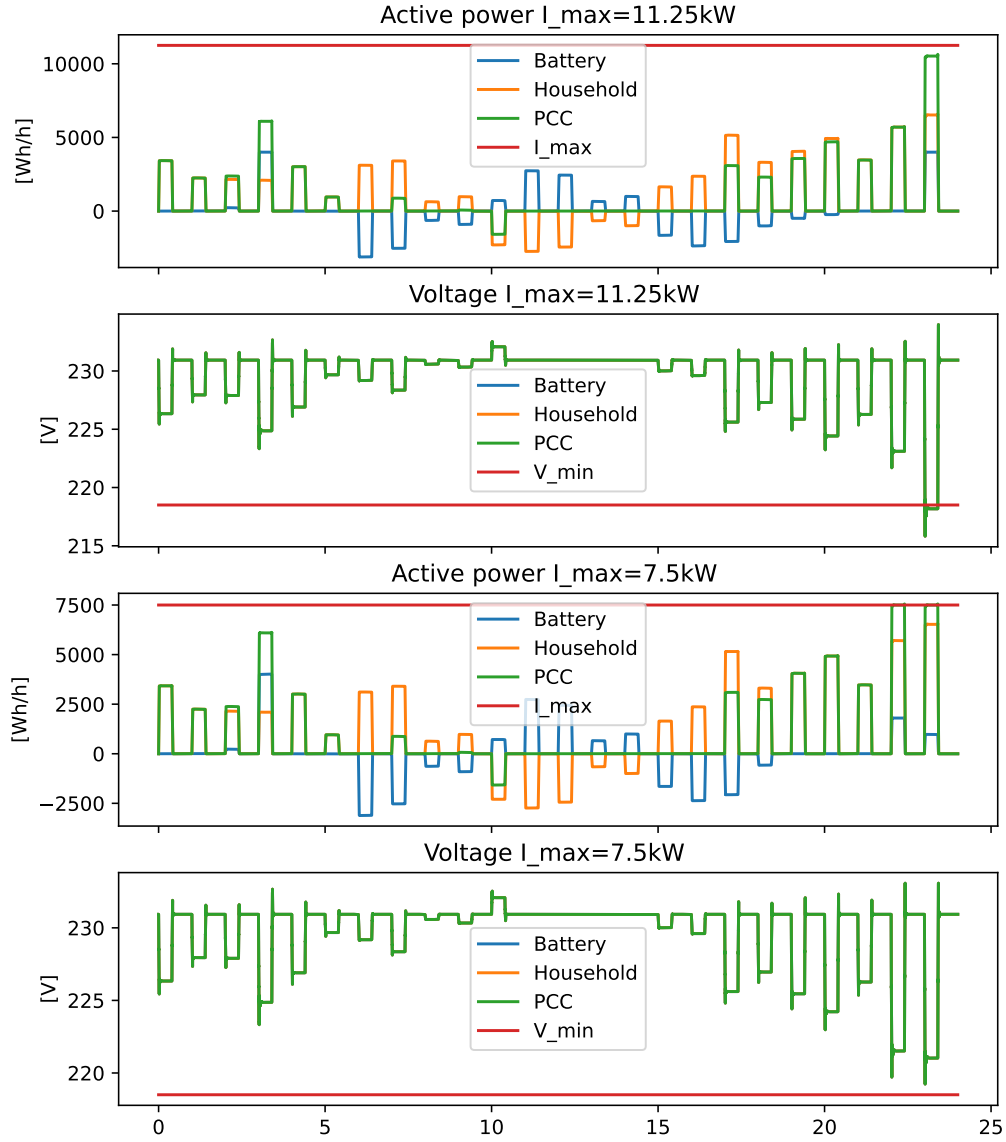


Figure 26: Summer: Power peak 2.5, first and last simulation

Power peak 3

With the power peak factor at 3, the power is 3 times as high as the base case for a $\frac{1}{3}$ of an hour. The voltage can be within the range of eq. (5). The maximum power at PCC (I_{max}) starts at, $4.5kW * 3 = 13.5kW$ since that is higher than any power during the base case. If the voltage constraint, eq. (5) is violated, I_{max} is lowered by a step size of $0.5kW * 3 = 1.5kW$.

$$218.5 \leq V \leq 241.5 \quad (5)$$

The winter simulation in Figure 27 presents the first and last simulation in the co-simulation iteration. The active power in the first iteration was lower than I_{max} the entire day, and the voltage constraint was violated at 03:00 and 14:00 to 19:00, 21:00 and 23:00. The last iteration had an I_{max} of 9kW. The voltage constraint was violated multiple times every hour from 14:00

to 19:00 and 21:00 to 23:00. The co-simulation stopped at I_{max} of 9kW because the optimization model was not able to find a result with I_{max} of 7.5kW.

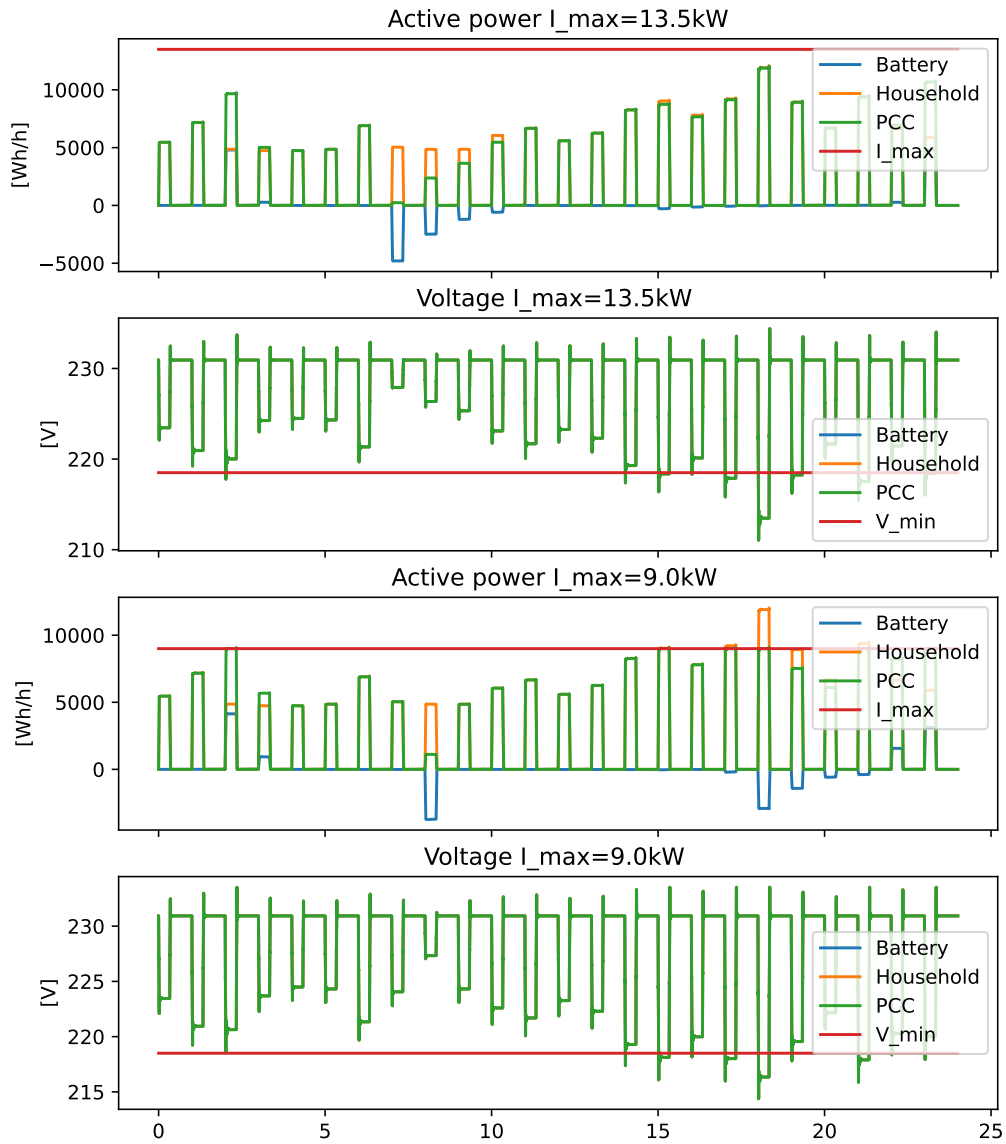


Figure 27: Winter: Power peak 3, first and last simulation

The summer simulation in Figure 28 presents the first and last simulation in the co-simulation iteration. The iteration did not use the maximum power at PCC for the first iteration, and the voltage constraint was violated at 23:00. The last iteration was with I_{max} of 6kW.

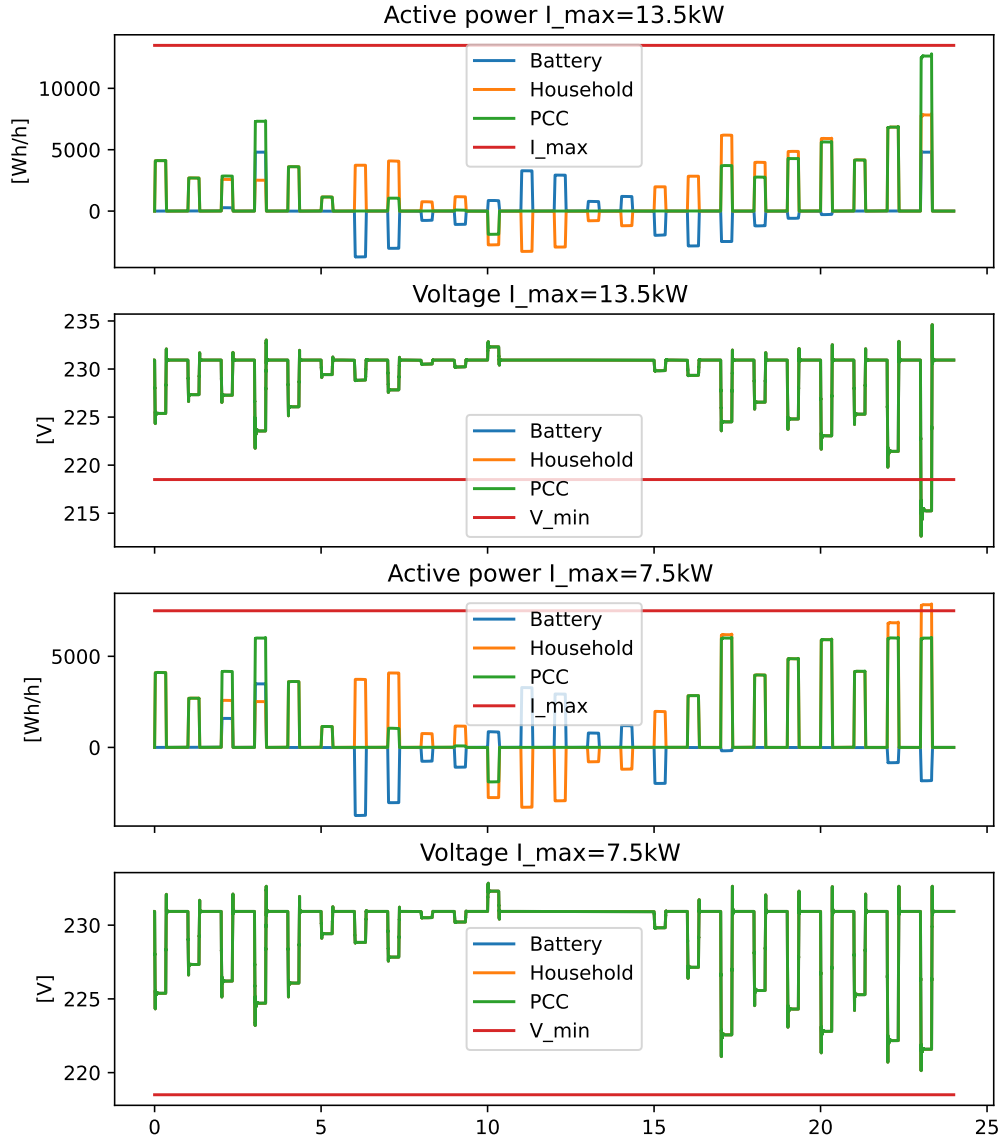


Figure 28: Summer: Power peak 3, first and last simulation

4.2.3 Power peak larger battery

With a larger battery, the optimization is different from the Section 4.2.2, and the voltage for each iteration of co-simulation might be different from battery of 3.3 kWh and 15 kWh. The difference can be found in Tables 3 and 4.

Power peak 2

Similar to Section 4.2.2, with the power peak factor at 3, the maximum power at PCC (I_{max}) starts at 9kW. I_{max} is lowered by a step size of 1kW.

The winter simulation in Figure 31 presents the first and last simulation in the co-simulation iteration. The iteration was at maximum power at PCC for the first iteration at 02:00, 03:00 and

21:00 to 23:00, and the voltage constraint at 21:00. The last iteration had an I_{max} of 7.5kW. The voltage constraint was not violated.

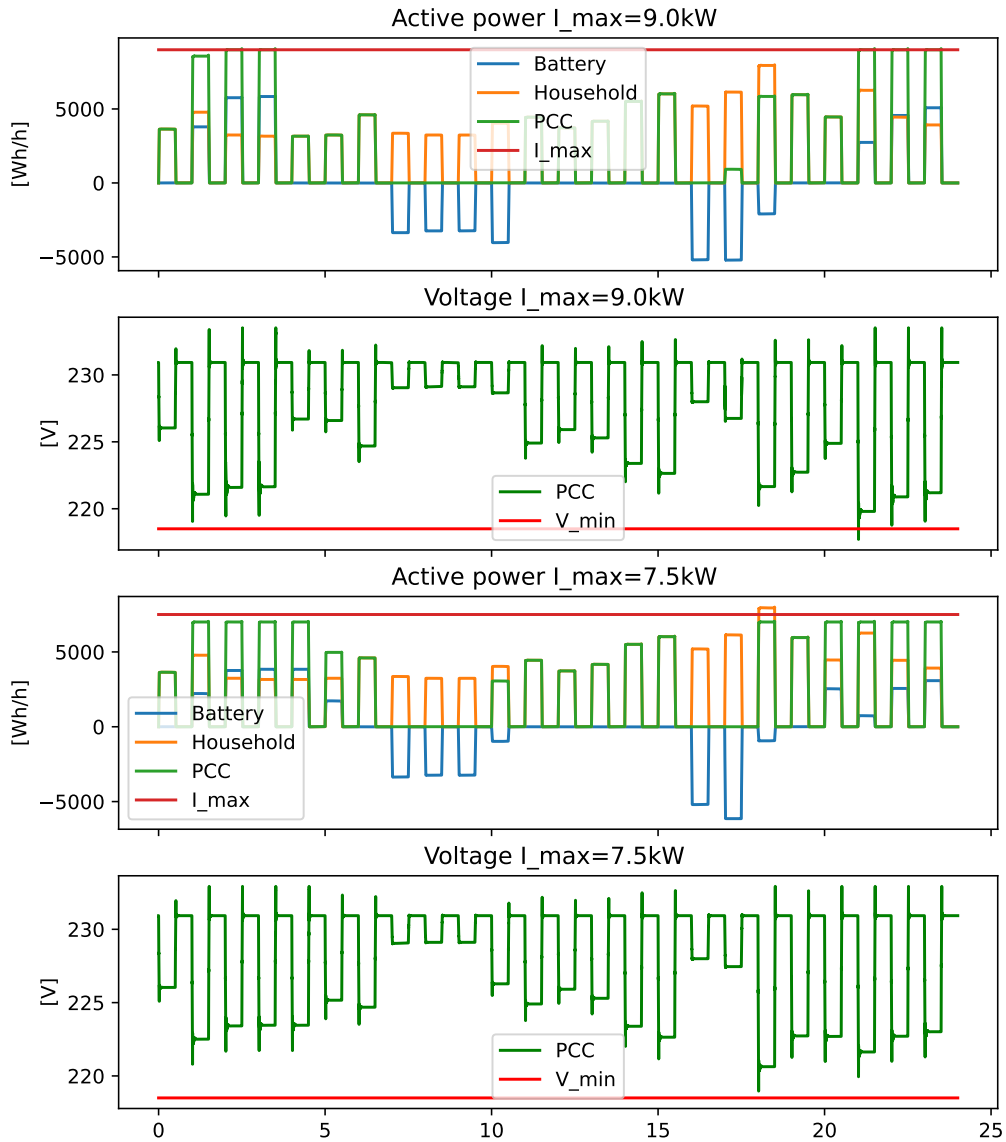


Figure 29: Winter: Power peak 2 with a larger battery, first and last simulation

The summer simulation in Figure 30 presents the first and last simulation in the co-simulation iteration. The simulation hit maximum power at PCC for the first iteration at 02:00, 03:00 and 23:00, and the voltage constraint was violated at 23:00. The last iteration was with I_{max} of 8kW without any voltage violations.

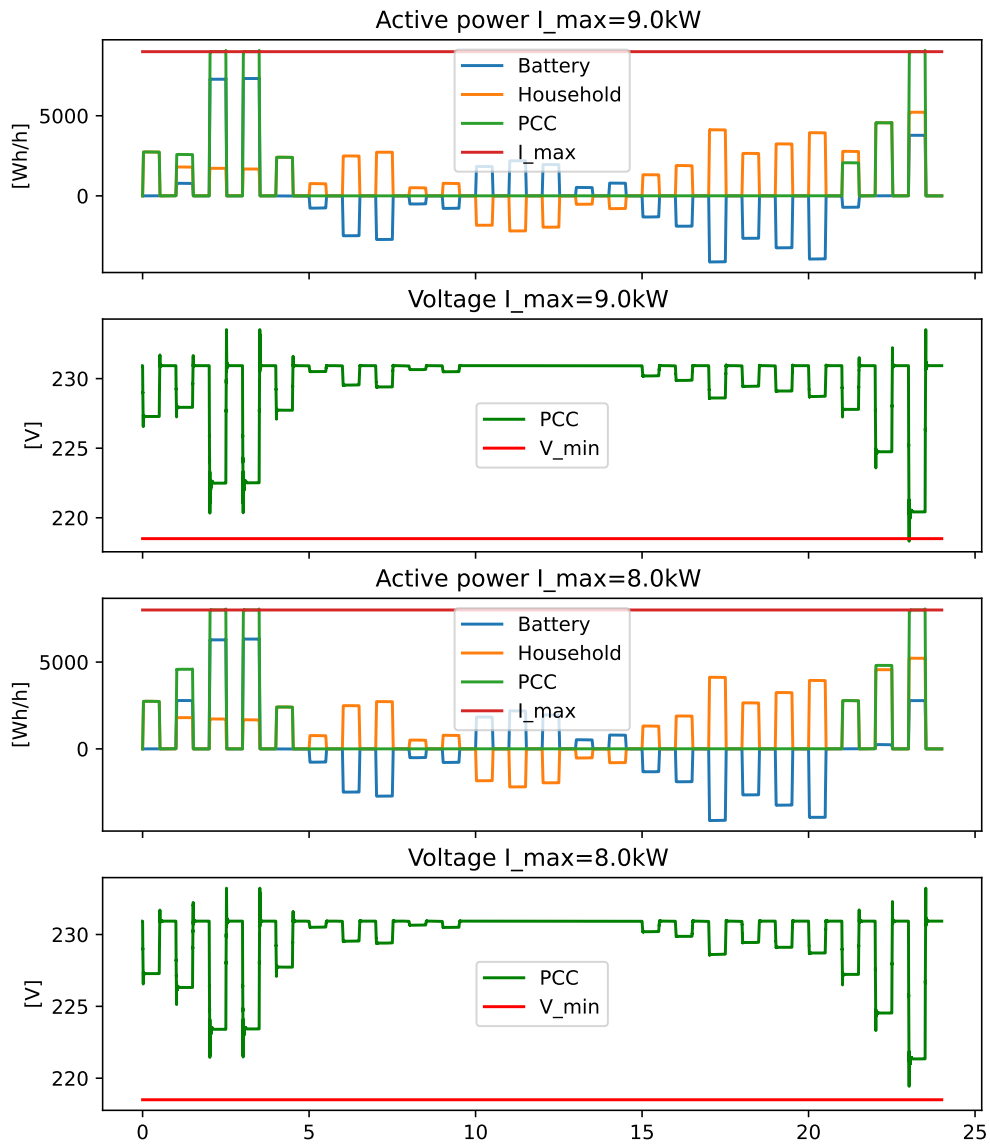


Figure 30: Summer: Power peak 2 with a larger battery, first and last simulation

Power peak 2.5

Similar to Section 4.2.2, with the power peak factor at 2.5, the maximum power at PCC (I_{max}) starts at $11.25kW$. I_{max} is lowered by a step size of $1.25kW$.

The winter simulation in Figure 31 presents the first and last simulation in the co-simulation iteration. The iteration was at maximum power at PCC for the first iteration at 02:00, 03:00 and 21:00 to 23:00, and the voltage constraint was violated at when maximum power at PCC was used, but in addition to at 01:00 and 18:00. The last iteration had an I_{max} of $6.25kW$. The voltage constraint was not violated.

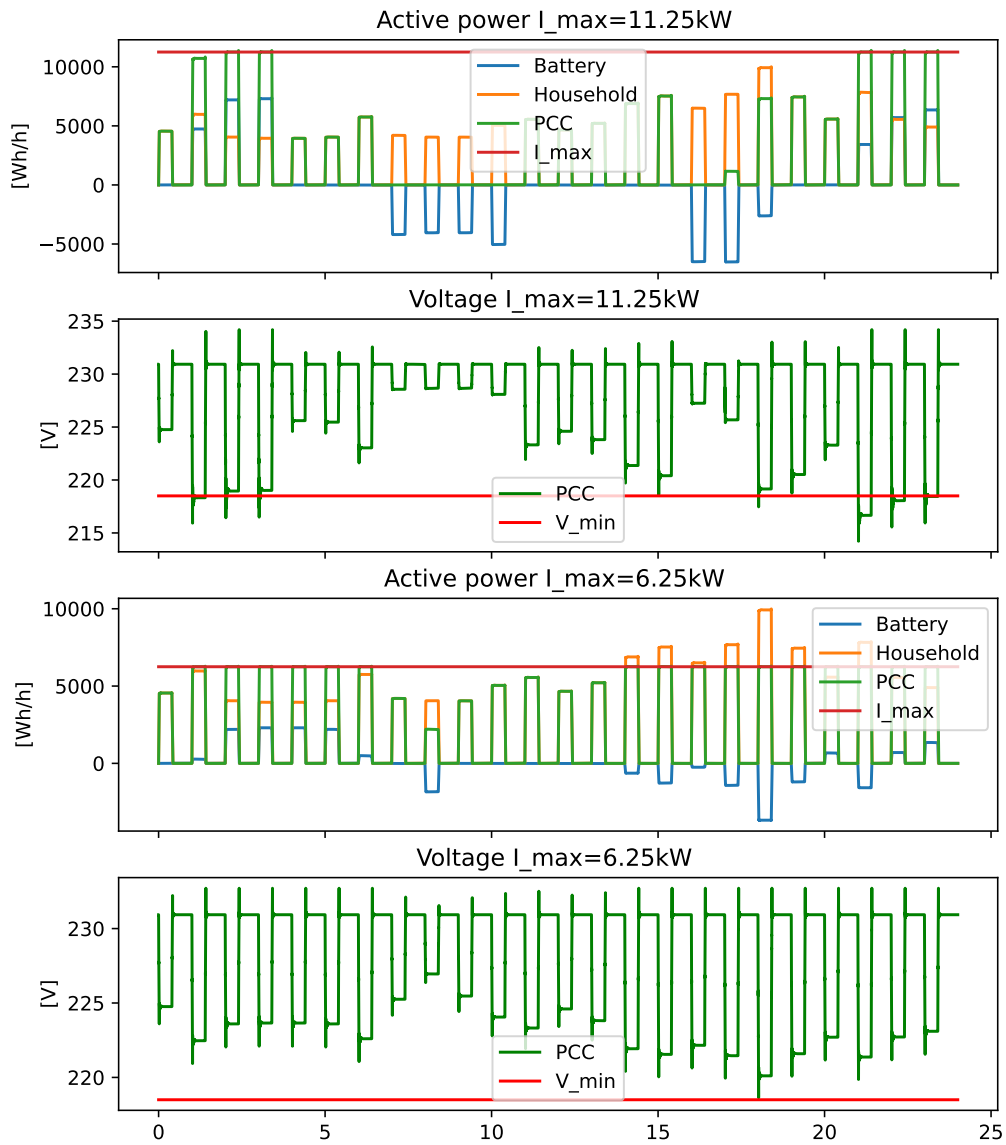


Figure 31: Winter: Power peak 2.5 with a larger battery, first and last simulation

The summer simulation in Figure 32 presents the first and last simulation in the co-simulation iteration. The simulation hit maximum power at PCC for the first iteration, and the voltage constraint was violated at the same hours, 02:00, 03:00 and 23:00. The last iteration was with I_{max} of 7.5kW without any voltage violations.

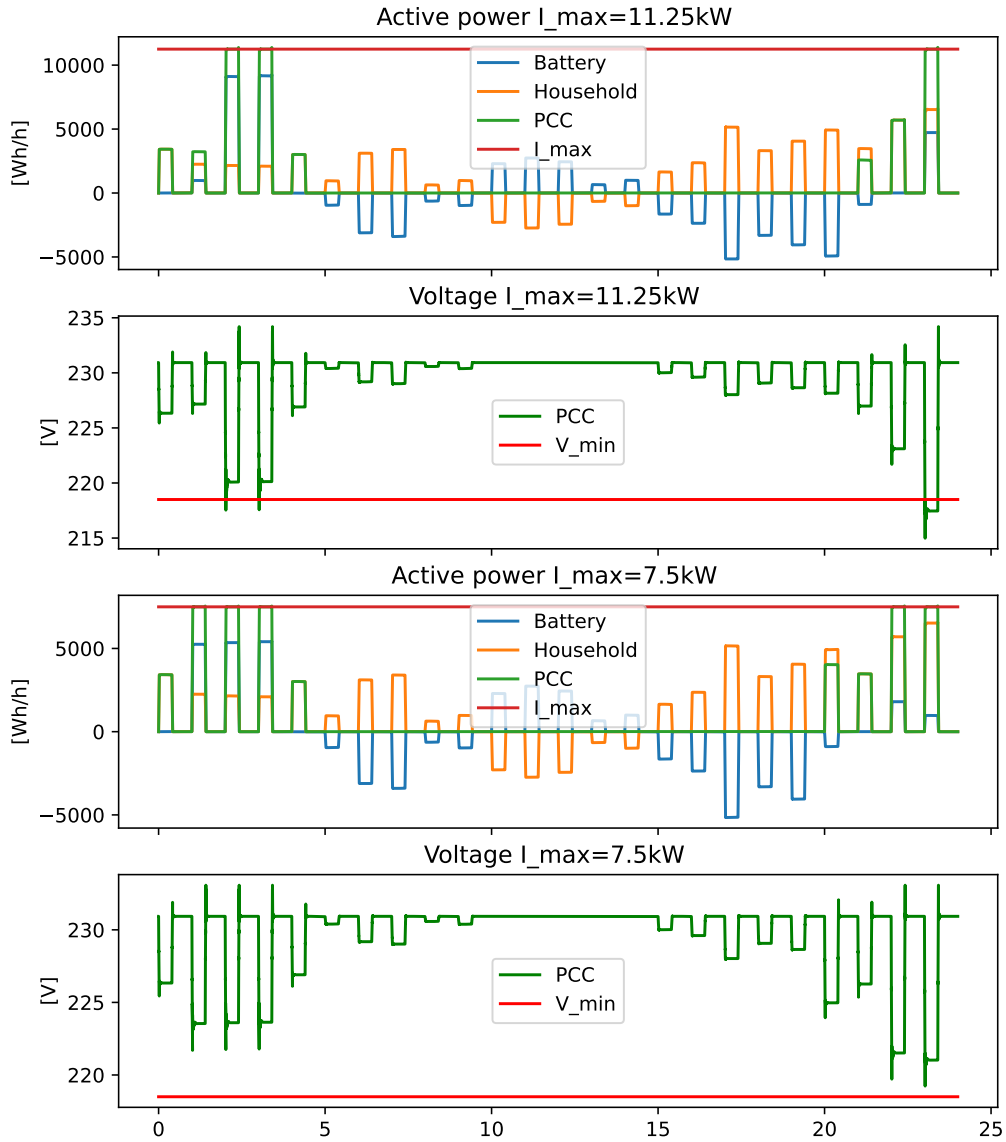


Figure 32: Summer: Power peak 2.5 with a larger battery, first and last simulation

Power peak 3

Similar to Section 4.2.2, with the power peak factor at 3, the maximum power at PCC (I_{max}) starts at 13.5kW . I_{max} is lowered by a step size of 1.5kW .

The winter simulation in Figure 33 presents the first and last simulation in the co-simulation iteration. In the first simulation the I_{max} limit is reached 6 times, and the voltage constraint was violated at 01:00-03:00, 14:00, 15:00 and 21:00 to 23:00. The last iteration had an I_{max} of 7.5kW . The voltage constraint was violated 14:00, 15:00 and multiple times every hour from 15:00 to 21:00. The co-simulation stopped at I_{max} of 7.5kW because the optimization model was not able to find a result with I_{max} of 6kW .

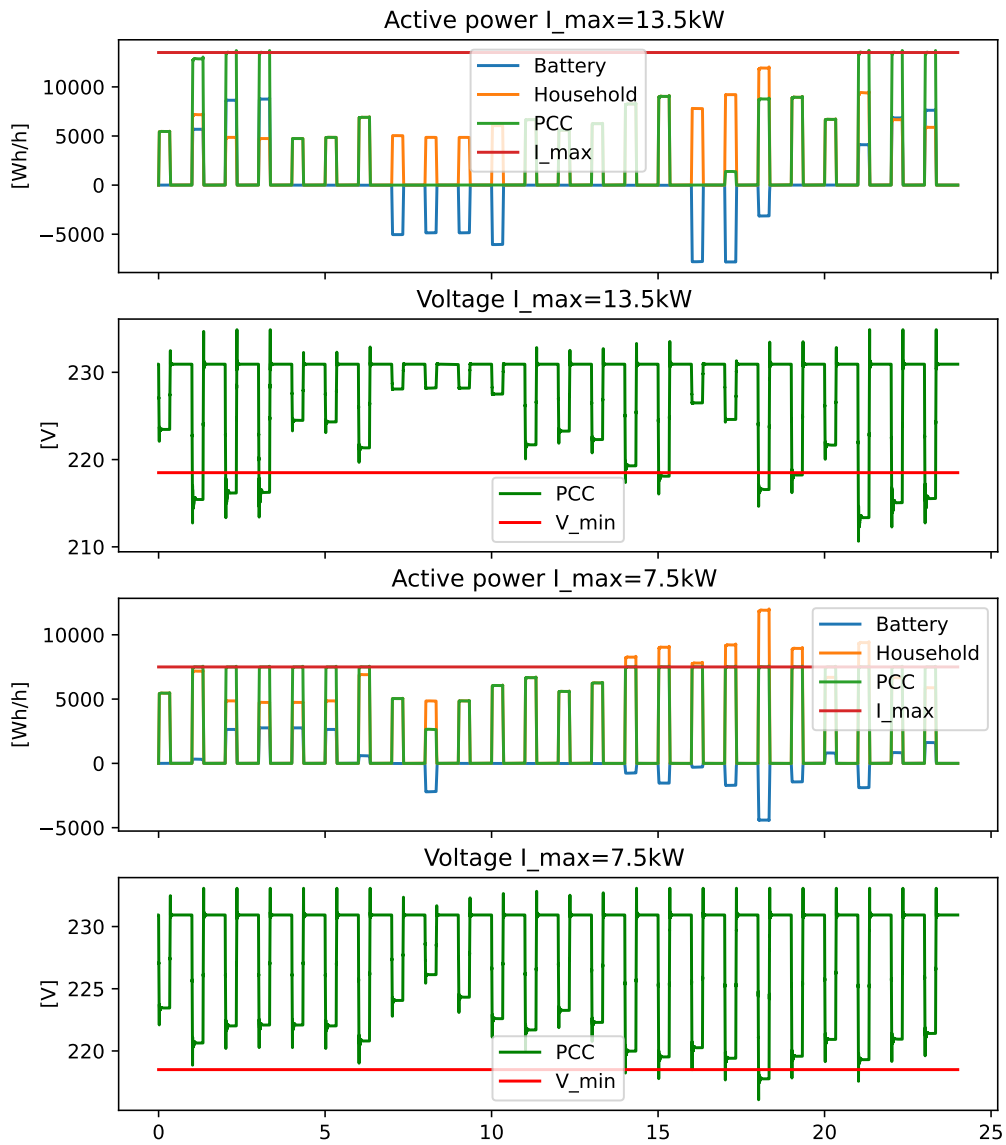


Figure 33: Winter: Power peak 3 with a larger battery, first and last simulation

The summer simulation in Figure 34 presents the first and last simulation in the co-simulation iteration. The simulation hit maximum power at PCC for the first iteration, and the voltage constraint was violated at the same hours, 02:00, 03:00 and 23:00. The last iteration was with I_{max} of 6kW without any voltage violations.

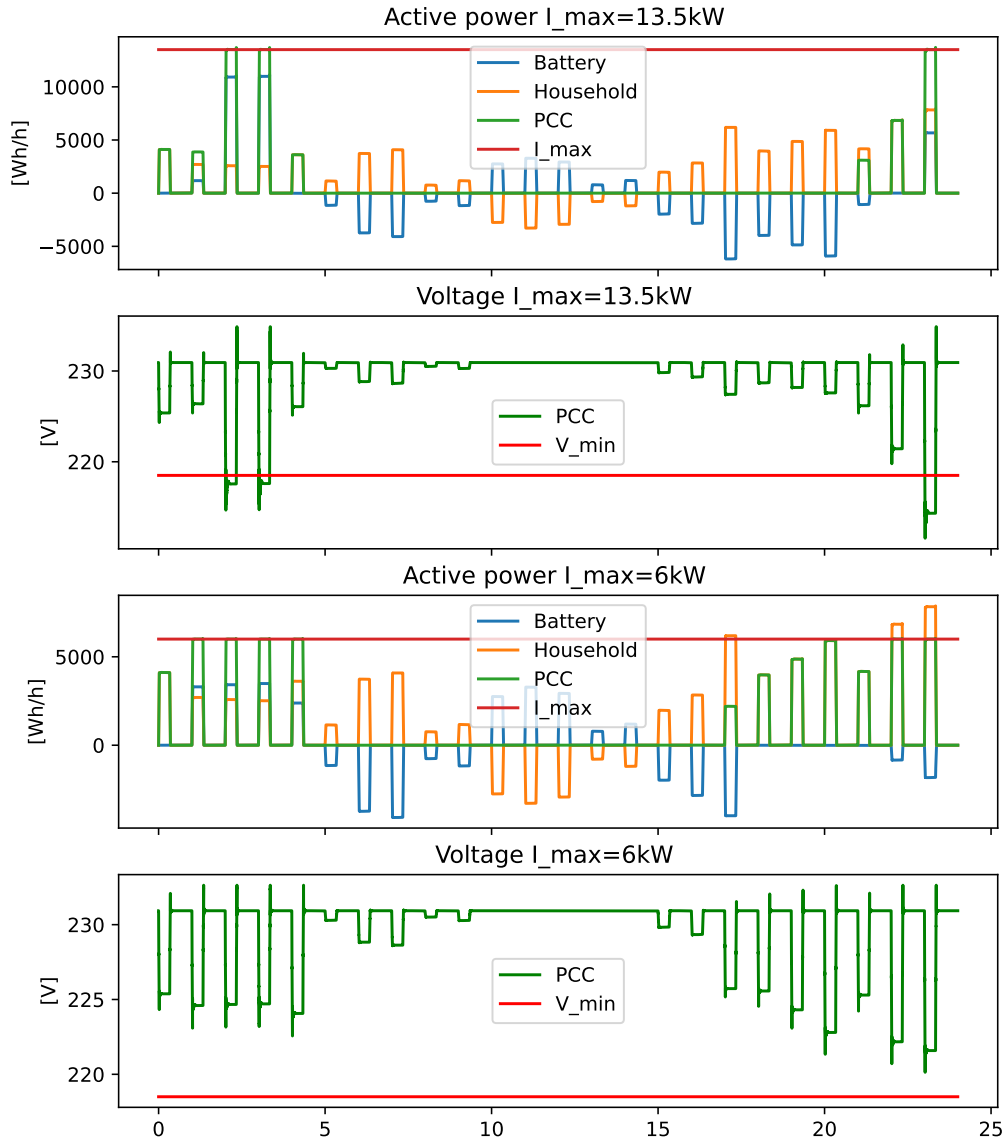


Figure 34: Summer: Power peak 3 with a larger battery, first and last simulation

4.3 Summary

Tables 3 and 4 summarizes the results for the co-simulation for base case and power peak with batteries at 3.3 kWh and 15 kWh for winter and summer simulation. The summary for spring and autumn is in Appendix A.4. The lowest voltage column is taken from the first simulation, when I_{max} was set to 4.5 kWh. The lowest voltage after co-simulation column is the lowest voltage from the last simulation. Either when the voltage is not violated anymore, or the optimization model was unable to find solution with I_{max} set to low.

The summarization in Table 3 is for all the winter simulations. The optimization model was not able to find a solution for power peak 3 and 2.5 with the 3.3 kWh battery, and power peak 3 for the 15 kWh battery. For the rest of the simulation, the co-simulation script found a solution.

Table 3: Summary of voltage for the winter simulations for the first and last iteration

| Case | Lowest voltage [V] | Size of battery [kWh] | Lowest voltage after co-simulation [V] |
|----------|--------------------|-----------------------|--|
| | 3.3 | 225.43 | |
| Peak 2 | 217.94 | 3.3 | 218.97 |
| Peak 2.5 | 214.53 | 3.3 | 217.25 |
| Peak 3 | 211.05 | 3.3 | 214.38 |
| Peak 2 | 217.71 | 15 | 218.97 |
| Peak 2.5 | 214.22 | 15 | 218.64 |
| Peak 3 | 210.64 | 15 | 216.07 |

The summarization in Table 3 is for all the summer simulations. The co-simulation script found a solution for all the simulation.

Table 4: Summary of voltage for the summer simulations for the first and last iteration

| Case | Lowest voltage [V] | Size of battery [kWh] | Lowest voltage after co-simulation [V] |
|----------|--------------------|-----------------------|--|
| Base | 225.94 | 3.3 | 225.94 |
| Peak 2 | 218.97 | 3.3 | 218.97 |
| Peak 2.5 | 215.82 | 3.3 | 219.24 |
| Peak 3 | 212.61 | 3.3 | 220.13 |
| Peak 2 | 218.32 | 15 | 219.44 |
| Peak 2.5 | 214.99 | 15 | 219.24 |
| Peak 3 | 211.58 | 15 | 220.13 |

Table 5 and 6 presents the value of the objective function in the optimization model for different I_{max} . The cost is for the electricity for the entire day. For I_{max} of 2.5 and 2 for winter with a battery of 3.3 kWh, I_{max} of 2 for winter with a battery of 15 kWh, I_{max} of 2 with a battery of 3.3 kWh and I_{max} of 2 with a battery of 15 kWh, the optimization model was not able to find a solution. As described in 4.2.2 the step size for each iteration is 0.5 * power peak factors. The first iteration starts with 4.5. With a power peak factor of 3, the maximum power at PCC is: 13.5, 12, 10.5, 9, 7.5, 6.

Table 5: Cost in NOK for power with different maximum power at PCC for a battery of 3.3 kWh

| Maximum power at PCC | Summer | Spring | Autumn | Winter |
|-------------------------|--------|---------|---------|---------|
| 4.5 * power peak factor | 6.1503 | 11.5405 | 18.9565 | 18.3958 |
| 4 * power peak factor | 6.1513 | 11.5405 | 18.9565 | 18.3958 |
| 3.5 * power peak factor | 6.1536 | 11.5405 | 18.9645 | 18.4042 |
| 3 * power peak factor | 6.1600 | 11.5405 | 18.9763 | 18.4228 |
| 2.5 * power peak factor | 6.1753 | 11.5444 | 19.0237 | N/A |
| 2 * power peak factor | 6.2055 | 11.5582 | N/A | N/A |

Table 6: Cost in NOK for power with different maximum power at PCC for a battery of 15 kWh

| Maximum power at PCC | Summer | Spring | Autumn | Winter |
|-----------------------------|---------------|---------------|---------------|---------------|
| 4.5 * power peak factor | 5.9106 | 11.5321 | 18.9429 | 18.0823 |
| 4 * power peak factor | 5.9171 | 11.5329 | 18.9453 | 18.1139 |
| 3.5 * power peak factor | 5.9239 | 11.5332 | 18.9548 | 18.1706 |
| 3 * power peak factor | 5.9490 | 11.5337 | 18.9701 | 18.2761 |
| 2.5 * power peak factor | 5.9845 | 11.5409 | 18.9990 | 18.4103 |
| 2 * power peak factor | 6.0453 | 11.5564 | N/A | N/A |

5 Discussion

This section will look at the results from the case study, alongside the co-simulation. Some part in this section is taken from [1].

The main objective in this case is to ensure that the quality of the voltage supply is within a $\pm 5\%$ range. That is ensured with co-simulation. An optimization model in Python that minimizes the price, and a Simulink model that simulates the power grid and receives the voltage as an output are used in a co-simulation platform to exchange data. To simulate the intra-hourly effects, power peaks with factors 2, 2.5 and 3 are used. The house has a load, PV and battery. Two different battery sizes were used in the with power peaks. The difference between the standard battery of 3.3 kWh and a larger battery of 15 kWh were simulated to analyze the difference in power at PCC during power peaks. One day from each season was chosen to simulate. April 21st, June 16th, October 16th and December 21st.

5.1 Base case

The results from the optimization model in the base case shows the cheapest way to import/export power from the power grid before max power at PCC is introduced. From the Figures 15-21, it can be interpreted that the battery is used to charge when the price is low. The battery discharged power when the price is high, depending on how much power is generated with PV throughout the day. In the winter and summer Figures (15 and 19), the price affecting charging/discharging are most noticeable. Because the power generation from PV, load and price are parameters and not variable, it can easily be calculated at what time it is cheapest to charge and discharge the battery. PV generation and load are real time variables in reality, but in this thesis they are known in advance. The efficiency of the battery is also a factor in how the battery charges. If the price variance is too low, the loss from charging/discharging makes it cheaper to import from the grid, even if the price is higher.

With a battery efficiency of 95% and low price difference during the days in the simulation, the battery was mostly used for charging when the residual load was negative. In Figure 21, the autumn simulation, the residual load is positive the entire day, and the price difference between highest and lowest are not big. The battery only charges once when the price is lowest, and discharges once when the price is highest.

The grid tariff in the model is only applied to the import and not export. The battery is therefore charged to store excess electricity (when residual load is less than zero). Excess electricity is then used later the same day when the battery is discharged. This is shown in the spring simulation, Figure 17, where the import is 0 in many hours, and there is excess electricity in the system. From the summer simulation, Figure 19, the system has to export electricity to the power grid. This is due to the residual load being less than zero many hours that day, and the battery can only hold 3.3 kWh. The electricity is sold when the price is highest to earn as much as possible.

The Simulink results for base case show the voltage in within the range ± 8 V of nominal voltage, well within the $\pm 5\%$ (11.5 V) range. That is due to the fact that hourly metering hides the power peaks, and in turn, the voltage drops/spikes. Hence, it is not representative of the real voltage in the LV network is.

5.2 Power peaks and battery cases

The voltage is not violated for the base case, and the co-simulation is not used. When power peaks are introduced, maximum power at PCC, I_{max} , was set to 4.5kW because that was higher than any base case hour for any of the four days. This can be seen for all the first simulation in Figures 23-28, no one of them at power at PCC at the red line. When a larger battery was introduced to the system, 4.5kW was the limit for the first iteration. However, for many of the first iteration, the max at PCC was used. The end result was not affected because there was a voltage violation in the first simulation. The 3.3 kWh battery is a small home battery, and 15 kWh is a large battery.

For the winter simulation (Table 3), power peak 2 had the same result for small and large batteries. Power peak 2.5 with a small battery, did not get a voltage within the range. For a larger battery, the optimization model was able to find a solution. For power peak 3, neither the small nor the larger battery was able to find a feasible solution. Even so, the end result for the larger battery was better at 216.07 V compared to 214.38 V.

For the summer simulation there was only difference between the number of iterations from small and large battery with a power peak of 2. Both simulation ended with a voltage within the given range. With the battery of 15 kWh, I_{max} for the last iteration was 8kW, which means that it used two iterations. The smaller battery of 3.3 kWh, there was only one iteration.

For this thesis peak factors of 2, 2.5 and 3 were used. That results in resolutions of 30-min, 24-min and 20-minutes. Figure 3 shows a 30-min, 15-min, 10-min and 5-minute time resolution. The 30-min resolution did not catch the power peak, but the 15-minutes were much closer. The smallest resolution in the thesis is 20 minutes, and that is probably close enough to get a rough understanding of the voltage drop during the hour.

It is easier for the optimization model to find a solution for smaller I_{max} for summer than winter, due to several factors. With more PV and smaller load, it is easier to have enough power for the household load without importing from the power grid. With a larger battery, it is easier to charge it up to use later during the day. That is why for power peak 2.5, there was a solution with a battery of 15 kWh, in contrast to 3.3 kWh.

The step size of 0.5 * power peak factor was chosen as each iteration took 8-10 minutes, and there were up to 6 iterations between 4.5kW and 2kW with that step size. With a smaller step size, the co-simulation might have been able to find a feasible solution for some cases where the model was not able to find it with the given step size.

5.3 Chosen days

There are many days in a year, and in this thesis four days, one from each season, were chosen to simulate the effect of co-simulation on the quality of voltage supply. Each day was chosen deliberately, Figures 11-14 compares the load and PV generation for all the days in the month chosen. December 21st was chosen because of the low PV generation and low load. April 21st was chosen due to the high PV generation and varying load curve. June 16th was chosen because of the high PV generation and low load, to see if the system would export power or not. October 16th was chosen for the high load curve peaks. If any other day in any of the season had been chosen, the result would be different. In the winter, there are one hour over 6 kWh/h while on

December 21st, the highest consumption as under 4kwh/h. Figure 11 shows that there are days in December with more PV generation. If one of the days with more PV generation were chosen, the optimization model might have been able to find a solution for power peak factor 3. It might have been able to find a solution because the PV generation would result in less power imported at PCC. The summer day, June 16th, has high PV generation and low load. If it had low PV generation and high load, it would perhaps have struggled to find a valid solution, similar to what the winter simulation did for power peak factor 3.

5.4 Spot price

Considering the optimization model minimizes costs, the spot price affects the charging and discharging of the battery greatly. The prices in this thesis are low, and do not vary much compared to the price in 2021 and 2022 [36]. The results would look different if 2021 prices were used instead of 2015. It would not affect a feasible solution to the optimization, however the charging times would be different.

5.5 Voltage requirements

The voltage limit at $\pm 5\%$ range is less than the limit of $\pm 10\%$ determined by law. That is because there is never a certainty of how much load there is at any given time, and with 5% there is room to go over without breaking the regulation.

Voltage drops when the power consumption is higher, and increases when the power production increases. To make sure that voltage was within the range in Eq. (5), I_{max} was implemented in the optimization model and through co-simulation lowered. Although it worked, it was not the only possible way to achieve it, and it did not take into account whether the battery was discharging at the same time or not. The results imply that, it looks like there were greater voltage drops when the battery was discharging than when it was not, with the same power at PCC. Even though the voltage drop was lower with battery discharging than not, it was not as low as when all the power was imported. Using power from the battery rather than importing it was better for the quality of supply. That is due to of the voltage lose in the power line when importing.

Voltage requirement was set to $\pm 5\%$ of nominal voltage. The Norwegian regulation on quality of electricity supply has a limit of $\pm 10\%$ of nominal voltage. The difference of $\pm 5\%$ difference in voltage between the regulation and this thesis requirement was chosen to give room for the DSOs.

5.6 Battery cost

From Figure 2 an assumption can be made that batteries will become cheaper in the future. Still, a larger battery of 15 kWh is significantly more expensive than a small battery of 3.3 kWh with the forecasted prices. The base cases show that if a prosumer only wants to use the battery to store the power generated by the PV, a 3.3 kWh battery is sufficient when hourly metering is used, as there was only a one-hour need to export in the summer. Yet, for the DSO, the voltage was violated without a maximum rate of power from the PCC for all four seasons with power peak factor 3. It is in the DSOs interest to have a bigger battery so that the co-simulation can find a solution that is with the given voltage range. Who is going to pay for the larger battery?

From Tables 5 and 6 at I_{max} of 4.5, the biggest difference in cost between battery of 3.3 kWh and 15 kWh is during the winter with 18.3958 NOK and 18.0823 NOK. The difference in cost makes it possible to save 0.3135 NOK per day (114.43 NOK a year) by buying the larger battery. Figure 7 shows a battery price of around 200 USD per kWh, with a capacity difference of 11.7 kWh the difference in price is 2340 USD (22 680 NOK). The price of the battery is too high for the prosumer to buy the larger battery, but the DSO can benefit from having it. The DSO would have to upgrade the LV network if the voltage is not in regulation [7], and it might be cheaper to pay the difference between the small and bigger battery for the prosumer.

For each iteration in the co-simulation model, the cost in the optimization model becomes higher or equal to the previous iteration. This means that the household loses money by helping the DSO. Hence, it is therefore fair to assume that the DSO should pay more, or equal to, the lost revenue from the co-simulation. From Table 5 and 6, the highest difference for the I_{max} 4.5 and 2.5 was the winter with the battery of 15 kWh. The costs are 18.0823 NOK and 18.4103 NOK, giving a difference of 0.328 NOK per day. With a difference of 0.328 NOK per day for 365 days the yearly difference is 119.72 NOK.

6 Conclusion and future work

6.1 Conclusion

This section presents the methodology used, and the results from answering the question: How can a co-simulation framework coordinate a battery optimization model and a load flow simulation to improve voltage quality in the distribution grid?

A house connected to the LV network with battery and PV was modelled. Co-simulation was used to combine two models: an optimization model of the battery and a load flow simulation of the lines connecting the house to the LV network. The co-simulation was used by having an optimization model and a Simulink model simulate the voltage when the house was charging and discharging the battery. With the co-simulation framework, the voltage quality was improved. By implementing a maximum power at PCC, the voltage drop became smaller.

The methodology was demonstrated on a case study, assessing how the co-simulation created handles different power resolutions. To simulate different power resolution, power peaks factors were used. With the use of power peaks, the data exchange on the co-simulation platform was used to improve the quality for each iteration. When comparing the batteries of 3.3 kWh and 15 kWh, the results show that the larger battery was able to give better voltage quality after co-simulation. It was easier for the co-simulation to find a solution in days with high PV generation because when the residual load went negative, charging the battery for future use was more cost-effective than exporting it.

Voltage requirement was set to $\pm 5\%$ of nominal voltage. The Norwegian regulation on quality of electricity supply has a limit of $\pm 10\%$ of nominal voltage. The difference of $\pm 5\%$ in voltage between the regulation and this thesis requirement was chosen to give room for the DSOs.

With different power resolution and power peak factors, the voltage drop becomes greater. The highest power peak factor in this thesis is 3, leading to a duration of 20 minutes for the peak. That resulted in voltage violation for every season before the co-simulation, but only a violation after simulation for autumn for a 3.3 kWh battery and winter with both a 3.3 kWh and a 15 kWh battery. The co-simulation was not able to find a solution when the I_{max} variable too small. With other step sizes for I_{max} , there might have been a solution for every day.

The cost difference in power consumption with a large and small battery was not significant, as the maximum difference found was 119.72 NOK a year. The prices for the results are from 2015, and with the spot prices from 2021 or 2022 that cost would probably be higher. It could be a good solution for the DSOs to use residential batteries instead of upgrading the LV network, depending on the cost of upgrading the LV network. The prosumer would probably not buy the 15 kWh battery, however the DSOs would benefit from having it available.

Co-simulation can be used to coordinate a battery optimization model and a load flow simulation to improve voltage quality in the distribution grid by the two models exchanging data on a co-simulation platform. The two models are an optimization model that calculate the cheapest way to charge and discharge the battery, and a load flow simulation model that outputs the voltage for the system. The bigger the battery, the greater chance of an adequate quality of the voltage. Battery costs are still high, and the cost of the battery therefore have to be taken into account when designing the system. The optimization model minimizes costs and decides when the battery

should charge and discharge, then the Simulink model simulates the voltage. The data exchanges on the co-simulation platform makes it possible for the two models to adapt and change charging and discharging pattern if the voltage quality is violated.

6.2 Future work

The co-simulation framework in this thesis could be expanded by including more houses and for longer periods of time. If more houses were included, a local energy community could be established. Within that community there would be demand for an energy market, and the chance of overvoltage are higher with more houses producing power in the same LV network. The co-simulation framework would need to be expanded to handle the overvoltage, which could be done by including a constraint on the minimum power at PCC. With a bigger co-simulation script, a separate co-simulation platform should be considered. MATLAB works for the framework established in this thesis, however, with more complex co-simulation, a dedicated co-simulation platform would be preferred.

In this thesis, there are some simplifications such as deterministic variables and no battery degradation. All the variables in this thesis are deterministic variables. In a real life scenario, the variables are stochastic, and the optimization model could include stochastic variables to be more realistic. The battery would degrade over time depending on how it is being used [38]. The optimization model could incorporate a degradation model. A degradation model would alter the charging and discharging pattern, and with less battery capacity, the profitability for the prosumer and DSO would change.

The data sets used in this thesis are from Steinkjer in 2015. In recent years, the spot price for electricity has changed in Norway. It would therefore be interesting to do a sensitivity analysis on different prices, and PV generation. The battery would perhaps do arbitrage between the price during peak and offpeak hours. The battery is the only flexible asset in the system, and it is possible to implement other flexible assets such as EV, smart hot water heater or smart room heating. With more flexible assets, the home(s) have more options to improve the quality of voltage.

Bibliography

- [1] R. Hillestad, “Co-simulation for Framework for Local Energy Communities,” Specialization project report, Norwegian University of Science and Technology, Trondheim, NO, Dec. 2021.
- [2] H. Ritchie, “The price of batteries has declined by 97% in the last three decades,” Accessed: 16.03.2022. [Online]. Available: <https://ourworldindata.org/battery-price-decline>
- [3] M. Roser, “Why did renewables become so cheap so fast?” Accessed: 16.03.2022. [Online]. Available: <https://ourworldindata.org/cheap-renewables-growth>
- [4] Rocky Mountain Institute, “Distributed energy resource cost/value framework,” Accessed: 16.03.2022. [Online]. Available: <https://appsrv.pace.edu/VOSCOE/?do=DownloadFile&res=57HBE033116120253>
- [5] NVE, “Solkraft,” Accessed: 25.04.2022. [Online]. Available: <https://www.nve.no/energi/energisystem/solkraft/>
- [6] —, “Solcellers påvirkning på strømmettet,” Accessed: 26.04.2022. [Online]. Available: <https://www.nve.no/reguleringsmyndigheten/nytt-fra-rme/nyheter-reguleringsmyndigheten-for-energi/solcellers-pavirkning-pa-stromnettet/>
- [7] Lovdata, “Forskrift om leveringskvalitet i kraftsystemet - Lovdata,” Accessed: 25.04.2022. [Online]. Available: <https://lovdata.no/dokument/SF/forskrift/2004-11-30-1557>
- [8] H. Taxt, “FINE - Flexible Integration of Local Energy Communities into the Norwegian Electricity Distribution System,” Accessed: 13.09.2021. [Online]. Available: <https://www.sintef.no/en/projects/2020/fine/>
- [9] M. Armendariz, M. Chenine, L. Nordström, and A. Al-Hammouri, “A co-simulation platform for medium/low voltage monitoring and control applications,” in *ISGT 2014*, 2014, pp. 1–5.
- [10] NEK, “NEK IEC 60038:2009,” 2009, Accessed: 26.04.2022. [Online]. Available: <https://www.standard.no/no/nettbutikk/produktkatalogen/produktpresentasjon/?ProductID=387580>
- [11] NVE, “NETT - NVE,” Accessed: 26.04.2022. [Online]. Available: <https://www.nve.no/energi/energisystem/nett/>
- [12] T. Steigen, “Solar PhotoVoltaics in Norway: a state of the art study,” Accessed: 13.04.2022. [Online]. Available: <https://nmbu.brage.unit.no/nmbu-xmlui/bitstream/handle/11250/2567308/steigen2018.pdf?sequence=1&isAllowed=y>
- [13] C. I. Ciontea and F. Iov, “A Study of Load Imbalance Influence on Power Quality Assessment for Distribution Networks,” *Electricity*, vol. 2, no. 1, pp. 77–90, 2021. [Online]. Available: <https://www.mdpi.com/2673-4826/2/1/5>
- [14] G. A. Putrus, P. Suwanapingkarl, D. Johnston, E. C. Bentley, and M. Narayana, “Impact of electric vehicles on power distribution networks,” in *2009 IEEE Vehicle Power and Propulsion Conference*, 2009, pp. 827–831.
- [15] T. Aziz and N. Ketjoy, “Pv penetration limits in low voltage networks and voltage variations,” *IEEE Access*, vol. 5, pp. 16 784–16 792, 2017.

-
- [16] O. Gandhi, D. S. Kumar, C. D. Rodríguez-Gallegos, and D. Srinivasan, “Review of power system impacts at high PV penetration Part I: Factors limiting PV penetration,” *Solar Energy*, vol. 210, pp. 181–201, 2020. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0038092X20307118>
- [17] M. Longson, “Residential storage growth continues despite Covid-19 headwinds,” Feb. 2021, Accessed: 25.04.2022. [Online]. Available: <https://www.pv-magazine.com/2021/02/18/residential-storage-growth-continues-despite-covid-19-headwinds/>
- [18] J. Hole and H. Horne, “Batterier vil bli en del av kraftsystemet,” pp. 1–5, 2019, Accessed: 26.04.2022. [Online]. Available: https://publikasjoner.nve.no/faktaark/2019/faktaark2019_14.pdf
- [19] L. Mauler, F. Duffner, W. G. Zeier, and J. Leker, “Battery cost forecasting: a review of methods and results with an outlook to 2050,” *Energy & Environmental Science*, vol. 14, no. 9, pp. 4712–4739, 2021. [Online]. Available: <https://doi.org/10.1039/d1ee01530c>
- [20] Sonnen, “Saubere und bezahlbare energie für alle!” Accessed: 25.04.2022. [Online]. Available: <https://sonnen.de/>
- [21] Tesla, “Powerwall,” Accessed: 25.04.2022. [Online]. Available: <https://www.tesla.com/powerwall>
- [22] A. Pena-Bello, E. Barbour, M. C. Gonzalez, M. K. Patel, and D. Parra, “Optimized PV-coupled battery systems for combining applications: Impact of battery technology and geography,” *Renewable and Sustainable Energy Reviews*, vol. 112, pp. 978–990, 2019. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1364032119303880>
- [23] NVE, “Smarte strømmålere (AMS),” Accessed: 26.04.2022. [Online]. Available: <https://www.nve.no/reguleringsmyndigheten/kunde/strom/stromkunde/smartestrommalere-ams/>
- [24] B. The Editors of Encyclopaedia, “power”. *encyclopedia britannica*, Accessed: 14.04.2022. [Online]. Available: <https://www.britannica.com/science/power-physics>
- [25] S. T. Baretto and O. D. Eide, “Forbrukerfleksibilitet: Et alternativ til nettinvesteringer? En analyse av potensialet for forbrukerfleksibilitet for Agder Energi Nett,” Master’s thesis, Universitetet i Agder - NOR, 2018.
- [26] Co-simulation. [Online]. Available: <https://opensimulationplatform.com/co-simulation/>
- [27] TU DELFT, “1.4 Co-Simulation | 1. Modelling Smart Grids | Smart Grids: The Basics | edX,” Accessed: 11.12.2021. [Online]. Available: <https://learning.edx.org/course/course-v1:DelftX+IEPG1x+2T2021/block-v1:DelftX+IEPG1x+2T2021+type@sequential+block@587f220b890b4b518f6c8935eb78be61/block-v1:DelftX+IEPG1x+2T2021+type@vertical+block@1589bb5f2c5f4298a4d774b970809f1c>
- [28] C. Binder, M. Fischinger, L. Altenhuber, D. Draxler, G. Lastro, and C. Neureiter, “Enabling architecture based Co-Simulation of complex Smart Grid applications,” *Energy Informatics*, vol. 2, no. S1, p. 20, Sep. 2019. [Online]. Available: <https://energyinformatics.springeropen.com/articles/10.1186/s42162-019-0084-0>
-

-
- [29] W. El-Baz, P. Tzscheutschler, and U. Wagner, "Integration of energy markets in microgrids: A double-sided auction with device-oriented bidding strategies," *Applied Energy*, vol. 241, pp. 625–639, 2019. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0306261919303460>
- [30] D. Cutler, T. Kwasnik, S. Balamurugan, T. Elgindy, S. Swaminathan, J. Maguire, and D. Christensen, "Co-simulation of transactive energy markets: A framework for market testing and evaluation," *International Journal of Electrical Power & Energy Systems*, vol. 128, p. 106664, Jun. 2021. [Online]. Available: <https://linkinghub.elsevier.com/retrieve/pii/S0142061520342095>
- [31] B. Hayes, S. Thakur, and J. Breslin, "Co-simulation of electricity distribution networks and peer to peer energy trading platforms," *International Journal of Electrical Power & Energy Systems*, vol. 115, p. 105419, Feb. 2020. [Online]. Available: <https://linkinghub.elsevier.com/retrieve/pii/S0142061519302972>
- [32] P. Verma, B. O'Regan, B. Hayes, S. Thakur, and J. G. Breslin, "EnerPort: Irish Blockchain project for peer- to-peer energy trading: An overview of the project and expected contributions," *Energy Informatics*, vol. 1, no. 1, p. 14, Dec. 2018. [Online]. Available: <https://energyinformatics.springeropen.com/articles/10.1186/s42162-018-0057-8>
- [33] J. Coignard, E. Munsing, J. MacDonald, and J. Mather, "Co-simulation Framework for Blockchain Based Market Designs and Grid Simulations," in *2018 IEEE Power & Energy Society General Meeting (PESGM)*. Portland, OR: IEEE, Aug. 2018, pp. 1–5. [Online]. Available: <https://ieeexplore.ieee.org/document/8586124/>
- [34] A. Elhefny, Z. Jiang, and J. Cai, "Co-simulation and energy management of photovoltaic-rich residential communities for improved distribution voltage support with flexible loads," *Solar Energy*, vol. 231, pp. 516–526, 2022. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0038092X21010112>
- [35] R. Rana, K. Berg, M. Z. Degefa, and M. Löschenbrand, "Modelling and simulation approaches for local energy community integrated distribution networks," *IEEE Access*, pp. 1–1, 2022.
- [36] Nord Pool, "See hourly day-ahead prices." Accessed: 13.09.2021. [Online]. Available: <https://www.nordpoolgroup.com/en/Market-data1/Dayahead/Area-Prices/ALL1/Hourly/>
- [37] NVE, "Nettleiestatistikk," Accessed: 10.05.2022. [Online]. Available: <https://www.nve.no/reguleringsmyndigheten/publikasjoner-og-data/statistikk/nettleiestatistikk/>
- [38] J. S. e. a. Edge, "Lithium ion battery degradation: what you need to know," *Phys. Chem. Chem. Phys.*, vol. 23, no. 14, pp. 8200–8221, 2021, publisher: The Royal Society of Chemistry. [Online]. Available: <http://dx.doi.org/10.1039/D1CP00359C>

A Appendix

The appendix has four part. The first part is descriptions of parts of the Simulink model, "Values from MATLAB to Simulink from the upper layer", and "Timestamp" from the lower layer. The results from spring and autumn for battery sizes: 3.3 kWh and 15 kWh. The last part is a summary of the spring and autumn simulations.

A.1 Simulink setup

Values from MATLAB to Simulink

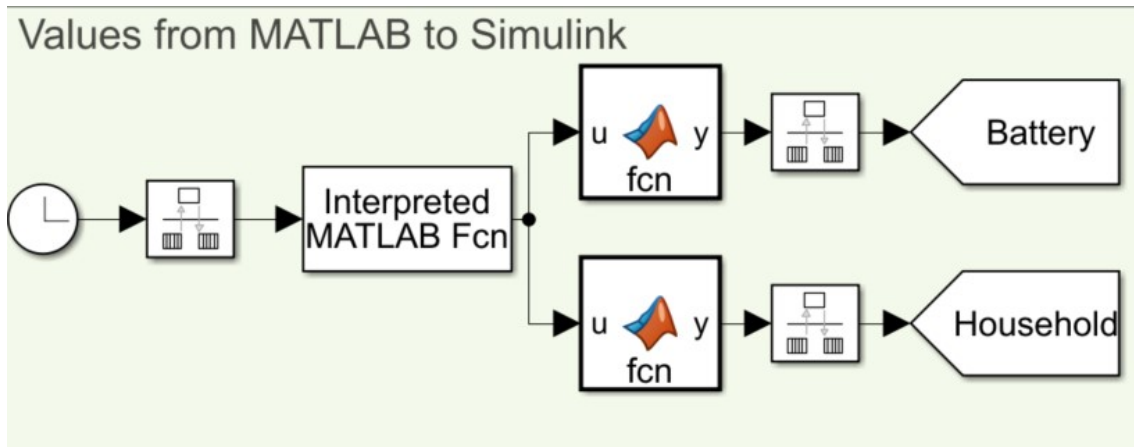


Figure 35: From MATLAB to Simulink, two vectors

The link between the MATLAB script and the Simulink model is shown in Figure 35. The figure is a part of the subsystem in Figure 7 and has two branches with the same purpose, for the battery and for the household. The clock on the left is keeping track of the simulation time in Simulink. The second block makes sure that data is transferred at the right rate. A rate transition can have different functionalities. In this setup, the three rate transition blocks have two different purposes. The first-rate transition block keeps track of time and runs at distinct intervals. In this model, the time is set to 24. The block restarts when the clock hits 24 and starts the process again, this makes it so that the rest of the steps in Figure 35 only happen once every 24 hours. When the 24-hour interval is over, the Interpreted MATLAB Fcn is activated. The block runs a MATLAB script. The MATLAB script gets the values for charging and discharging of the battery, power produced by PV and the load for the house. Calculations for eq. (7) and (6) happen in the end of the script as a single vector with 48 values. The 24 first values are the values for the household load/generation, and the last 24 values are the charging/discharging for the battery. The vector has to be split into values for the household and the battery. This is what happens after the branching. The top and bottom of the branching are identical, except from what part of the vector it uses further. The top branch uses the values for the battery, and the bottom is for the household. "MATLAB function" is a block that runs a MATLAB script in Simulink. In this model, the MATLAB script is either outputting the first or the last 24 values from the vector with the household load/generation or battery charging/discharging. There is a rate transition block after the MATLAB function block. The rate transition block with $1/z$ is a unit delay. A unit in these simulations is 0.0001 hour, the same as a time step. The final block is a Goto block and has a corresponding From block in the

subsystem. The two Goto blocks send the values to the "Input load/generation for households" and "Battery charge/discharge" in Figure 8. The From block corresponding with "Battery" and "Household" Goto blocks will be described further in "Input load/generation for households" and "Battery charge/discharge".

$$household_t = L_t - PV_t \quad (6)$$

$$battery_t = c_t - d_t \quad (7)$$

Timestamp

The purpose of the timestamp part is to connect the values from the input vector to the hours of the day. The block to the right is a switch with three inputs. A switch switches between what it sends as the output when an inequality is true or untrue. The bottom input is the output when the inequality is untrue. The top input is the output when the inequality is true. The middle input is what the inequality measures. The inequality is $input \geq 2$. The input is the clock, so the switch switches output when the second hour starts. The bottom input is 1. The top input is described below. The block to the left in Figure 36 is a stepwise increasing function. It goes from 0 to 23, after 23 it starts over at 0. the double block makes the output from the stepwise block into numbers so that it can be used in calculations. Since it goes from 0 to 23, 1 is added to every value from the stepwise function. The values from the additive block then ranges from 1 to 24. A unit delay is used before the input is sent to the switch. The output from the witch is always the hour of day in the simulation and is used in Input load/generation and Battery charge/discharge.

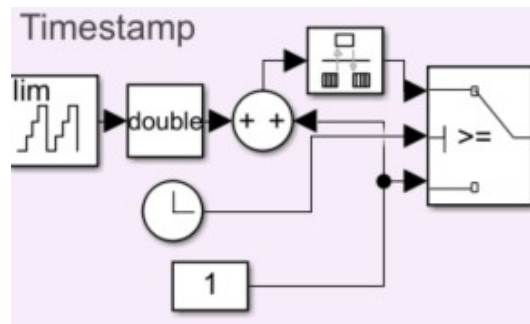


Figure 36: Timestamp

A.2 Power peaks spring and autumn

This section presents the results for power peaks with a 3.3 kWh battery for spring and autumn with power peak factors 2, 2.5 and 3.

A.2.1 Power peak 2

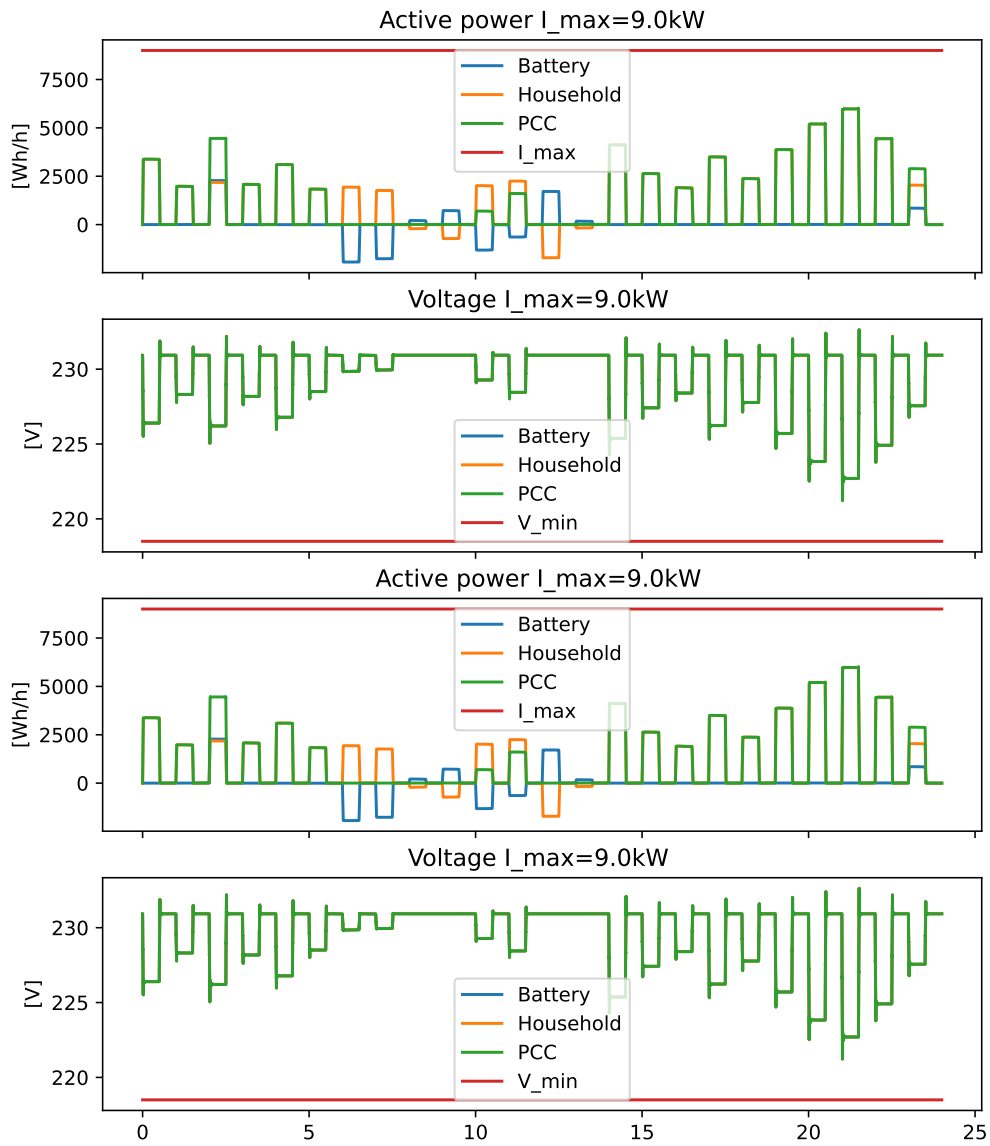


Figure 37: Spring: Power peak 2, first and last simulation

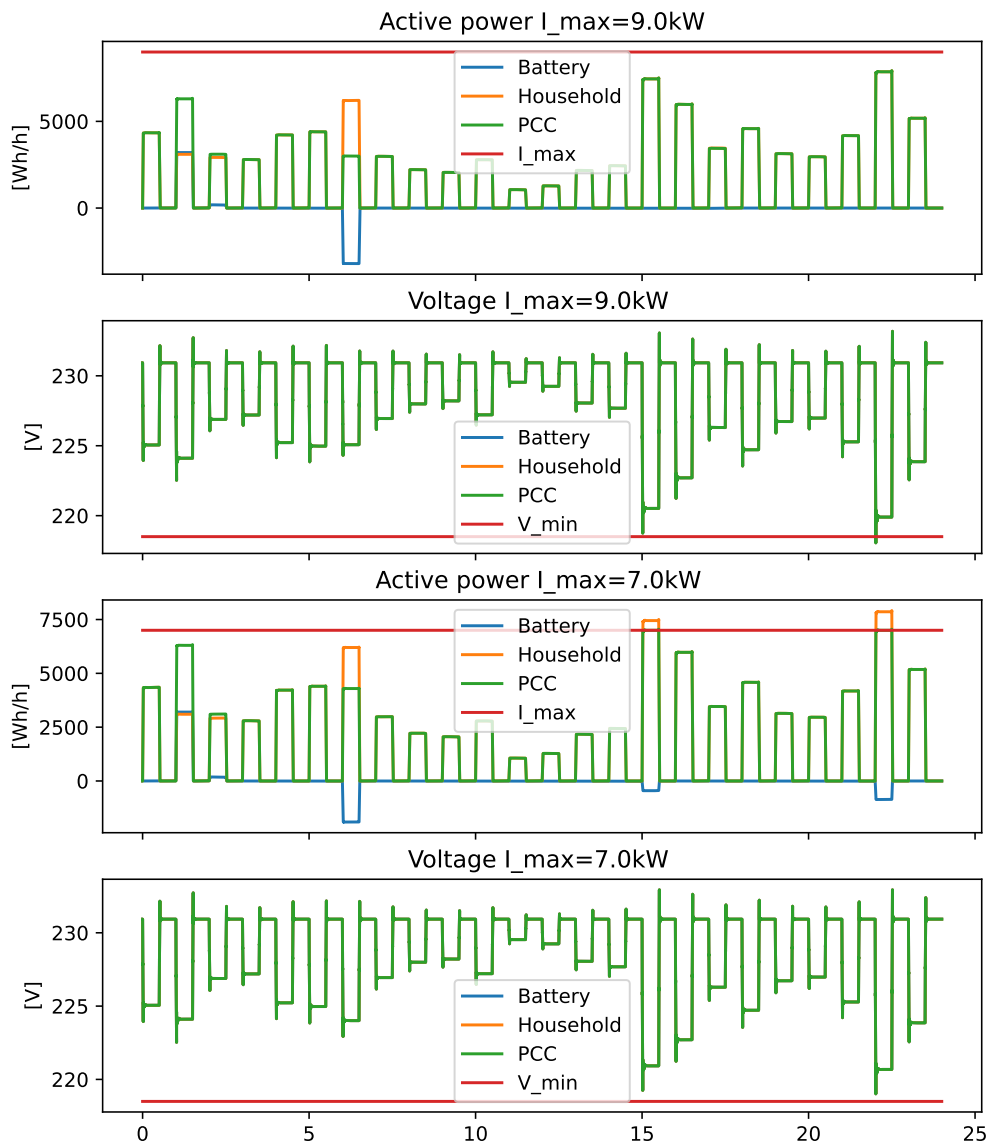


Figure 38: Autumn: Power peak 2, first and last simulation

A.2.2 Power peak 2.5

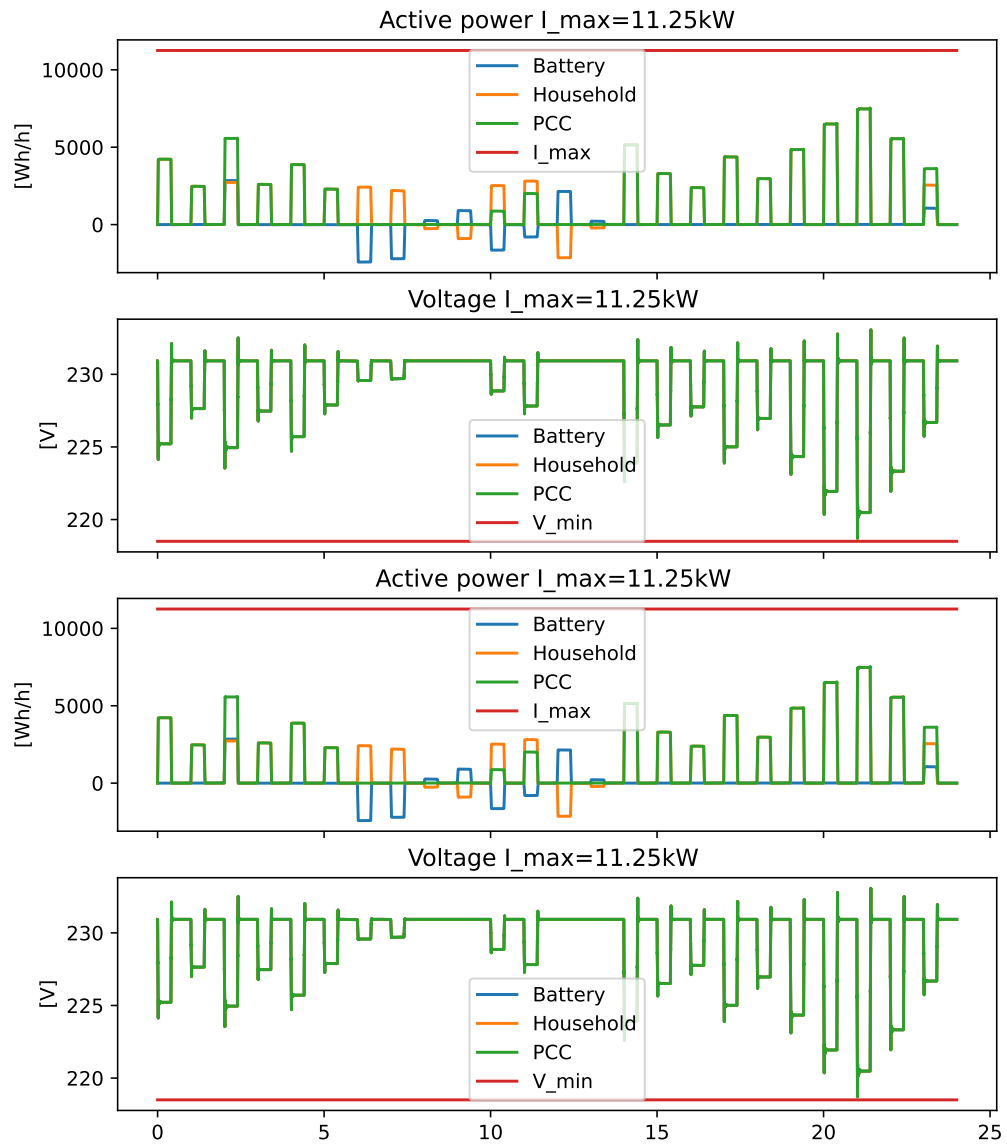


Figure 39: Spring: Power peak 2.5, first and last simulation

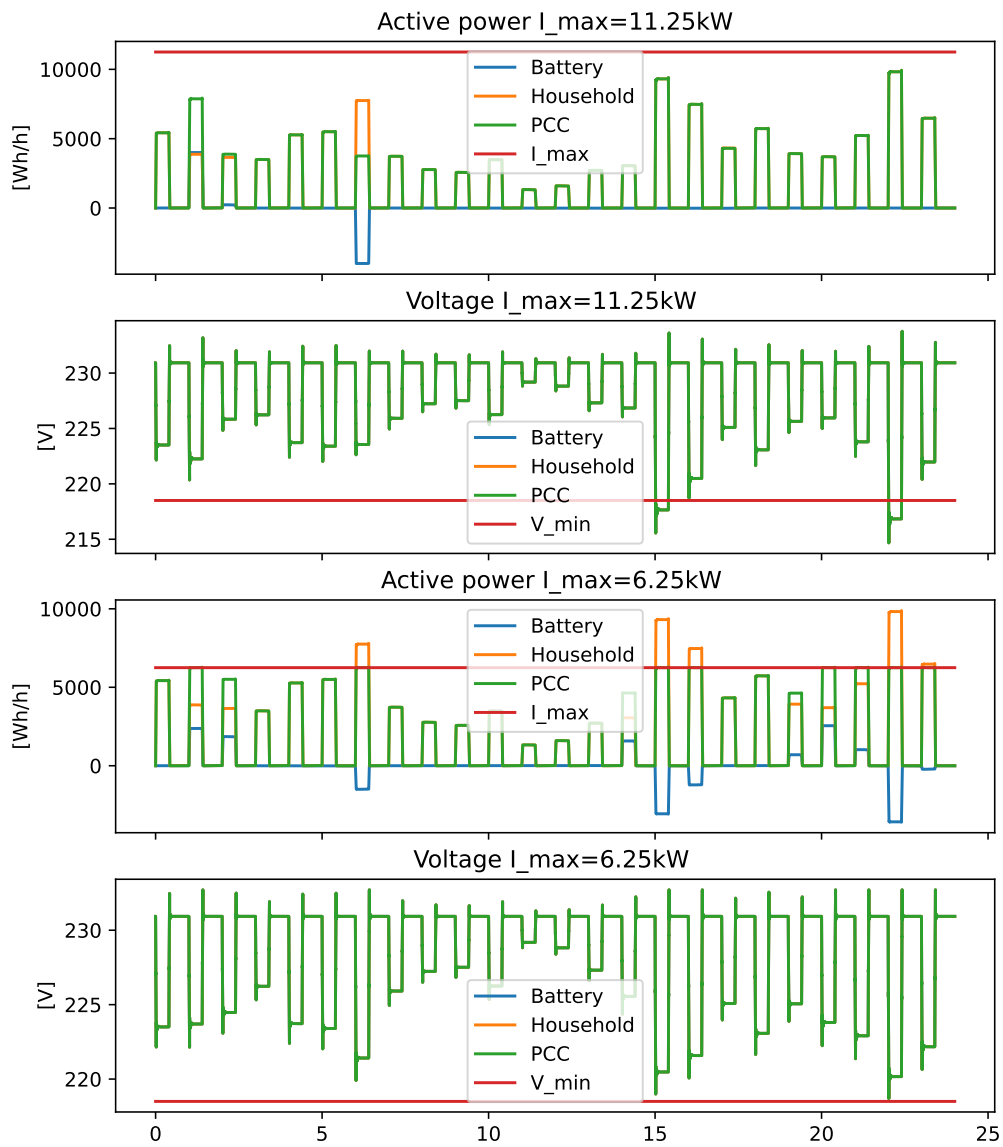


Figure 40: Autumn: Power peak 2.5, first and last simulation

A.2.3 Power peak 3

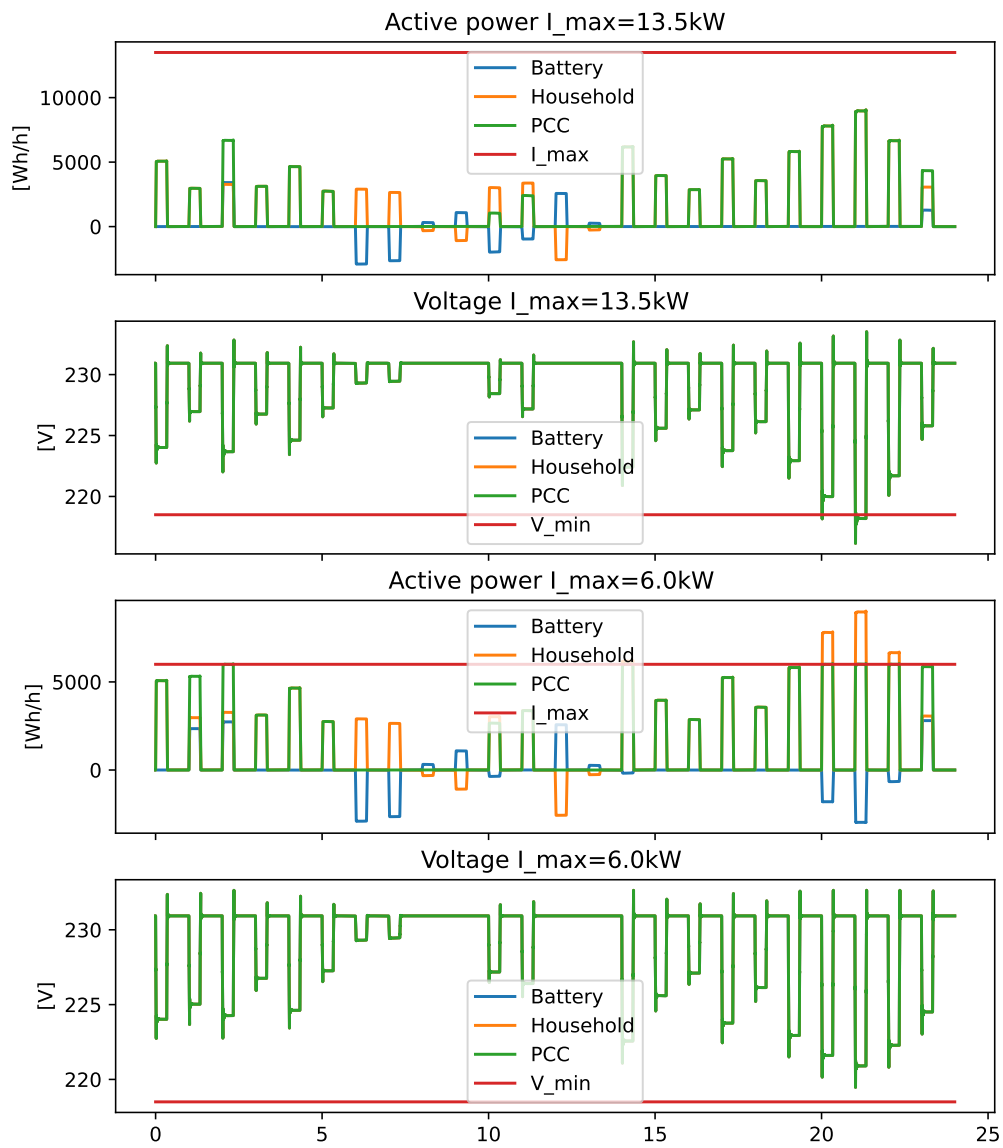


Figure 41: Spring: Power peak 3, first and last simulation

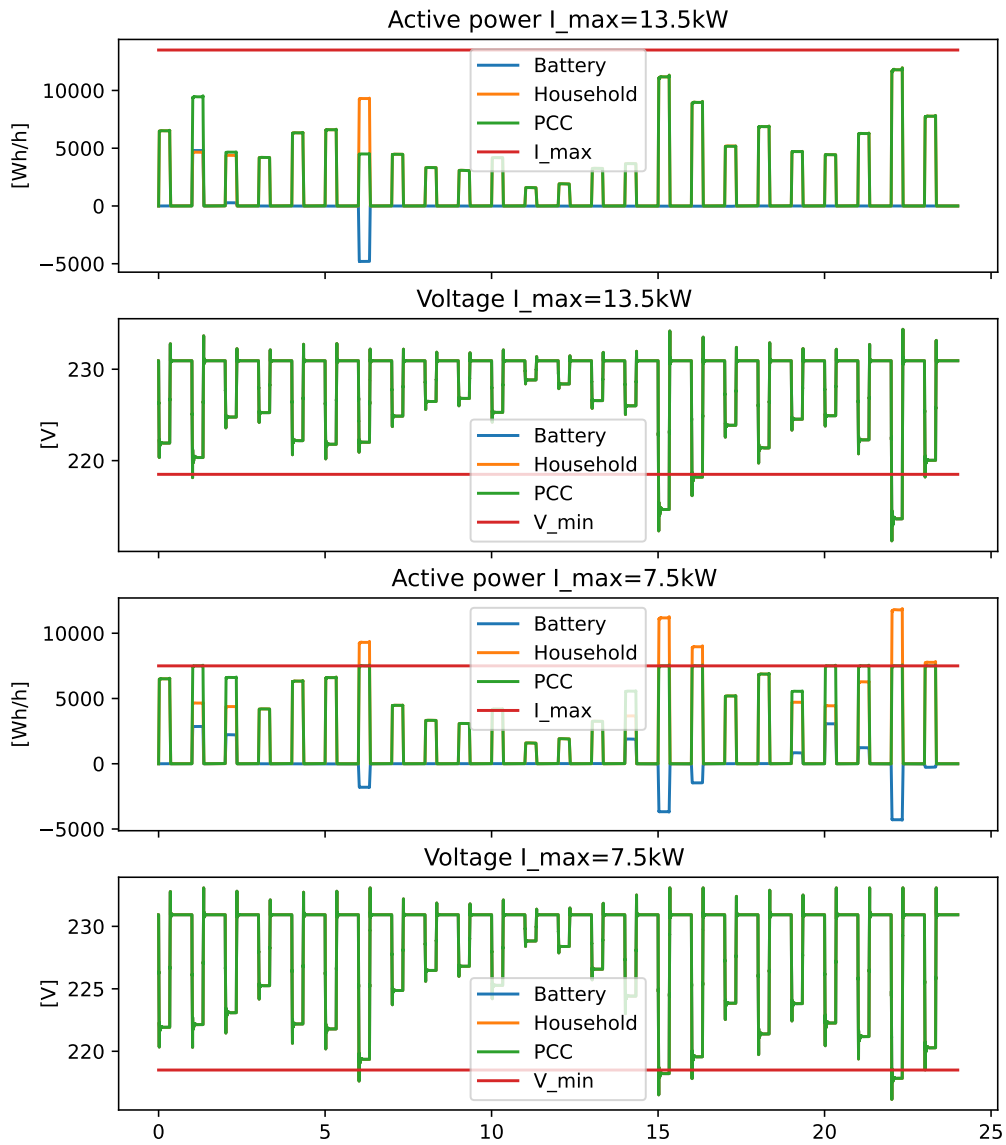


Figure 42: Autumn: Power peak 3, first and last simulation

A.3 Power peaks with larger battery spring and autumn

This section presents the results for power peaks with a 15 kWh battery for spring and autumn with power peak factors 2, 2.5 and 3.

A.3.1 Power peak 2

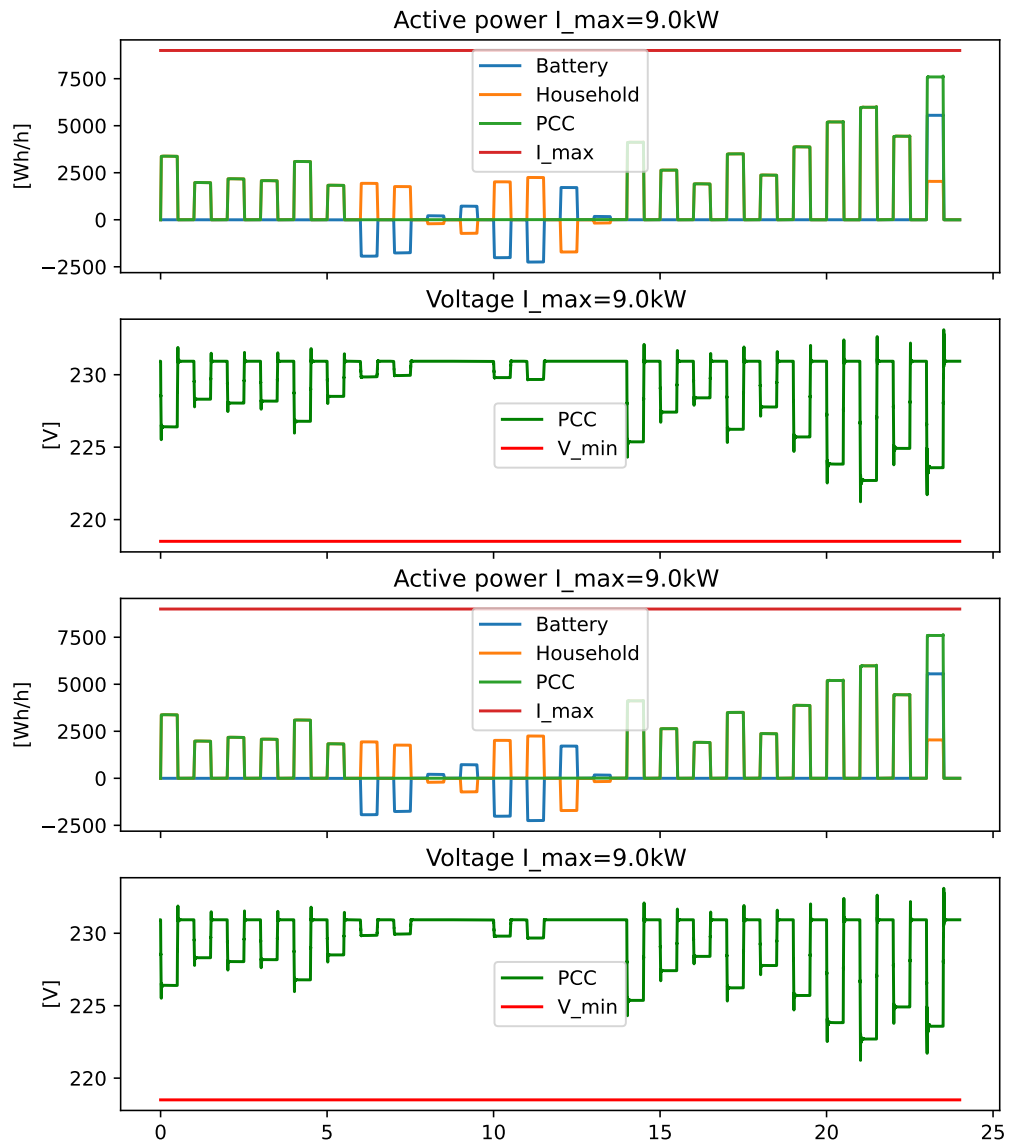


Figure 43: Spring: Power peak 2 larger battery, first and last simulation

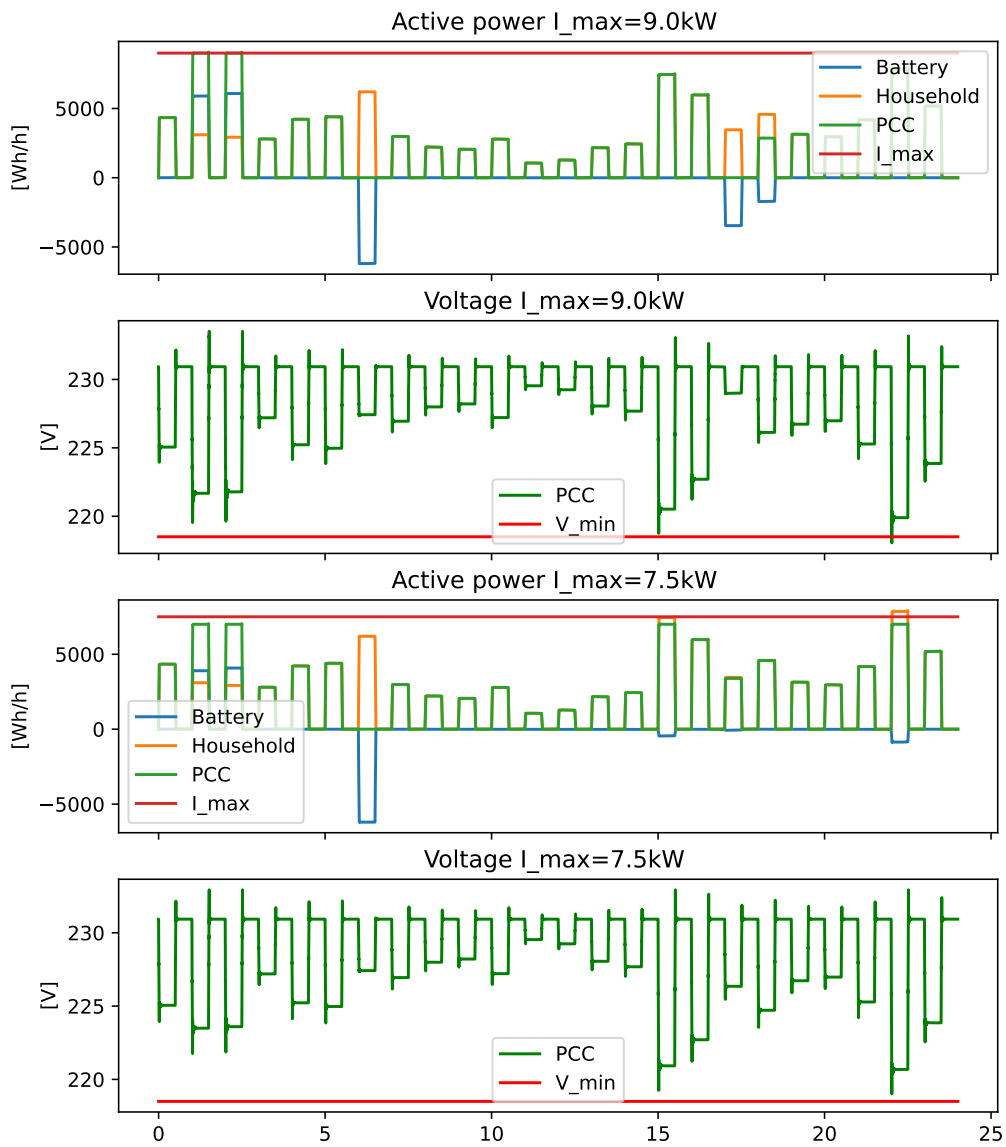


Figure 44: Autumn: Power peak 2 larger battery, first and last simulation

A.3.2 Power peak 2.5

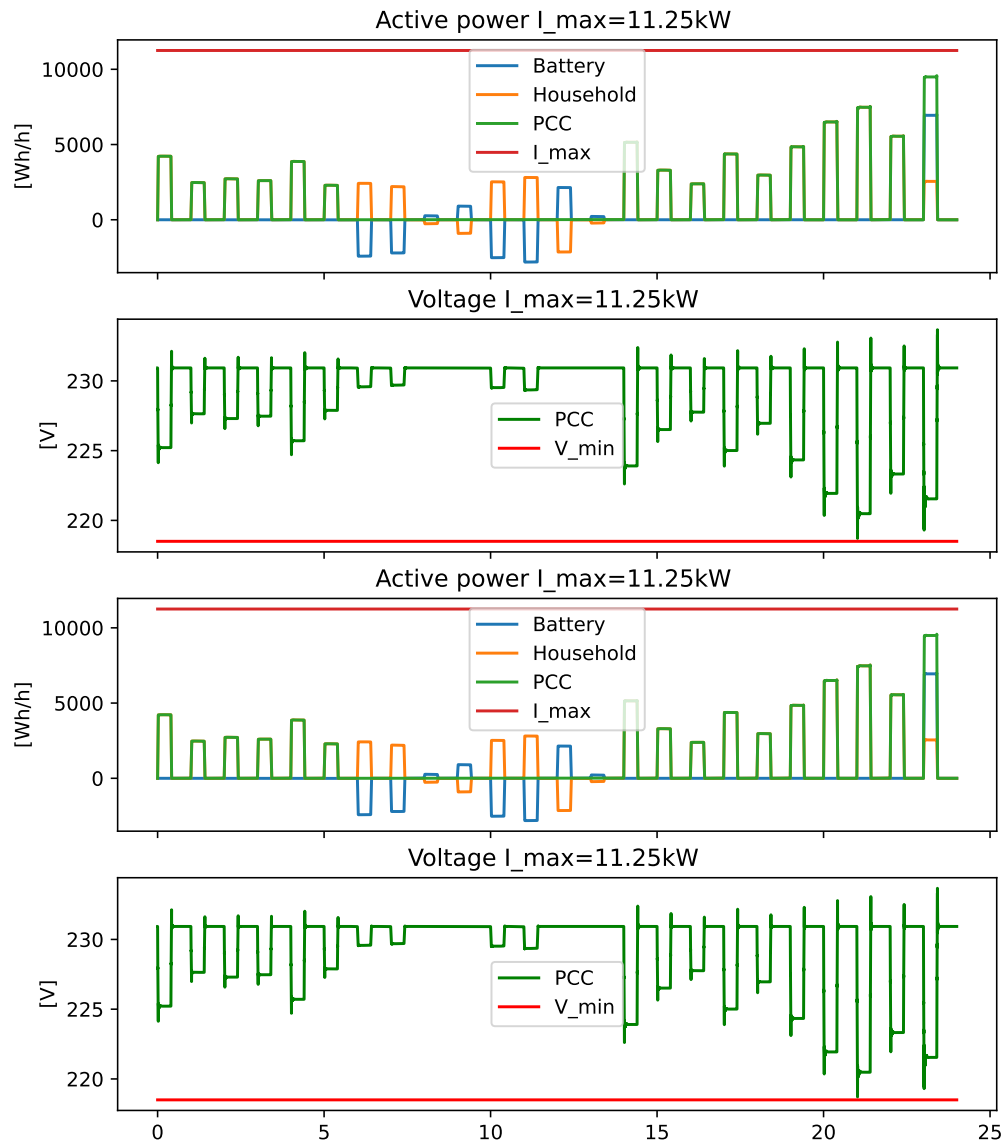


Figure 45: Spring: Power peak 2.5 larger battery, first and last simulation

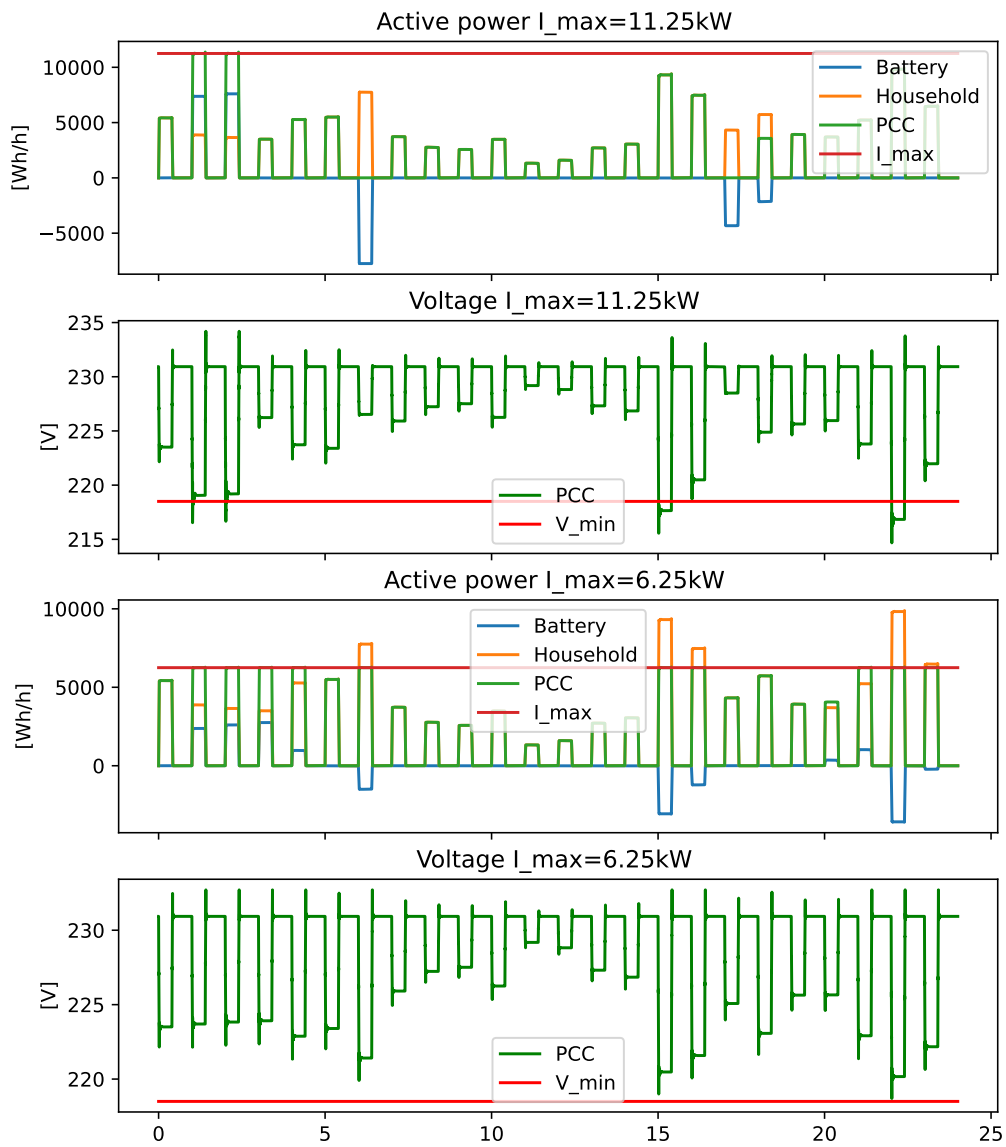


Figure 46: Autumn: Power peak 2.5 larger battery, first and last simulation

A.3.3 Power peak 3

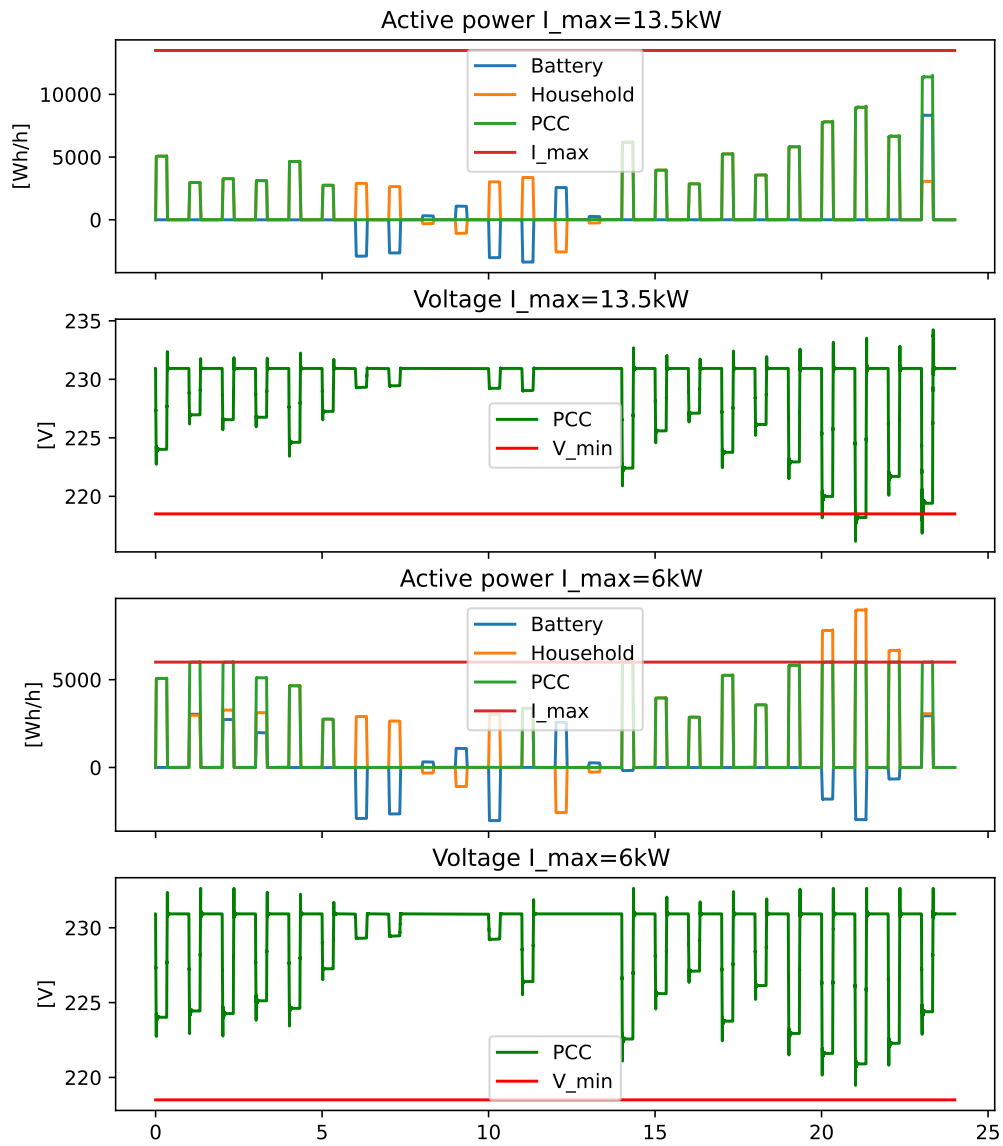


Figure 47: Spring: Power peak 3 larger battery, first and last simulation

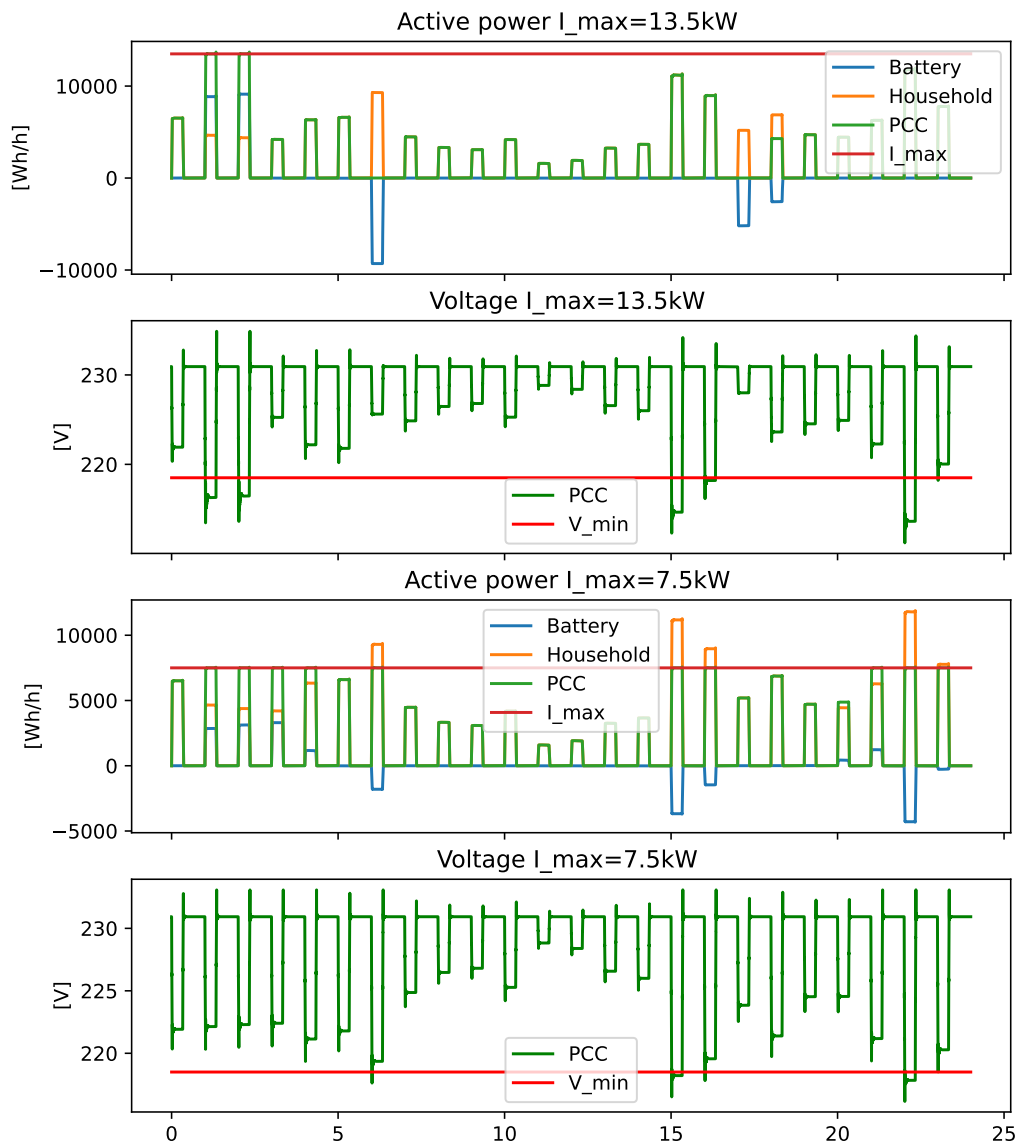


Figure 48: Autumn: Power peak 3 larger battery, first and last simulation

A.4 Summary of spring and autumn voltages

Table 7: Summary of voltage for the spring simulations for the first and last iteration

| Case | Lowest voltage [V] | Size of battery[kWh] | Lowest voltage after co-simulation[V] |
|----------|--------------------|----------------------|---------------------------------------|
| Base | 226.83 | 3.3 | 226.83 |
| Peak 2 | 221.23 | 3.3 | 221.23 |
| Peak 2.5 | 218.71 | 3.3 | 218.71 |
| Peak 3 | 216.15 | 3.3 | 219.47 |
| Peak 2 | 221.23 | 15 | 221.23 |
| Peak 2.5 | 218.71 | 15 | 218.71 |
| Peak 3 | 216.15 | 15 | 219.47 |

Table 8: Summary of voltage for the autumn simulations for the first and last iteration

| Case | Lowest voltage [V] | Size of battery[kWh] | Lowest voltage after co-simulation[V] |
|----------|--------------------|----------------------|---------------------------------------|
| Base | 226.83 | 3.3 | 226.83 |
| Peak 2 | 218.06 | 3.3 | 219.01 |
| Peak 2.5 | 214.67 | 3.3 | 218.70 |
| Peak 3 | 211.22 | 3.3 | 216.15 |
| Peak 2 | 211.22 | 15 | 216.15 |
| Peak 2.5 | 214.67 | 15 | 218.70 |
| Peak 3 | 216.15 | 15 | 219.47 |

